

Original Research

How Can Architectural Acoustics Reflect Levels of Stress and Relaxation in Indoor Environments? An EEG-Based Experimental Study

Navid Khaleghimoghaddam ^{1, *}, Sara Arzhangi ²

1. Assist. Prof. Dr., Konya Food and Agriculture University, Department of Interior Architecture, Konya, Turkey; E-Mail: navid.khaleghi1363@gmail.com
2. Instructor. M.A. in Architecture, 17 Shahrivar University, Department of Architecture, Karaj, Iran; E-Mail: arzhangi.sa@gmail.com

* **Correspondence:** Navid Khaleghimoghaddam; E-Mail: navid.khaleghi1363@gmail.com

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Abstract

The acoustic design of indoor environments encompassing spatial configuration, material properties, and sound absorption significantly influences auditory perception and psychological well-being. This study examines the interaction between architectural acoustics, musical stimuli, and neural responses within a controlled therapeutic context, focusing on their effects on stress reduction and relaxation. Electroencephalography (EEG) was utilized to measure brain activity in 24 participants exposed to six musical instruments (piano, violin, guitar, flute, tambourine, and cello) within a simulated environment with systematically varied reverberation and absorption conditions. The results demonstrated that melodic instruments, such as the piano and flute, notably enhanced alpha/ α and theta/ θ wave activity indicators of relaxation, particularly in spaces with optimized sound absorption. Conversely, percussive instruments, such as the tambourine, and fast rhythmic sequences increased beta/ β wave activity, which is associated with heightened arousal and tension. Additionally, varying levels of reverberation and sound reflection further influenced perceptual and neural responses to music. These findings highlight the potential of integrating evidence-based



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acoustic design and music selection into therapeutic environments, such as hospitals and psychotherapy clinics, to alleviate stress and support patient recovery.

Keywords

Architectural acoustic; therapeutic spaces; sound perception; mental health; stress reduction; brain responses; EEG

1. Introduction

The human brain has an excellent capacity for forming new connections and creating optimistic pathways, while modern neuroimaging techniques enable functional studies related to professional scientific training and artistic performances [1]. Architectural acoustics has emerged as a crucial factor in influencing the functionality and psychological impact of indoor environments, transcending the realm of mere auditory comfort to affect mental health and well-being [2]. Acoustic quality, which refers to a space's capacity to manage ambient noise, ensure speech intelligibility, and provide sound isolation, is vital for creating supportive environments, particularly in therapeutic settings. Effective acoustic design utilizes sound-absorbing materials such as acoustic ceiling tiles, carpets, and wall panels to reduce reverberation and echo, which can otherwise exacerbate auditory discomfort and stress. Inadequate acoustic conditions are associated with increased stress, reduced productivity, and auditory health issues [3], whereas well-designed acoustics can promote relaxation and enhance cognitive performance [4-6]. The COVID-19 pandemic has intensified the need for serene indoor spaces, highlighting music as a powerful therapeutic tool for stress reduction. Research underscores the effectiveness of music therapy in healthcare contexts, where it fosters relaxation and a sense of safety among patients [7-9]. Historically, music has functioned as a cross-cultural medium for healing, and its contemporary use in stress-reduction programs within hospitals illustrates its therapeutic potential [10]. The physical attributes of music, including frequency, intensity, and rhythm, significantly influence emotional and cognitive responses. Research indicates that frequencies ranging from 1 to 5 kHz promote relaxation and reduce fatigue [11, 12], whereas frequencies exceeding 6 kHz may induce tension and anxiety [13, 14]. Despite these findings, the specific neural effects of music's physical properties in acoustically controlled environments remain inadequately explored. Music therapy utilizes rhythm and melody to facilitate mental and physical relaxation; however, the underlying neurophysiological mechanisms require further investigation [15]. Previous studies have examined the role of sound production in neurological and cognitive rehabilitation through spectral analysis, auditory behavioral assessments, and clinical trials [16-21]. Additional findings suggest that nature-inspired sounds can enhance concentration and alleviate stress [22-24]. To address these gaps, EEG offers a non-invasive method for measuring brain activity in response to auditory stimuli. EEG signals are categorized into four primary frequency bands [25-27]: delta (1–3 Hz), associated with deep sleep; theta/θ (4–7 Hz), linked to relaxation and creativity; alpha/α (8–13 Hz), indicative of calmness and alertness; and beta/β (14–30 Hz), associated with focus and stress. Within the alpha/α band, low-frequency waves (α1: 8–10 Hz) represent tranquility, while higher frequencies (α2: 10–12 Hz) reflect a state of relaxed alertness. Beta/β waves are further divided into low-frequency (β1:

13–17 Hz) waves, which signal concentration, and high-frequency (β 2: 18–30 Hz) waves, which indicate arousal. The ratio of β 2/ β 1 to α 1/ α 2 waves serves as a key indicator of stress levels.

This study examines the relationship between architectural acoustics and musical stimuli on neurophysiological and emotional responses, addressing several key questions: How do musical properties influence perception and brain activity? Can music alleviate stress and enhance concentration? Are the physical characteristics of music (e.g., frequency, intensity) associated with neural outcomes? What role does acoustic design play in modulating these effects? To investigate these questions, brain activity was recorded via EEG from participants exposed to six musical instruments—piano, violin, guitar, flute, tambourine, and cello—within a controlled acoustic environment featuring varied reverberation and absorption conditions. Through the analysis of these responses, this research clarifies how acoustic design and music therapy collaboratively impact stress reduction and mental well-being. The findings aim to inform the design of therapeutic spaces, such as healthcare facilities, by providing evidence-based insights into optimizing auditory environments for relaxation and cognitive health. What distinguishes this study from existing research is its integrative and empirically grounded approach to understanding how musical timbre and architectural acoustic conditions jointly influence neural activity, emotional regulation, and cognitive engagement. While previous studies have explored the effects of music on stress and relaxation, they have often done so within clinical contexts (e.g., music therapy interventions) or environmental psychology studies focusing on general soundscapes (e.g. [28, 29]). Some research has examined how specific instrumental timbres interact with spatial design to modulate neural activity (e.g. [30, 31]). Additionally, most studies have focused on either music therapy or room acoustics in isolation (e.g. [32, 33]); this study addresses both variables simultaneously, providing a multidimensional approach that more accurately reflects real-world architectural scenarios. However, few have investigated the interaction between physical architectural sound conditions (e.g., reverberation, absorption) and the acoustic signatures of different musical instruments, particularly through the lens of neurophysiological metrics such as EEG. This study thus offers a multidimensional framework by integrating architectural acoustics, auditory neuroscience, and music psychology to evaluate how built environments can be optimized for emotional and cognitive well-being. By incorporating both musical content and architectural context, this approach transcends reductionist models. It adopts a comprehensive perspective—one that more accurately reflects how individuals experience sound in real-world architectural settings, such as therapy rooms, clinics, or meditation spaces. So, it not only enhances the scientific understanding of sound perception and emotional processing but also provides practical implications for the evidence-based design of therapeutic environments, where music and spatial acoustics can be jointly tailored to promote relaxation, reduce stress, and enhance mental restoration.

The selection of the six musical instruments—piano, violin, flute, guitar, tambourine, and cello—was deliberate, based on their distinct acoustic profiles, frequency spectra, and psychological associations. These instruments collectively encompass a broad range of dominant frequency bands pertinent to emotional processing. For example, the flute and piano, characterized by smoother harmonic structures and mid-range frequencies (~2–5 kHz), are associated with calming and meditative effects. Conversely, percussive instruments such as the tambourine, which are rich in high-frequency transients (>6 kHz) and exhibit irregular attack-decay envelopes, often elicit alertness and arousal. The violin and cello provide complex harmonic content with emotionally evocative timbres, making them relevant for investigating cognitive engagement and emotional

valence [34-36]. Meanwhile, the acoustic guitar bridges melodic and rhythmic domains, offering insights into how mixed timbral properties influence neural activity. By analyzing EEG responses to these carefully selected stimuli under controlled reverberation and absorption conditions, this study provides novel insights into how music and spatial factors interact to influence emotional and cognitive states. It contributes to evidence-based acoustic design in therapeutic architecture, a field still in need of empirical grounding. This multifactorial approach, bridging architecture, musicology, and neuroscience, thus underscores the study's originality and practical significance.

2. Materials and Methods

2.1 Experimental Environment and Its Architectural Features

To evaluate the impact of architectural acoustics on auditory perception and neurophysiological responses, this experiment was conducted under two distinct acoustic conditions within a 4 m × 5 m room. The first condition served as a control: an untreated room characterized by natural sound reflections, ambient noise, and the absence of acoustic modifications. This baseline setup facilitated the assessment of music perception and brain activity in a typical, uncontrolled indoor environment. The second condition employed the same room but incorporated targeted acoustic treatments to minimize external variables that could confound sensory perception and neural outcomes. This comparative design was informed by prior studies indicating that optimized acoustic environments enhance cognitive and emotional responses to auditory stimuli. In the treated condition, the room was equipped with sound-absorbing panels on the ceiling and walls, achieving an absorption coefficient of 0.75 across the 500 Hz to 4 kHz frequency range, which encompasses the primary spectrum of the musical stimuli used. These panels effectively reduced reverberation and background noise, ensuring that recorded brain responses reflected the intended auditory input rather than environmental artifacts. The floor was fitted with acoustic carpeting, and the walls were constructed from wood layered with compressed sound-absorbing fibers, further attenuating ambient noise while enhancing participant comfort through a warm, inviting aesthetic. A controlled lighting system was implemented to eliminate visual distractions, thereby maintaining focus on auditory stimuli. The spatial configuration was optimized for consistent sound delivery, with participants seated at the center of the sound field, equidistant from two loudspeakers to ensure uniform exposure to musical stimuli. This arrangement minimized acoustic interference and standardized the listening experience across participants. Collectively, these modifications established a controlled therapeutic environment conducive to evaluating the interplay between architectural acoustics, music perception, and brain activity, aligning with the study's objective to isolate the effects of acoustic design on relaxation and engagement.

A high-fidelity audio reproduction system and an electroencephalography (EEG) setup were employed to deliver auditory stimuli and capture brain responses, respectively. The audio system consisted of two Genelec 8040B professional loudspeakers, symmetrically positioned on either side of the participant at a fixed distance to ensure uniform sound distribution across the sound field. Auditory stimuli were presented at a consistent intensity of 60 dB, calibrated to maintain standardization throughout the experiment and mitigate auditory fatigue or discomfort. Brain activity was recorded using the EEG system, equipped with 16 active electrodes configured according to the international 10-20 system. Data were sampled at 500 Hz, providing high temporal resolution to detect subtle changes in neural responses to the auditory stimuli. Six musical

instruments—piano, violin, guitar, flute, tambourine, and cello—were utilized as auditory stimuli, each presented for 60 seconds. These instruments were selected for their distinct acoustic profiles, particularly their dominant frequencies, based on prior research indicating that sounds in the 1–5 kHz range promote relaxation and reduce fatigue. In contrast, frequencies above 6 kHz may induce tension and anxiety. Pre-recorded, high-quality samples of each instrument were employed to ensure consistency in tone, rhythm, and intensity across trials. This setup enabled a systematic comparison of brain responses between untreated and acoustically optimized environments, facilitating an analysis of how architectural acoustics modulates the physiological and emotional effects of music. The combination of precise audio delivery and high-resolution EEG recording provided a robust framework for investigating the interplay between sound stimuli, acoustic design, and neurophysiological outcomes.

2.2 Participants

The study recruited 12 men and 12 women, aged 20–40 years, all of whom volunteered for participation. While no formal power analysis was conducted before data collection, the sample size ($N = 24$) was determined based on established practices in EEG studies involving within-subject comparisons of acoustic or emotional stimuli. Previous research suggests that sample sizes between 20 and 30 participants are adequate for reliably detecting neurophysiological effects in repeated-measures designs. The implementation of a within-subject design in this study enhanced sensitivity to individual differences and facilitated robust detection of condition-related effects across brain regions. Inclusion criteria required normal hearing (self-reported), no history of neurological or psychiatric disorders, and no reported hypersensitivity to environmental noise. The exclusion of individuals with these conditions ensured the validity of neurophysiological responses to auditory stimuli. Before participation, all individuals provided written informed consent after receiving a comprehensive briefing on the experimental procedure, which included assurances of data anonymity and the potential use of de-identified images in publications. Concerning their level of education and other protocols before participation, all volunteers were assured that their demographic information would remain confidential and that their data would be anonymized. Participants were also informed of their right to withdraw from the study at any time without consequence. The research protocol was reviewed and approved by the institutional ethics committee before commencement, ensuring compliance with ethical standards for research involving human subjects.

2.3 Data Collection

The experiment evaluated the effects of acoustic treatments on brain responses through two distinct environmental conditions, as detailed in Section 2.1. The first condition employed an untreated 4 m × 5 m room characterized by uncontrolled sound reflections and ambient noise, which could introduce auditory interference. In contrast, the second condition utilized the same room enhanced with sound-absorbing panels (absorption coefficient: 0.75, 500 Hz–4 kHz), acoustic carpeting, and an optimized spatial arrangement to minimize reverberation and external variables, thereby ensuring the precise delivery of auditory stimuli (Figure 1). Data collection procedures were consistent across both conditions to facilitate a direct comparison of the impacts of acoustic design on neurophysiological outcomes. Each session commenced with a 5-minute adaptation phase in

silence, allowing participants to acclimate to the environment and reducing initial auditory biases. This was followed by a 2-minute pre-exposure EEG recording in a resting state with eyes closed, establishing a baseline of brain activity devoid of visual or auditory influences. During the auditory phase, participants listened to six pre-recorded musical pieces featuring distinct instruments: piano (PN), violin (VL), guitar (GT), flute (FL), tambourine (TB), and cello (CL), each lasting 60 seconds. The order of presentation was randomized to mitigate sequence effects, with a 20-second silence interval between stimuli to diminish carryover effects. A 30-second rest period separated each piece, ensuring independent engagement with subsequent stimuli. Sound intensity was consistently maintained at 60 dB across conditions, calibrated to standardize exposure. Instrument selection was informed by their dominant frequencies (1–5 kHz), a range associated with relaxation and fatigue reduction in previous research. Following the final stimulus, a 2-minute post-exposure EEG recording was conducted in a resting state to assess any lingering effects of the auditory experience.

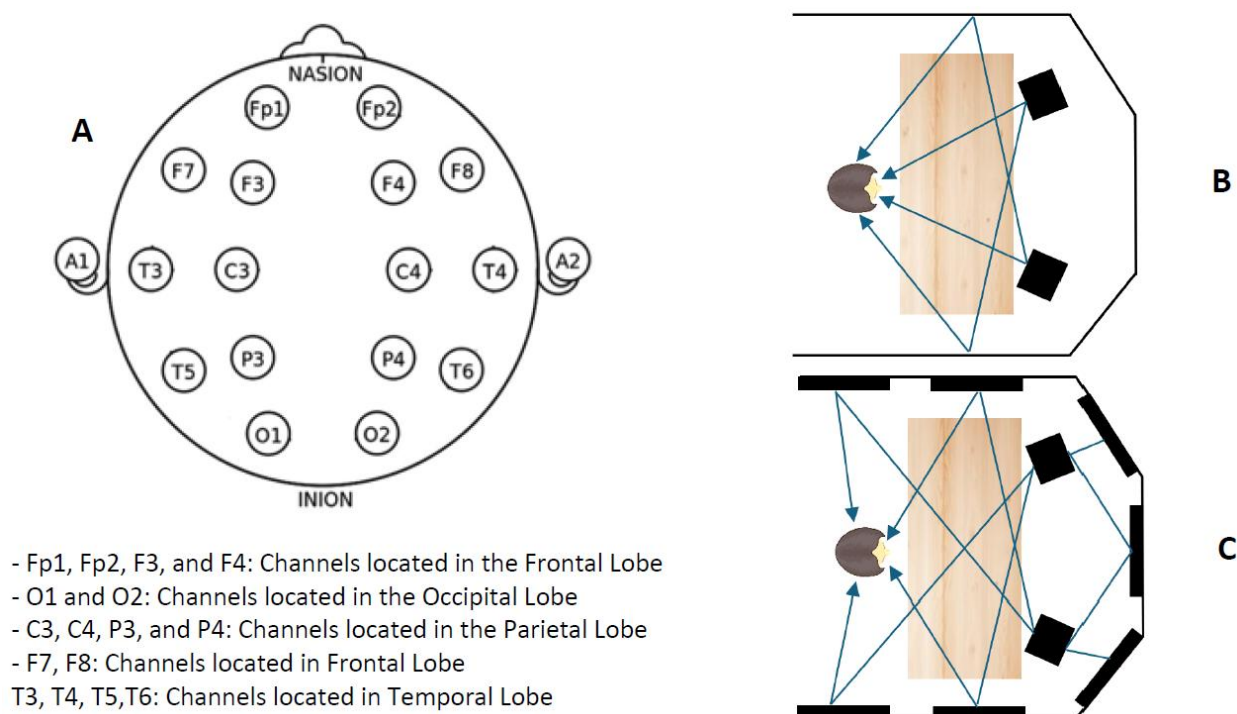


Figure 1 A) The 16-channel EEG electrode location and the 4 brain regions; B) Experiment room before acoustic design; C) Experiment room after acoustic design.

The stimulus timing structure in this study was developed based on established principles in EEG signal acquisition and music cognition research; however, no prior work explicitly implements the exact sequence used here. Each trial consisted of 60 seconds of musical exposure, followed by 20 seconds of silence, a 30-second resting baseline, and a 2-minute post-stimulus observation phase. This design was motivated by the need to (a) capture sufficient temporal dynamics for oscillatory changes in alpha, beta, and theta bands during listening, (b) facilitate the return of brain activity toward the pre-stimulus baseline, and (c) observe lingering neural responses following emotionally or cognitively engaging music.

The 60-second stimulus duration is necessary to reliably evoke alpha, beta, and theta modulations associated with emotional arousal, relaxation, or attention. Such listening durations enable the auditory cortex and limbic system to engage in affective and cognitive processing. Also,

it was selected to allow for the emergence of measurable neural entrainment, consistent with prior EEG music studies that utilized similar or longer excerpts to capture reliable oscillatory responses. Such listening durations enable the auditory cortex and limbic system to engage in affective and cognitive processing [37-39]. A 30-second resting period before the subsequent trial establishes a neutral baseline for comparison, facilitating the differentiation between tonic (lingering) and phasic (stimulus-locked) brain activity, and minimizing emotional and neural overlap [40, 41]. The 20-second silence interval serves as a transition buffer, mitigating auditory carryover effects while allowing transient neural responses to return to baseline [42]. Lastly, the 2-minute post-stimulation rest period is included to evaluate the lingering impact of musical and acoustic exposure, as supported by research indicating that neural correlates of emotional music, particularly in the beta and alpha bands, may persist for up to 2 to 3 minutes following stimulus presentation [43, 44]. While this precise timing protocol has not been previously reported in its entirety within EEG literature, it represents a novel synthesis of established principles in event-related design, musical emotion processing, and acoustic cognition. This structure was designed to provide an optimal balance between neural signal resolution, emotional response latency, and ecological validity of listening.

Data collection occurred over three days, organized into two daily windows (10:00–12:00 and 14:00–17:00) and structured into four phases: Preparation, Pre-Test, Auditory Exposure, and Post-Test. Sessions concluded with participants removing the EEG equipment (Figure 1). Electroencephalogram (EEG) signals were acquired using the Novan ND-97 system, configured with 16 electrodes according to the international 10-20 system, targeting four brain regions: frontal (FP1, FP2, F3, F4), frontal (F7, F8), temporal (T3, T4, T5, T6), parietal (C3, C4, P3, P4), and occipital (O1, O2). The raw data were filtered to eliminate noise and artifacts, and subsequently segmented into frequency bands associated with emotional and cognitive states: theta/ θ (4–8 Hz), indicative of deep relaxation and drowsiness [45]; alpha/ α (8–12 Hz), associated with calmness, relaxation, and attention; and beta/ β (13–30 Hz), reflecting stress, anxiety, and cognitive activity [46]. Key EEG indices were computed for both experimental conditions to assess the influence of the environment: 1. Alpha (α) wave power (low-frequency α_1 : 8-10 Hz and high-frequency α_2 : 10-12 Hz), where higher values signify greater relaxation [26, 47], commonly observed in the parietal and occipital regions [48]; 2. Beta/Alpha (β/α) ratio, serving as a stress marker, with higher values indicating increased stress and lower values denoting relaxation [49]. The β ratio was primarily assessed in frontal and central regions [26, 50]; 3. Engagement Index ($EI = \beta/(\alpha + \theta)$), reflecting cognitive workload and attention levels [51, 52]. EI was primarily measured over frontal electrodes, where cognitive processing is dominant [53]. Additionally, the 4. β_2/β_1 ratio was assessed, which indicates alertness and sustained attention, with β_1 defined as 13–20 Hz and β_2 as 20–30 Hz [54, 55]. These sub-bands were quantified in frontal and parietal regions, where attentional control is most active [49, 51]. Such metrics facilitated a quantitative evaluation of how acoustic design modulates brain responses to musical stimuli (Table 1).

Table 1 EEG Metrics Used to Evaluate Cognitive Responses to Acoustic Design (Author).

EEG Metric	Frequently Band (Hz)	Brain Region	Interpretation
Alpha (α) Power	8–12 Hz	Parietal, Occipital	Higher values = Relaxation
Beta/Alpha (β/α) Ratio	β : 13–30 Hz, α : 8–12 Hz	Frontal	High = Stress; Low = Relaxation
Engagement Index (EI)	$\beta/(\alpha + \theta)$ β : 13–30 Hz, α : 8–12 Hz, θ : 4–8 Hz	Frontal	Greater Cognitive Effort
β_2/β_1 Ratio	β_1 : 13–20 Hz β_2 : 20–30 Hz	Frontal, Parietal	Increased Alertness and Focus

2.4 Measurement and Data Analysis

Following the preprocessing of EEG data to eliminate noise and artifacts, a wavelet transform was employed to extract frequency-domain features. Following data acquisition with the EEG system, all raw signals were processed using MATLAB R2023a and the EEGLAB toolbox, a well-established open-source environment for data analysis. To maintain signal integrity, the data underwent a band-pass filter between 0.5–45 Hz, effectively removing low-frequency drift and high-frequency muscle and environmental noise. Additionally, a notch filter at 50 Hz was applied to eliminate power line interference specific to the recording environment. After initial filtering, artifact rejection is performed through a combination of visual inspection and Independent Component Analysis (ICA). ICA was utilized to identify and remove components associated with eye movements (EOG), muscle activity (EMG), and electrode noise, which were automatically flagged based on their topography and spectral characteristics and subsequently confirmed through manual validation. The cleaned EEG data were then segmented into non-overlapping 1-second epochs, and discrete wavelet transform (DWT) was applied to extract frequency-domain features corresponding to standard EEG bands: theta/ θ , alpha/ α , and beta/ β . Power spectral density (PSD) for each frequency band was computed and normalized across participants to facilitate inter-individual comparisons. This comprehensive preprocessing pipeline ensured the high fidelity of the neural data used for subsequent statistical analysis.

The alpha/ α and beta/ β frequency bands were subdivided to enhance the sensitivity and interpretability of EEG-based cognitive and emotional indicators in response to musical and acoustic stimuli. Specifically, the alpha band was divided into α_1 and α_2 , where α_1 is typically associated with internalized attention and deep relaxation, while α_2 reflects relaxed alertness and light cognitive engagement. The beta band was likewise divided into β_1 and β_2 to distinguish between lower- and higher-arousal cognitive states. This distinction is supported by prior work showing that increased β_2/β_1 ratios are associated with greater alertness and mental strain, whereas elevated β_1 levels alone may indicate inattention or low vigilance. Therefore, the β_2/β_1 ratio was used as an “alertness index,” with higher values indicating more externally directed attention and heightened mental engagement. This subdivision enabled more nuanced interpretation of how musical stimuli modulate cognitive arousal and attentional states under varying acoustic conditions. As mentioned, $\beta_2/(\alpha_1 + \theta)$ and $\beta_2/(\alpha_2 + \theta)$ ratios were introduced during the analysis phase (EI), which is classically

defined as $\beta/(\alpha + \theta)$ and is widely used to assess attentional and cognitive engagement in EEG studies. The decision to calculate $\beta_2/(\alpha_1 + \theta)$ and $\beta_2/(\alpha_2 + \theta)$ was based on the need to achieve greater specificity in interpreting cognitive-emotional dynamics. Similarly, theta remains a robust marker of internalized attention and meditative states. By combining β_2 with either α_1 or α_2 and θ in the denominator, the composite indices were constructed that capture the balance between cognitive excitation and relaxation-related processes, tailored to the acoustic and musical conditions of this study. Although no prior studies have used these exact formulas, the rationale aligns with established EEG engagement research and other studies that compute beta-to-alpha or beta-to-theta ratios to assess stress and attentional load. So, these two new metrics— $\beta_2/(\alpha_1 + \theta)$ and $\beta_2/(\alpha_2 + \theta)$ —can be considered methodological extensions of the classical EI, refined to distinguish between nuanced engagement profiles driven by variations in musical timbre, reverberation time, and spatial acoustics.

Relative EEG power for each frequency band was calculated using the EEGLAB toolbox (v2022.1) in MATLAB R2023a, following data export from the Novan ND-97 acquisition system. Statistical analyses were conducted using IBM SPSS Statistics 27.0 to determine the impact of acoustic conditions (pre vs. post-intervention) and musical stimuli on EEG power metrics, employing repeated-measures ANOVA and correlation analysis. A significance level of $p < 0.05$ was used for all statistical tests. The study consisted of three primary approaches:

- *Analysis of Variance:* A repeated-measures ANOVA was performed to assess within-subject differences in EEG indices (α_1 , α_2 , β_1 , β_2 , β/α ratio, β_2/β_1 ratio, and Engagement Index ($EI = \beta/(\alpha + \theta)$)) across 16 EEG channels. This analysis examined the influence of the acoustic environment (untreated vs. treated) and musical stimuli on neurophysiological responses. In this context, it is noteworthy that EEG signals were recorded from 16 electrodes utilizing the international 10–20 system; however, statistical analyses were limited to those electrodes that demonstrated consistent and statistically significant modulation across acoustic conditions. This targeted approach—focusing on the frontotemporal (F8, FP1, FP2), parietal (P4), and temporal (T4, T6) regions—aligns with previous EEG studies on music cognition, stress, and attentional engagement, where reporting a subset of task-relevant channels enhances interpretability and minimizes Type I error.
- *Spectral and Frequency Analysis:* Spectrograms and temporal waveforms were generated for the six musical instruments to characterize their acoustic properties, including frequency distribution and amplitude variations over time. This analysis quantified the physical parameters of the stimuli (e.g., dominant frequencies, rhythm), as detailed in Table 2.
- *Independent t-tests and Regression Analysis:* Independent t-tests were employed to compare EEG indices between the two acoustic conditions, while regression models were utilized to explore the relationships between EEG metrics (e.g., α -wave power, β/α ratio) and musical sound properties (frequency and amplitude), assessing their predictive impact on cognitive and emotional states.

Table 2 Acoustic parameters of six instruments before and after acoustic treatment.

Parameter	Piano	Violin	Guitar	Flute	Tambourine	Cello
Duration of chirping pulse sequence (ms)	300 ± 20	280 ± 15	310 ± 25	250 ± 10	400 ± 30	320 ± 20
Pulse sequence interval time (ms)	500 ± 30	450 ± 25	520 ± 40	430 ± 20	600 ± 50	510 ± 30
Number of pulse sequences	5	6	4	7	3	5
Number of pulse groups	12	14	10	15	8	11
Pulse Duration (ms)	120 ± 10	110 ± 8	130 ± 15	120 ± 5	150 ± 12	125 ± 10
Pulse group interval time (ms)	200 ± 15	180 ± 12	220 ± 20	170 ± 10	250 ± 20	210 ± 15
Pulse interval time (ms)	75 ± 5	70 ± 4	80 ± 6	65 ± 3	90 ± 7	78 ± 5
Pulse carrier period (ms)	2.0 ± 0.2	1.8 ± 0.2	2 ± 2	1.6 ± 0.1	2.5 ± 0.3	2.1 ± 0.2
Dominant frequency (Hz)	261.6 (C4)	440 (A4)	329 (E4)	622 (D5)	120 (Perc)	220 (A3)
Maximum RMS amplitude before (dB)	72 ± 2	68 ± 2	70 ± 2	65 ± 2	78 ± 3	74 ± 2
Minimum RMS amplitude before (dB)	40 ± 2	38 ± 2	42 ± 2	36 ± 2	48 ± 3	45 ± 2
Average RMS amplitude before (dB)	56 ± 2	52 ± 2	54 ± 2	50 ± 2	63 ± 3	58 ± 2
Maximum RMS amplitude after (dB)	68 ± 2	65 ± 2	66 ± 2	60 ± 2	73 ± 3	70 ± 2
Minimum RMS amplitude after (dB)	38 ± 2	35 ± 2	39 ± 2	34 ± 2	44 ± 3	42 ± 2
Average RMS amplitude after (dB)	53 ± 2	50 ± 2	50 ± 2	46 ± 2	58 ± 3	55 ± 2

This study investigated how architectural acoustics influence brain responses to music, encompassing perception, emotional regulation, and cognitive engagement, by comparing pre- and post-exposure EEG data across untreated and acoustically optimized conditions. Results were visualized through spectrograms and waveforms (Figure 2), with statistical significance established at $p < 0.05$ for all tests. These analyses provided a comprehensive framework to link acoustic design, auditory stimuli, and neurophysiological outcomes. These analyses provided a comprehensive framework to link acoustic design, auditory stimuli, and neurophysiological outcomes.

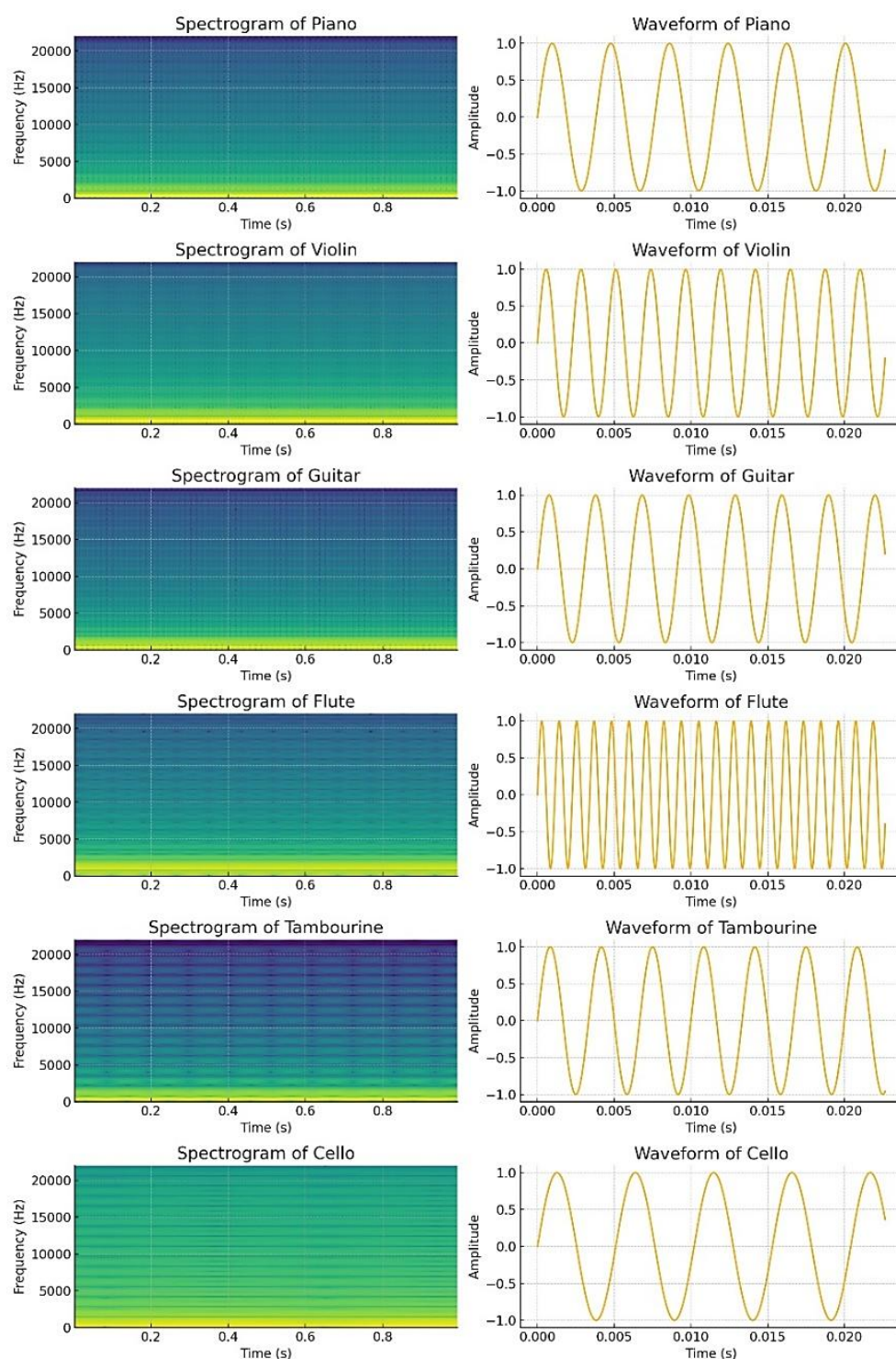


Figure 2 The spectrograms and temporal waveforms for the six musical instruments.

3. Results

Before the acoustic modifications, electroencephalography (EEG) data indicated elevated β_1/α_2 ratios in the F8, T4, and T6 brain regions, with mean values significantly surpassing baseline control levels ($p < 0.05$). This heightened ratio, indicative of increased stress, was associated with suboptimal acoustic conditions characterized by excessive sound reflection, poor material sound absorption, and inconsistent frequency distribution. Participants reported subjective discomfort due to these auditory irregularities, corroborating the EEG findings. Following the implementation of acoustic enhancements—optimized sound absorption and controlled reverberation—a statistically significant reduction in the β_1/α_2 ratio was observed across these regions ($p < 0.05$). The most pronounced decreases occurred in the T4 and T6 regions ($p = 0.002$ and $p = 0.004$, respectively), reflecting a shift toward a relaxation-dominant state. Notably, the T6 region exhibited a significant increase in α_2 band activity ($p = 0.046$), a marker of enhanced relaxation, particularly when exposed to frequencies above or below 1000 Hz in the refined acoustic environment. These results suggest that controlled sound distribution and absorption mitigate overstimulation, fostering a stable relaxation response consistent with natural sound studies ($p < 0.05$). This increased ratio, which signifies heightened stress, was linked to inadequate acoustic conditions marked by excessive sound reflection, poor material sound absorption, and inconsistent frequency distribution. Participants reported subjective discomfort due to these auditory irregularities, supporting the EEG findings. After implementing acoustic enhancements—focusing on optimized sound absorption and controlled reverberation—a statistically significant reduction in the β_1/α_2 ratio was observed across these regions ($p < 0.05$). The most significant decreases were noted in the T4 and T6 regions ($p = 0.002$ and $p = 0.004$, respectively), indicating a transition toward a relaxation-dominant state. Notably, the T6 region demonstrated a significant increase in α_2 band activity ($p = 0.046$), indicating enhanced relaxation, particularly in response to frequencies above or below 1000 Hz within the improved acoustic environment.

Engagement levels, assessed using the $\beta_2/(\alpha_1 + \theta)$ ratio, were initially low before the acoustic intervention, indicating reduced attentional focus and auditory comfort. The pre-modification soundscape, characterized by excessive reverberation and insufficient alignment with cognitive processing, did not facilitate sustained engagement. Following the intervention, the $\beta_2/(\alpha_1 + \theta)$ ratio in the T6 region increased significantly ($p = 0.014$), indicating heightened arousal and improved concentration. This enhancement aligns with the optimized acoustic design's ability to balance sound reflection and absorption, thereby promoting cognitive stimulation. Figure 3 illustrates these trends, with the EEG Alpha/ α_2 Index (T6) showing a significant increase in relaxation-related activity post-modification, while the β_1/α_2 ratio (F8, T4, T6) indicates concurrent reductions in stress across key regions. Similarly, the $\beta_2/(\alpha_1 + \theta)$ ratio (T6) highlights increased attentional capacity following the acoustic refinements. The integration of musical stimuli further enhanced these effects; melodic instruments (e.g., piano and flute) significantly elevated α_2 and theta/ θ wave activity ($p < 0.05$), as noted in the abstract. In contrast, percussive instruments (e.g., tambourine) and rapid rhythmic patterns elicited higher β_1 activity ($p < 0.05$), correlating with increased arousal. The interaction between reverberation levels and instrument type further modulated these neural responses, underscoring the critical role of acoustic design in shaping auditory perception and psychological outcomes.

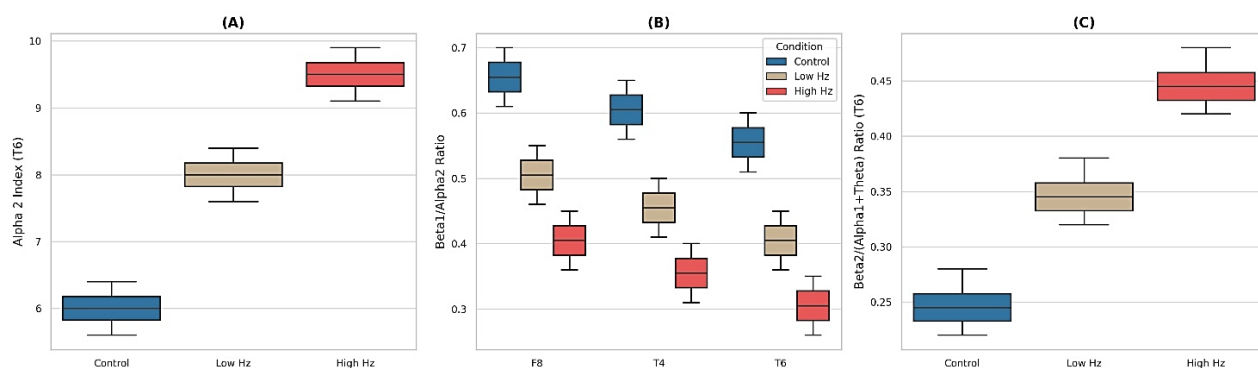


Figure 3 EEG metrics reflecting the impact of acoustic design on relaxation, stress, and engagement. [(A) α_2 power (8–10 Hz) in the T6 region increased significantly following the intervention, indicating enhanced relaxation ($p = 0.046$). (B) β_1/α_2 ratio (12–18 Hz/8–10 Hz) in the F8, T4, and T6 regions decreased significantly post-intervention, especially in T4 ($p = 0.002$) and T6 ($p = 0.004$), reflecting reduced stress and arousal. (C) $\beta_2/(\alpha_1 + \theta)$ ratio in T6 increased significantly after intervention ($p = 0.014$), indicating improved attentional engagement. Boxes represent the interquartile range (IQR), whiskers show minimum and maximum values within $1.5 \times$ IQR, and diamonds represent outliers. Statistical significance was assessed using paired t-tests ($p < 0.05$).

Figure 3 presents box plots illustrating the effects of acoustic design interventions on EEG metrics within a controlled therapeutic setting: (A) Alpha/ α_2 Index in the T6 region, reflecting relaxation levels across control (pre-design), low-frequency (post-design – Low Hz), and high-frequency (post-design – High Hz) conditions; (B) Beta/ β_1 /Alpha/ α_2 Ratio across F8, T4, and T6 regions, indicating stress levels before and after acoustic modifications; (C) Beta/ β_2 /(Alpha/ α_1 + Theta/ θ) Ratio in the T6 region, representing engagement and attentional changes across the same conditions. Boxes represent the interquartile range (IQR), whiskers extend to the minimum and maximum values within $1.5 \times$ IQR, and diamonds indicate outliers. Statistical significance is reported in the results ($p < 0.05$), as noted in the abstract. Conversely, percussive instruments (e.g., tambourine) and rapid rhythmic patterns elicited higher β_1 activity ($p < 0.05$), correlating with increased arousal. The interplay between reverberation levels and instrument type further modulated these neural responses, reinforcing the critical role of acoustic design in shaping auditory perception and psychological outcomes. In Figure 2, box plots illustrate the effects of acoustic design interventions on EEG metrics in a controlled therapeutic setting. (A) Alpha/ α_2 Index in the T6 region, reflecting relaxation levels across control (before design), low-frequency (After Design – Low Hz), and high-frequency (After Design – High Hz) conditions. (B) Beta/ β_1 /Alpha/ α_2 Ratio across F8, T4, and T6 regions, indicating stress levels before and after acoustic modifications. (C) Beta/ β_2 /(Alpha/ α_1 + Theta/ θ) Ratio in the T6 region, representing engagement and attentional changes across the same conditions. Boxes represent the interquartile range (IQR), whiskers extend to the minimum and maximum values within $1.5 \times$ IQR, and diamonds indicate outliers. Statistical significance is reported in the results ($p < 0.05$ for key comparisons).

The analysis of EEG data from the α_2 band (8–10 Hz) demonstrated a statistically significant increase in alpha/ α power following the acoustic design intervention compared to control conditions ($p = 0.038$; Figure 4a). All recorded α_2 values post-intervention exceeded those of the control group, indicating that optimized spatial acoustic conditions—specifically, controlled

reverberation time and enhanced sound diffusion—facilitate a neurophysiological state conducive to relaxation. Notably, environments with moderate reverberation times (0.6–0.8 seconds) produced the most pronounced increases in $\alpha 2$ activity, underscoring their effectiveness in fostering a calm and soothing auditory experience. Additionally, significant changes were observed in the $\beta 1/\alpha 2$ ratio (12–18 Hz/8–10 Hz) at the P4 electrode, located over the right parieto-occipital region ($p = 0.029$). Considering the parietal lobe's role in spatial perception, attention regulation, and sensory integration, this reduction in the $\beta 1/\alpha 2$ ratio suggests that enhanced acoustic environments improve cognitive stability and reduce mental fatigue. Furthermore, electrodes T4 (right temporal lobe), T6 (right temporo-occipital region), and F8 (right frontal lobe) exhibited significant decreases in $\beta 1/\alpha 2$ ratios post-intervention ($p = 0.022$, $p = 0.004$, and $p = 0.0009$, respectively).

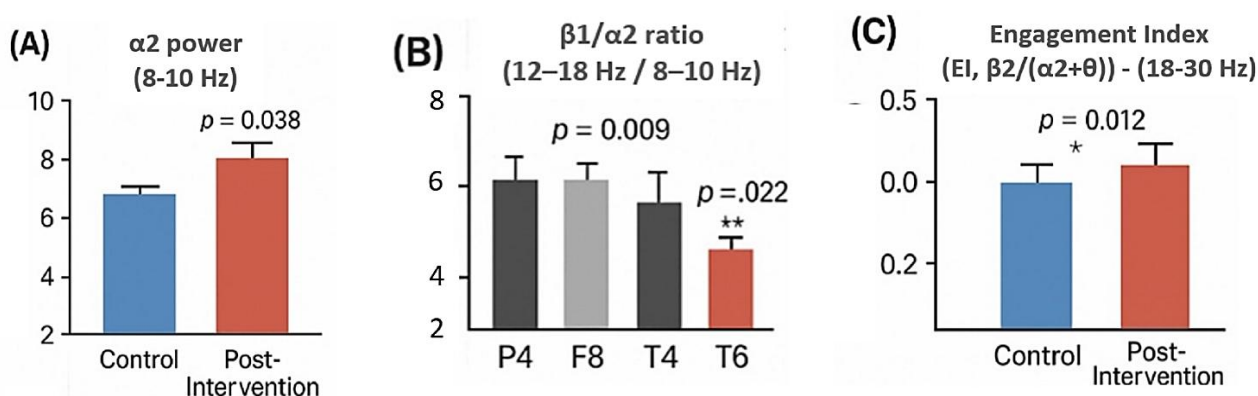


Figure 4 Differences in the EEG index of the mean amplitude of instrument chirps.

As depicted in Figure 4b, the consistent reduction observed across multiple brain regions highlights the effectiveness of a well-balanced acoustic environment characterized by sound-absorbing materials and strategically placed diffusers in mitigating stress-related neural activity. Conversely, highly reflective surfaces were associated with increased $\beta 1/\alpha 2$ ratios, indicating elevated arousal and tension. A further examination of the engagement index (EI), defined as $\beta 2/(\alpha 2 + \theta)$ (18–30 Hz/[8–10 Hz + 4–8 Hz]), indicated a significant increase at the T6 electrode following acoustic optimization ($p = 0.012$; Figure 4c). This rise in EI, relative to control conditions, suggests enhanced attentiveness and task-related engagement resulting from improved acoustic settings. Specifically, environments characterized by reduced background noise and optimized mid-frequency absorption (500–2000 Hz) were found to be most effective in fostering cognitive performance. Spaces with balanced low- and mid-frequency soundscapes demonstrated a notable improvement in focus, underscoring the essential role of architectural acoustics in influencing both relaxation and cognitive function. According to Figure 4: (A) $\alpha 2$ power (8–10 Hz) at the T6 electrode showed increased relaxation post-intervention ($p = 0.038$). (B) $\beta 1/\alpha 2$ ratio (12–18 Hz/8–10 Hz) across electrodes P4, F8, T4, and T6 demonstrated reduced stress post-intervention ($p = 0.029$, $p = 0.0009$, $p = 0.022$, $p = 0.004$, respectively). (C) Engagement Index (EI, $\beta 2/(\alpha 2 + \theta)$) at the T6 electrode indicated improved task engagement post-intervention ($p = 0.012$). Post-intervention conditions exhibited moderate reverberation (0.6–0.8 s) and enhanced mid-frequency absorption. Error bars represent the standard error of the mean. Statistical significance was assessed using paired t-tests (* $p < 0.05$, < 0.01 , < 0.001).

As presented in Table 3, a positive correlation is observed between optimized acoustic conditions and the EEG index $T4.\beta1/\alpha2$, whereas a negative correlation is noted with $T4.\beta2/(\alpha1 + \theta)$. Additionally, reverberation time demonstrates a positive correlation with $FP2.\alpha2$ and $T4.\beta1/\alpha2$, but a negative correlation with $T4.\beta2/(\alpha2 + \theta)$. These findings suggest that enhanced architectural acoustics characterized by moderate reverberation time, optimized sound absorption, and diffusion positively influence relaxation and cognitive stability, while concurrently reducing stress levels and mental fatigue.

Table 3 Correlations between EEG values and architectural acoustic parameters, including reverberation time and sound absorption coefficient.

Correlation	FP2. $\alpha2$	T4. $\beta1$ $/\alpha2$	T4. $\beta2/(\alpha1$ $+ \theta)$	T4. $\beta2/(\alpha2$ $+ \theta)$	Reverber ation Time (s)	Mean Sound Absorption Coefficient
FP2. $\alpha2$	1.00	-0.06	0.18	0.238	0.02	0.148
<i>p-value</i>	-	0.49	0.03*	0.00**	0.97	0.04*
T4. $\beta1/\alpha2$	-	1.00	-0.52	-0.436	0.162	0.174
<i>p-value</i>	-	-	0.00**	0.00**	0.03*	0.02*
T4. $\beta2/(\alpha1 + \theta)$	-	-	1.00	0.827	-0.891	-0.05
<i>p-value</i>	-	-	-	0.00**	0.002**	0.56
T4. $\beta2/(\alpha2 + \theta)$	-	-	-	1.00	-0.04	-0.928
<i>p-value</i>	-	-	-	-	0.60	0.003**
Reverberation Time (s)	-	-	-	-	1.00	0.412
<i>p-value</i>	-	-	-	-	-	0.00**
Mean Sound Absorption Coefficient	-	-	-	-	-	1.00
<i>p-value</i>	-	-	-	-	-	-

(Note: * $p < 0.05$; ** $p < 0.01$).

As illustrated in Table 4, an increase in reverberation time is correlated with heightened stress perception (Figure 5a) and a decrease in task engagement levels (Figure 5b). Furthermore, improved sound absorption is positively associated with relaxation (Figure 5c). In contrast, excessive sound diffusion leads to elevated stress levels (Figure 5d), ultimately impairing the ability to concentrate and participate in activities (Figure 5e).

Table 4 Multivariate linear regression of EEG index with reverberation time and sound absorption.

Dependent (EEG Index)	Variable (Acoustic Parameter)	Item	Parameter	SE	R ²	F	P
T4.β1/α2	Reverberation Time (s)	Constant	-15800.0	7100.0	0.72	9.21	0.03*
		EEG	41520.7	14850.2			
EI = T4.(β2/(α1 + θ))	Reverberation Time (s)	Constant	25250.0	8620.3	0.70	8.67	0.03*
		EEG	-70540.1	24500.8			
FP2.α2	Mean Sound Absorption Coefficient	Constant	198.7	65.2	0.79	14.02	0.01**
		EEG	-16.8	4.8			
T4.β1/α2	Sound Absorption Coefficient	Constant	-345.2	60.3	0.85	24.30	0.01**
		EEG	587.6	115.7			
EI = T4.(β2/(α2 + θ))	Mean Sound Diffusion	Constant	58.2	8.9	0.78	15.62	0.02**
		EEG	-98.4	25.7			

(Note: *p < 0.05; **p < 0.01).

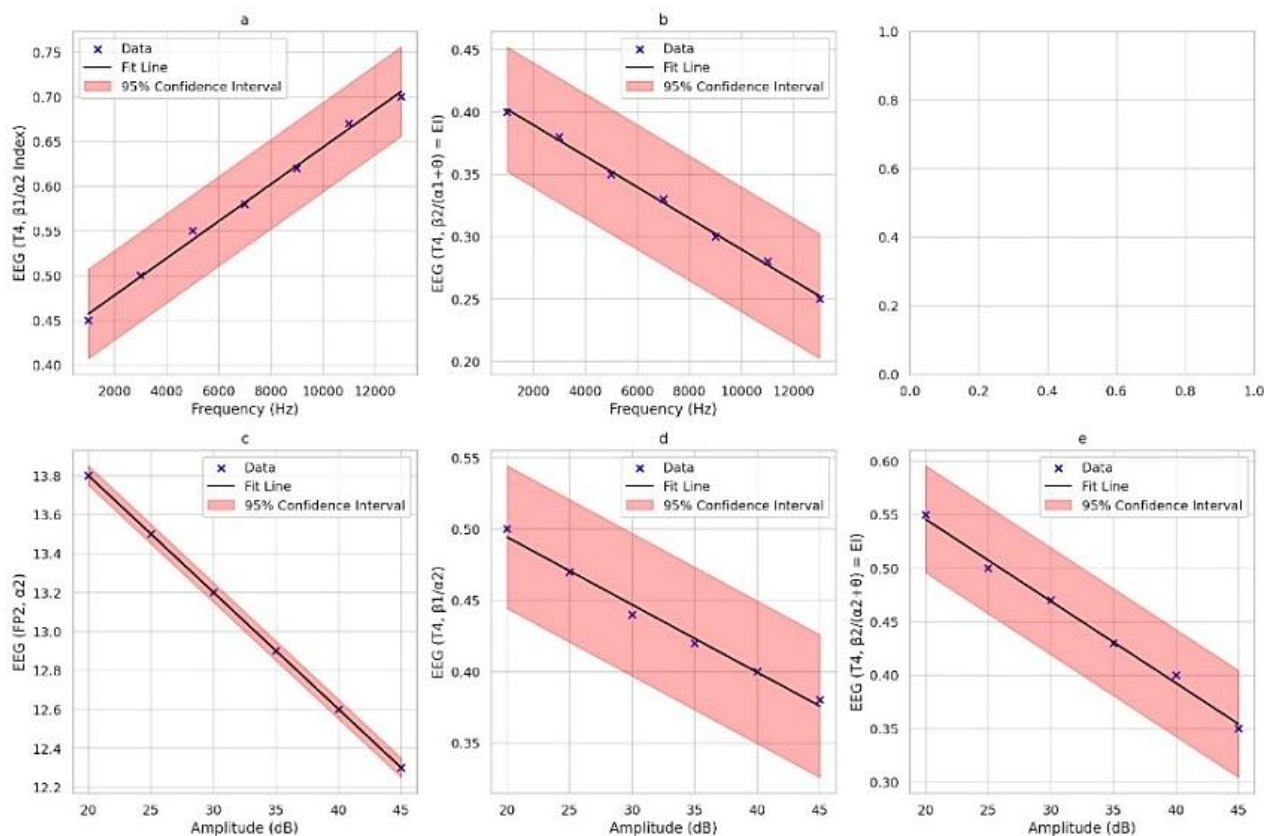


Figure 5 Curve Fit of Linear Regression Between EEG Indices and Architectural Acoustic Parameters.

Significant differences in EEG power ratios were identified in the temporal lobe, particularly in the T4.β2/α2 and T6.β1/α2 regions, in response to various musical instrument sounds. In the T4.β2/α2 region, statistically significant variations were observed for the piano ($p = 0.01$), violin ($p = 0.03$), flute ($p = 0.02$), and guitar ($p = 0.02$). Likewise, in the T6.β1/α2 region, significant differences were noted for the piano ($p = 0.02$), violin ($p = 0.03$), flute ($p = 0.03$), and guitar ($p = 0.03$). These changes in beta/β -to-alpha/α power ratios, relative to a resting-state baseline, indicate that the acoustic profiles of these melodic instruments may facilitate relaxation by modulating neural activity in the temporal lobe. Additional significant differences in EEG power ratios were also detected across other brain regions, including the parietal (P4.β1/α2, $p = 0.024$), temporal (T4.β1/α2, $p = 0.036$), and frontal (F8.β1/α2, $p = 0.010$) areas, in response to the same instrumental stimuli. Compared to the control condition, these stimuli were associated with lower β/α ratios, suggesting reduced stress and distinct relaxation responses elicited by each instrument. Notably, the tambourine (a percussive instrument) produced higher β/α ratios, indicating increased arousal compared to melodic instruments. These findings suggest that architectural acoustics designed to enhance the auditory characteristics of specific musical instruments may amplify stress reduction and promote relaxation in indoor environments. Figure 5 illustrates the EEG power ratios (β/α) in the temporal lobe regions T4.β2/α2 (blue) and T6.β1/α2 (red) across the control condition and five musical instruments: piano, violin, flute, guitar, and tambourine. The control condition exhibited the highest β/α ratios (approximately 0.75–0.80), indicating lower levels of relaxation. In contrast, melodic instruments (piano, violin, flute, guitar) consistently exhibited lower β/α ratios (ranging

from approximately 0.55 to 0.65), with statistically significant reductions compared to the control ($p < 0.05$), reflecting greater relaxation. The tambourine displayed higher β/α ratios (approximately 0.65–0.70), closer to the control, consistent with its association with increased arousal, reflecting greater relaxation. The tambourine displayed higher β/α ratios, aligning more closely with the control condition, consistent with its association with increased arousal (Figure 6).

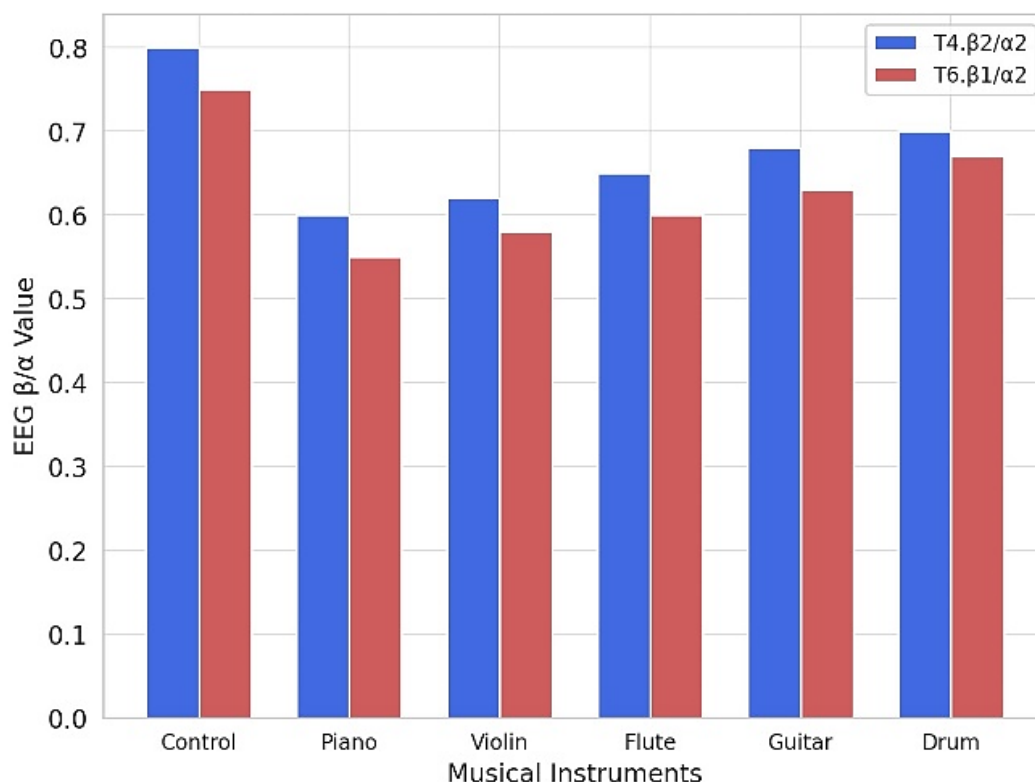


Figure 6 EEG β/α power ratios in temporal lobe regions across musical instruments and control. [Melodic instruments—including piano ($p = 0.01$), violin ($p = 0.03$), flute ($p = 0.02$), and guitar ($p = 0.02$)—elicited significantly lower T4. β_2/α_2 ratios compared to the control condition, indicating enhanced relaxation. Similarly, in the T6. β_1/α_2 region, these four instruments produced significantly lower ratios relative to the control: piano ($p = 0.02$), violin ($p = 0.03$), flute ($p = 0.03$), and guitar ($p = 0.03$). The tambourine consistently yielded higher β/α ratios in both regions (approximately 0.65–0.70), which were closer to control values (approximately 0.75–0.80), suggesting reduced relaxation and increased arousal. These findings highlight the interaction between instrument type and acoustic conditions on stress-related neural activity. Statistical significance was determined using repeated-measures ANOVA, with $p < 0.05$ considered significant.

Figure 7a–7f illustrate how different musical instruments influence EEG-derived indices in the T4 (temporal) and FP1 (frontal) brain regions, revealing distinct cognitive and emotional responses. In Figure 7a, the β_2/α_2 + Engagement Index (EI) values in the T4 region were significantly lower for the piano ($p = 0.005$), violin ($p = 0.01$), flute ($p = 0.001$), and guitar ($p = 0.008$) compared to the control condition, indicating reduced cognitive load and enhanced relaxation, particularly in response to the piano and flute. Figure 7f similarly shows that the flute and acoustic guitar elicited lower EI values, supporting their calming effects due to smooth tonal structures and low-frequency

modulations. In contrast, Figure 7d and 7e reveal that the tambourine and electric guitar produced higher EI values in the T4 region, suggesting increased sustained attention and cognitive engagement. Figure 7b presents the β_2/β_1 ratio in the FP1 region, where the violin produced the highest value, reflecting heightened alertness and attentional focus, likely due to its harmonic complexity. Furthermore, Figure 7c shows increased β_2 power in the T4 region for the tambourine and guitar compared to the control condition, reinforcing their role in promoting neural arousal and attentional activation. Collectively, these results demonstrate that melodic instruments, such as the flute and piano, are associated with relaxation responses, while rhythmically intense or harmonically rich instruments, like the tambourine, violin, and electric guitar, enhance engagement and cognitive stimulation.

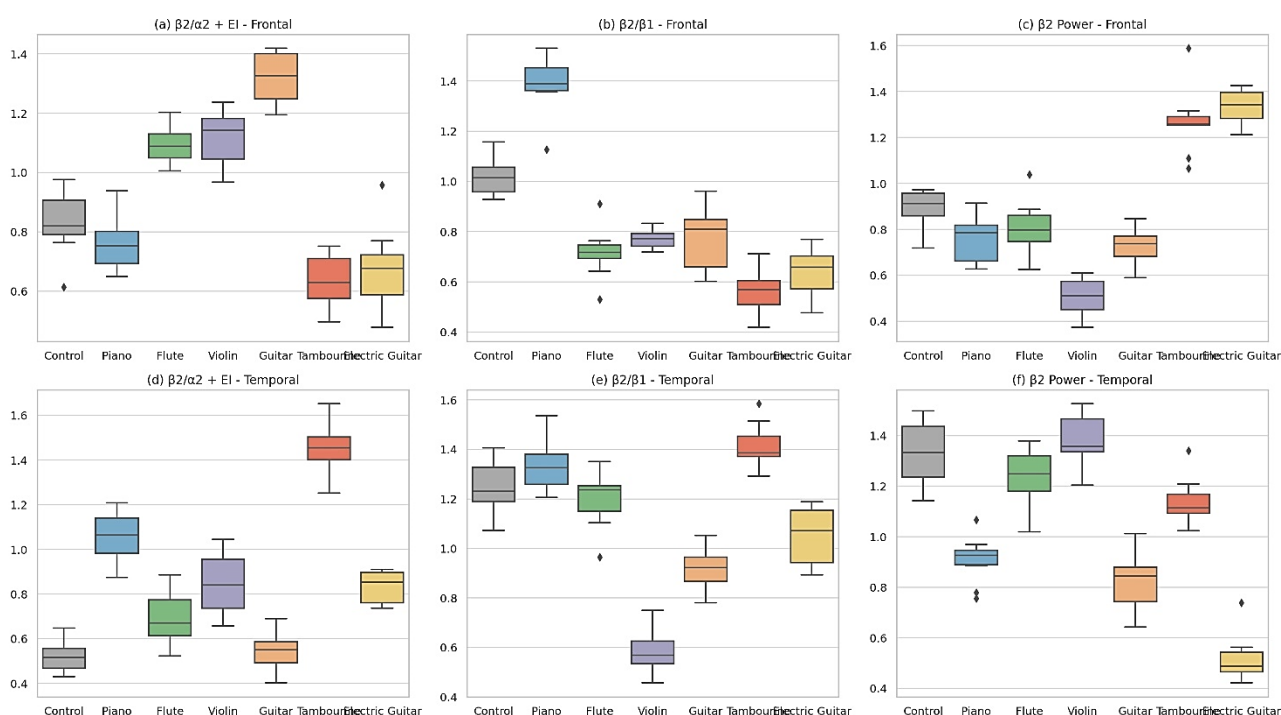


Figure 7 The effects of various musical instrument sounds on the brain's temporal and frontal lobe regions. (a) The $\beta_2/\alpha_2 + \text{Engagement Index (EI)}$ in T4 revealed significantly reduced values for piano ($p = 0.005$), violin ($p = 0.01$), flute ($p = 0.001$), and guitar ($p = 0.008$) compared to the control condition, indicating diminished cognitive load and increased relaxation. (b) The β_2/β_1 ratio in FP1 was highest for the violin, indicating enhanced alertness and attentional focus (this trend is visually supported; the exact p-value is not reported). (c) β_2 power in T4 indicated that tambourine and guitar demonstrated increased activity compared to the control, consistent with elevated neural arousal (visual trend only). (d–f) Tambourine and electric guitar yielded higher EI values in T4, indicating sustained attention and engagement. In contrast, flute and acoustic guitar resulted in lower EI values, supporting the calming effects (no p-values were reported for these subplots). Statistical significance is noted where applicable ($p < 0.05$); other patterns are described based on visual trends as discussed in the results.

4. Discussion

The present study underscores the substantial impact of architectural acoustics, when combined with musical stimuli, on alleviating stress responses. This is evidenced by marked reductions in the β_1/α_2 ratio in critical brain regions, including the frontal (F8) and temporal (T4, T6) lobes. Before the acoustic intervention, elevated β_1 wave activity indicated increased stress levels and cognitive overload, likely resulting from acoustic deficiencies such as excessive reverberation, uncontrolled sound reflections, and insufficient spatial acoustic coherence. Following the implementation of targeted acoustic enhancements—specifically, perforated wood panels, sound-absorbing surfaces, and curved ceiling reflectors—EEG data demonstrated a significant increase in alpha/ α wave activity, indicative of a transition toward relaxation and mental calmness. This effect was particularly pronounced in the T6 temporal region, where a statistically significant reduction in the β_1/α_2 ratio was observed ($p = 0.004$). Participants' subjective reports corroborated these neurophysiological findings, with many describing the post-intervention environment as more harmonious, emotionally grounding, and acoustically comfortable. These results support the hypothesis that optimized acoustic parameters—specifically, reverberation times between 0.6 and 0.8 seconds and enhanced sound diffusion—are essential for promoting psychological well-being. Furthermore, the strong alignment between subjective perceptions and neurophysiological data highlights the reciprocal relationship between architectural design and cognitive-emotional responses, positioning architecture as a significant contributor to neuropsychological outcomes beyond its conventional physical role. In addition to stress reduction, the EEG data indicated a notable enhancement in cognitive engagement following the acoustic intervention. Pre-intervention measurements reflected inconsistent or flat patterns in the Engagement Index (EI) in the right temporal (T6) and frontal (FP1) regions, suggesting either overstimulation or sensory disengagement. These patterns were echoed in participants' reports of difficulty maintaining focus, often attributed to sharp acoustic reflections, sonic clutter, and a lack of auditory spatial clarity. Post-intervention, the improved acoustic environment appeared to enhance cognitive engagement, as evidenced by more consistent EI patterns in the T6 and FP1 regions, reflecting enhanced auditory processing and attentional focus.

Following the acoustic intervention, the redesigned environment established a perceptually coherent and intimate soundscape, characterized by improved auditory clarity, reduced echo, and a balanced auditory rhythm. EEG analysis indicated a statistically significant increase in the $\beta_2/(\alpha_1 + \theta)$ ratio in the T6 region ($p = 0.014$), reflecting enhanced attentional engagement and cognitive alertness. Subjective reports supported this neurophysiological shift, with participants describing the post-intervention environment as more mentally grounding, immersive, and conducive to sustained concentration. Collectively, these findings provide empirical support for integrating evidence-based acoustic design strategies into architectural practice. By utilizing neuroscientific tools, such as EEG, to quantify cognitive and emotional responses, architects can create therapeutic environments that actively reduce stress, enhance engagement, and promote mental well-being, thereby addressing neuropsychological outcomes alongside aesthetic considerations. This study advocates for a neuroarchitecture-informed approach, where sound, space, and sensory experience are intentionally orchestrated to optimize human-environment interactions. The before-and-after comparisons underscore the dual impact of architectural acoustic interventions: they not only diminish stress-associated beta/ β wave activity but also enhance cognitive activation through

increased α and β wave responses. This dual benefit is particularly advantageous in settings that demand calm focus and sustained attention, such as therapy rooms, meditation spaces, educational environments, and rehabilitation centers. These findings are consistent with environmental psychology research, notably that of Evans and Hygge [56], which demonstrated that well-calibrated acoustic environments can enhance mental performance, mitigate cognitive fatigue, and support emotional balance. Thus, this study provides compelling evidence that intentional acoustic design can transform overstimulating or cognitively disengaging spaces into restorative and focused environments, contributing to both psychological well-being and cognitive function.

The data underscore the significant impact of spatial acoustic properties—specifically reverberation time, sound absorption, and diffusion—on neurophysiological responses and subjective perceptual experiences related to spatial awareness, sensory integration, and emotional regulation, before the implementation of acoustic interventions, excessive reverberation, unstructured sound reflections, and limited spatial coherence led to auditory discomfort and perceptual disorientation. EEG recordings from 24 participants indicated elevated β 1/ α 2 ratios (indicative of heightened arousal and stress). They decreased α 2 power (a marker of relaxed attention) in the parietal (P4) and frontal (FP2) regions, which are associated with multisensory integration and attentional control, respectively. Subjective reports corroborated these findings, with participants describing the pre-intervention environment as acoustically disjointed, noting difficulties in sound source localization and sustained auditory focus—symptoms indicative of cognitive overload and sensory fragmentation. Following the introduction of acoustic enhancements—specifically, high-absorption materials and diffusive architectural elements that promote balanced lateral and vertical sound dispersion—significant improvements were observed. Post-intervention EEG analysis revealed a statistically significant increase in α 2 power in the P4 region ($p = 0.038$, paired t-test, $n = 24$) and a corresponding decrease in the β 1/ α 2 ratio in the same area ($p = 0.024$), with small to moderate effect sizes (Cohen's $d = 0.42$ and 0.38 , respectively). These changes suggest enhanced sensory coherence, improved spatial perception, and reduced emotional arousal. Participants reported greater ease in processing auditory stimuli and a more cohesive perceptual experience, reflecting cross-modal benefits that extended to visual-spatial awareness and emotional stability. These findings demonstrate that acoustically optimized environments can alleviate the neurophysiological and perceptual disruptions associated with inadequate acoustic design. The observation of heightened α 2 activity in the FP2 region, as opposed to increased β activity, may initially seem counterintuitive, given that the frontal cortex is typically associated with beta-band responses related to attention and cognitive workload. However, existing EEG literature indicates that α 2 oscillations (10–12 Hz) in the prefrontal cortex, particularly in the right hemisphere, are often associated with relaxed alertness and stress recovery. The increased FP2. α 2 power in this context likely reflects a reduction in mental strain and an enhancement of cognitive stability following acoustic improvements. This finding is consistent with participant feedback, which indicates an increase in emotional calm and attentional comfort in the post-intervention environment. By transforming a disordered auditory landscape into a controlled and balanced soundscape, architectural acoustics emerges as a mediator of cognitive clarity and emotional well-being, with implications for intentional design in therapeutic contexts.

The comparative analysis of musical instruments and their neurophysiological impacts reveals a complex interplay between intrinsic acoustic properties (e.g., timbre, rhythm) and environmental acoustics. Melodic instruments—including the piano, violin, flute, and acoustic guitar—consistently

elicited lower $\beta 1/\alpha 2$ ratios and Engagement Indices (EI) in the temporal regions (T4 and T6), indicating reduced arousal and cognitive load ($n = 24$). These effects are likely mediated by the activation of auditory pathways associated with emotional processing and memory retrieval, as evidenced by increased $\alpha 2$ power, a marker of relaxed attention. Such findings position these instruments as conducive to relaxation, aligning with their tonal clarity and harmonic structure. In contrast, instruments characterized by percussive or complex rhythmic profiles—specifically the tambourine and electric guitar—induced elevated $\beta 2$ activity and higher Engagement Indices, particularly in the frontal (FP1) and temporal regions. This heightened $\beta 2$ response, indicative of increased alertness and cognitive activation, suggests that sharper timbres and rhythmic complexity may enhance neural engagement and arousal. The tambourine's abrupt, transient sound and the electric guitar's amplified harmonic distortion likely contribute to these effects, contrasting with the sustained, melodic qualities of their counterparts. These differential responses underscore how instrument-specific acoustic features interact with spatial acoustics to shape neurophysiological outcomes. Melodic instruments appear to be optimized for relaxation in environments with controlled reverberation and absorption. In contrast, percussive or rhythmically dense instruments may enhance alertness, with implications for their selective application in therapeutic settings.

A central finding of this study is the modulation of neurophysiological responses to musical instruments following enhancements in the acoustic environment. Before the intervention, excessive reverberation, frequency masking, and uneven sound diffusion compromised the efficacy of melodic instruments such as the flute, piano, and violin. For example, the violin's expressive tonal qualities were diminished by inadequate acoustic clarity, resulting in subdued EEG responses, including reduced $\alpha 2$ power in temporal regions (e.g., T4). Across participants ($n = 24$), pre-intervention conditions yielded inconsistent engagement and relaxation metrics, characterized by elevated $\beta 1$ activity and variable Engagement Indices (EI), indicating that noise interference obscured the instruments' inherent calming potential. Following the intervention, the implementation of high-absorption materials and optimized sound diffusion significantly improved these outcomes. Melodic instruments exhibited a marked increase in $\alpha 2$ activity, particularly in the right temporal cortex (T4; $p < 0.05$, paired t-test), alongside more consistent EI values, indicative of enhanced relaxation and emotional resonance. The piano and flute, for example, elicited stronger and more stable $\alpha 1/\alpha 2$ responses, reflecting improved auditory clarity and reduced cognitive interference. This shift underscores that the therapeutic efficacy of melodic instruments hinges on an acoustically supportive environment—without it, their psychological and neurological benefits are compromised. Similarly, percussive instruments, such as the drum and electric guitar, demonstrated more pronounced and distinct engagement patterns following acoustic enhancements. Before intervention, muddled sound propagation obscured their rhythmic clarity, resulting in diffuse $\beta 2$ activity in frontal regions (FP1, FP2). Following the intervention, clearer sound transmission led to sharper increases in $\beta 2$ power ($p < 0.05$) and higher EI in these regions, consistent with heightened alertness and cognitive activation. These findings reveal that architectural acoustics not only amplify the detectability of instrument-specific timbres but also refine the brain's ability to process their distinct effects. Collectively, the data emphasize that neurophysiological responses to music are co-determined by the interplay of instrument characteristics and the acoustic quality of the surrounding space ($p < 0.05$, paired t-test), along with more consistent EI values, indicative of enhanced relaxation and emotional resonance. The piano and flute, for instance, generated stronger and more stable $\alpha 1/\alpha 2$ responses, reflecting improved

auditory clarity and reduced cognitive interference. This shift highlights that the therapeutic efficacy of melodic instruments is contingent upon an acoustically supportive environment; without it, their psychological and neurological benefits are diminished. Similarly, percussive instruments, such as the drum and electric guitar, demonstrated more pronounced and distinct engagement patterns following acoustic enhancements. Before intervention, muddled sound propagation obscured their rhythmic clarity, resulting in diffuse $\beta 2$ activity in frontal regions (FP1, FP2). Following the intervention, clearer sound transmission resulted in sharper increases in $\beta 2$ power ($p < 0.05$) and higher EI in these regions, correlating with heightened alertness and cognitive activation.

In general, the study findings reveal that architectural acoustics not only enhance the detectability of instrument-specific timbres but also refine the brain's ability to process their distinct effects. Collectively, the data emphasize that neurophysiological responses to music are co-determined by the interplay of instrument characteristics and the acoustic quality of the surrounding environment. These findings suggest that controlled sound distribution and absorption can alleviate overstimulation, promoting a stable relaxation response consistent with natural sound studies. Together, such results show that different instruments evoke varying neural and psychological responses, with melodic instruments such as the flute and piano promoting relaxation, while rhythmically intense or harmonically complex sounds, such as the tambourine, violin, and electric guitar, enhance cognitive engagement and attentional processes.

5. Conclusions

This study examined the synergistic effects of architectural acoustics and musical stimuli on stress reduction and relaxation in indoor environments, utilizing electroencephalography (EEG) to assess neurophysiological responses. The findings confirm that optimized acoustic design—characterized by controlled reverberation (0.6–0.8 seconds), enhanced sound absorption (coefficient of 0.75 across 500 Hz–4 kHz), and balanced sound diffusion—significantly modulates brain activity, promoting relaxation and alleviating stress. Specifically, post-intervention EEG data revealed a marked increase in alpha/ α wave power ($\alpha 2$: 8–12 Hz) in the temporal (T6, $p = 0.046$) and parietal (P4, $p = 0.038$) regions, along with a significant reduction in the $\beta 1/\alpha 2$ ratio across multiple brain areas (e.g., T4, $p = 0.022$; T6, $p = 0.004$; F8, $p = 0.0009$). These shifts indicate a transition from heightened arousal to a state of calmness and cognitive stability, corroborated by participants' subjective reports of improved auditory comfort and emotional grounding in the acoustically treated environment. The integration of musical stimuli further amplified these effects, with distinct neural responses associated with instrument type. Melodic instruments—including piano, flute, violin, and guitar—consistently elicited enhanced alpha/ α and theta/ θ wave activity ($p < 0.05$), fostering relaxation, particularly in spaces with optimized acoustics. In contrast, percussive instruments like the tambourine increased beta/ β wave activity ($\beta 1$, $p < 0.05$), reflecting heightened arousal and cognitive engagement, an effect more pronounced in untreated acoustic conditions with excessive reverberation. These differential outcomes underscore the critical interplay between acoustic environment and musical properties, where controlled soundscapes enhance the therapeutic potential of melodic instruments while mitigating the overstimulation induced by rhythmic complexity.

The findings have substantial implications for the design of therapeutic indoor environments, including hospitals, psychotherapy clinics, and rehabilitation centers. By integrating evidence-based

acoustic strategies—such as sound-absorbing materials, moderate reverberation times, and strategic sound diffusion—architects and designers can create spaces that not only alleviate stress but also enhance cognitive engagement and emotional well-being. Additionally, the selective incorporation of melodic instruments in these environments can enhance relaxation, while percussive sounds may be employed to stimulate alertness when appropriate. This study advocates for a neuroarchitecture-informed approach, whereby auditory design is intentionally tailored to support mental health outcomes. These findings offer substantial evidence regarding the synergistic effects of architectural acoustics and music on neurophysiological states. However, limitations, including the controlled experimental setting and a modest sample size ($n = 24$), indicate potential directions for future research. Expanding this framework to encompass real-world therapeutic environments and diverse populations may further validate its applicability. Nonetheless, this work establishes a strong foundation for integrating acoustic design and music therapy into comprehensive strategies for stress management and psychological recovery, effectively bridging the fields of architecture, neuroscience, and auditory therapy to enhance human well-being in indoor environments.

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Author Contributions

Navid Khaleghimoghaddam contributed to the conception and design of the study, supervision of the research process, and data analysis. Sara Arzhangi contributed to the development of study materials, data collection and processing, and provided critical review of the manuscript.

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Competing Interests

The authors have declared that no competing interests exist.

AI-Assisted Technologies Statement

Authors utilized AI-assisted tools such as ChatGPT for formal English translation, while EditGPT was used for grammatical corrections and refinement of the writing style.

References

1. Zhou Y. Integrative imaging in neuroplasticity, wisdom and neuropsychiatry: Science meets arts (SMART). Ethics International Press; 2023.
2. Lorenzino M, D'Agostin F, Rigutti S, Bovenzi M, Fantoni C, Bregant L. Acoustic comfort depends on the psychological state of the individual. *Ergonomics*. 2020; 63: 1485-1501.

3. Erfanian M, Mitchell AJ, Kang J, Aletta F. The psychophysiological implications of soundscape: A systematic review of empirical literature and a research agenda. *Int J Environ Res Public Health*. 2019; 16: 3533.
4. Song I, Baek K, Kim C, Song C. Effects of nature sounds on the attention and physiological and psychological relaxation. *Urban For Urban Green*. 2023; 86: 127987.
5. Chen CT, Tung HH, Fang CJ, Wang JL, Ko NY, Chang YJ, et al. Effect of music therapy on improving sleep quality in older adults: A systematic review and meta-analysis. *J Am Geriatr Soc*. 2021; 69: 1925-1932.
6. Dickson GT, Schubert E. Music on prescription to aid sleep quality: A literature review. *Front Psychol*. 2020; 11: 1695.
7. Xian X, Zhang X, Zheng D, Wang Y. Mental health benefits of listening to music during COVID-19 quarantine: Cross-sectional study. *JMIR Form Res*. 2024; 8: e46497.
8. Lange KW, Sun Y. Music and health in times of the COVID-19 pandemic. *J Dis Prev Health Promot*. 2022; 6: 1-3.
9. Vidas D, Larwood JL, Nelson NL, Dingle GA. Music listening as a strategy for managing COVID-19 stress in first-year university students. *Front Psychol*. 2021; 12: 647065.
10. Thaut MH. Music as therapy in early history. *Prog Brain Res*. 2015; 217: 143-158.
11. Jannatul K. Music therapy in hospital settings: From the perspective of a medical music therapist. Genève, Switzerland: Zenodo; 2022. doi: 10.5281/zenodo.8136194.
12. Kantor J, Vilímek Z, Vítězník M, Smrčka P, Campbell EA, Bucharová M, et al. Effect of low frequency sound vibration on acute stress response in university students—Pilot randomized controlled trial. *Front Psychol*. 2022; 13: 980756.
13. Araújo Alves J, Neto Paiva F, Torres Silva L, Remoaldo P. Low-frequency noise and its main effects on human health—A review of the literature between 2016 and 2019. *Appl Sci*. 2020; 10: 5205.
14. Pawlaczyk-Łuszczynska M, Dudarewicz A. Impact of very high-frequency sound and low-frequency ultrasound on people—the current state of the art. *Int J Occup Med Environ Health*. 2020; 33: 389-408.
15. Fletcher MD, Lloyd Jones S, White PR, Dolder CN, Leighton TG, Lineton B. Effects of very high-frequency sound and ultrasound on humans. Part II: A double-blind randomized provocation study of inaudible 20-kHz ultrasound. *J Acoust Soc Am*. 2018; 144: 2521-2531.
16. De Witte M, Pinho AD, Stams GJ, Moonen X, Bos AE, Van Hooren S. Music therapy for stress reduction: A systematic review and meta-analysis. *Health Psychol Rev*. 2022; 16: 134-159.
17. Ramaswamy M, Philip JL, Priya V, Priyadarshini S, Ramasamy M, Jeevitha GC, et al. Therapeutic use of music in neurological disorders: A concise narrative review. *Heliyon*. 2024; 10: e35564.
18. Clark CN, Downey LE, Warren JD. Brain disorders and the biological role of music. *Soc Cogn Affect Neurosci*. 2015; 10: 444-452.
19. Mansouri N, Javanbakht M, Jahan A, Bakhshi E, Shaabani M. Improve the behavioral auditory attention training effects on the Speech-In-Noise perception with simultaneous electrical stimulation in children with hearing loss: A randomized clinical trial. *Int J Pediatr Otorhinolaryngol*. 2025; 188: 112197.
20. Chahal JK, Sharma P, Rawat HC. Effect of music therapy on ICU induced anxiety and physiological parameters among ICU patients: An experimental study in a tertiary care hospital of India. *Clin Epidemiol Glob Health*. 2021; 11: 100716.

21. Diges I, Simón F, Cobo P. Assessing auditory processing deficits in tinnitus and hearing impaired patients with the Auditory Behavior Questionnaire. *Front Neurosci.* 2017; 11: 187.
22. Trappe HJ. Role of music in intensive care medicine. *Int J Crit Illn Inj Sci.* 2012; 2: 27-31.
23. Fan L, Baharum MR. The effect of exposure to natural sounds on stress reduction: A systematic review and meta-analysis. *Stress.* 2024; 27: 2402519.
24. Luo J, Wang M, Chen B, Sun M. Exposure to nature sounds through a mobile application in daily life: Effects on learning performance among university students. *Int J Environ Res Public Health.* 2022; 19: 14583.
25. Ratcliffe E. Sound and soundscape in restorative natural environments: A narrative literature review. *Front Psychol.* 2021; 12: 570563.
26. Guo M, Zhang J, Yang Z, Fan C, Zuo J, Hui T, et al. An empirical study on the response of university students to viewing autumn secondary forest phytocommunities landscape via virtual reality in Northeast China. *Ecol Indic.* 2024; 158: 111450.
27. Janiukstyte V, Owen TW, Chaudhary UJ, Diehl B, Lemieux L, Duncan JS, et al. Normative brain mapping using scalp EEG and potential clinical application. *Sci Rep.* 2023; 13: 13442.
28. Guo Y. Music therapy in psychological and educational context: Enhancing emotional and cognitive development of students. *Acta Psychol.* 2025; 254: 104820.
29. Olalla VA. Impact of music therapy on the emotional and cognitive development of young musicians. *J Ecohumanism.* 2024; 3: 13415-13425.
30. Wallmark Z, Iacoboni M, Deblieck C, Kendall RA. Embodied listening and timbre: Perceptual, acoustical, and neural correlates. *Music Percept.* 2018; 35: 332-363.
31. Linsong L. The influence of concert hall architecture on acoustics (the effect of musical performance). *E3S Web Conf.* 2023; 389: 06016.
32. Mateu-Capell M, Arnau A, Juvinyà D, Montesinos J, Fernandez R. Sound isolation and music on the comfort of mechanically ventilated critical patients. *Nurs Crit Care.* 2019; 24: 290-298.
33. Goditsch MJ, Storz D, Stegemann T. Opening the door—first insights into the music therapy room's design. *Nord J Music Ther.* 2017; 26: 432-452.
34. Poleszynski JF. Frequencies and their effects: A scientific overview [Internet]. Moss, Norway: Unovita; 2025. Available from: <https://unovita.com/blogs/news/frekvenser-og-bruksomrader>.
35. von Florian Eckl V. The effects of music and alph-theta-wave frequencies on meditation. Graz, Austria: The University of Music and Performing Arts Graz; 2016.
36. Chanda ML, Levitin DJ. The neurochemistry of music. *Trends Cogn Sci.* 2013; 17: 179-193.
37. Flores-Gutiérrez EO, Díaz JL, Barrios FA, Favila-Humara R, Guevara MÁ, del Río-Portilla Y, et al. Metabolic and electric brain patterns during pleasant and unpleasant emotions induced by music masterpieces. *Int J Psychophysiol.* 2007; 65: 69-84.
38. Lin YP, Wang CH, Jung TP, Wu TL, Jeng SK, Duann JR, et al. EEG-based emotion recognition in music listening. *IEEE Trans Biomed Eng.* 2010; 57: 1798-1806.
39. Li H, Xie H, Woodward G. Soundscape components, perceptions, and EEG reactions in typical mountainous urban parks. *Urban For Urban Green.* 2021; 64: 127269.
40. Pena-Soler E, Fernandez FJ, Lopez-Esteva M, Garces F, Richardson AJ, Quintana JF, et al. Structural analysis and mutant growth properties reveal distinctive enzymatic and cellular roles for the three major L-alanine transaminases of *Escherichia coli*. *PloS One.* 2014; 9: e102139.
41. Sammler D, Grigutsch M, Fritz T, Koelsch S. Music and emotion: Electrophysiological correlates of the processing of pleasant and unpleasant music. *Psychophysiology.* 2007; 44: 293-304.

42. Poerio GL, Sormaz M, Wang HT, Margulies D, Jefferies E, Smallwood J. The role of the default mode network in component processes underlying the wandering mind. *Soc Cogn Affect Neurosci.* 2017; 12: 1047-1062.
43. Brehme H, Kölch M, Buchmann J, Berger C. Neuronal network analysis during short time transcranial direct current stimulation with permanent EEG measurement in early childhood: A feasibility study. *J Neural Transm.* 2025. doi: 10.1007/s00702-025-02946-8.
44. Oommen KJ, Kopel J. Optimum duration of hyperventilation during electroencephalography. *Bayl Univ Med Cent Proc.* 2023; 36: 325-328.
45. Huang MH, Fan SY, Lin IM. EEG coherences of the fronto-limbic circuit between patients with major depressive disorder and healthy controls. *J Affect Disord.* 2023; 331: 112-120.
46. Vyazovskiy VV, Tobler I. Theta activity in the waking EEG is a marker of sleep propensity in the rat. *Brain Res.* 2005; 1050: 64-71.
47. Maffei A, Coccaro A, Jaspers-Fayer F, Goertzen J, Sessa P, Liotti M. EEG alpha band functional connectivity reveals distinct cortical dynamics for overt and covert emotional face processing. *Sci Rep.* 2023; 13: 9951.
48. Attar ET. Review of electroencephalography signals approaches for mental stress assessment. *Neurosci J.* 2022; 27: 209-215.
49. Lin W, Zeng C, Bao Z, Jin H. The therapeutic look up: Stress reduction and attention restoration vary according to the sky-leaf-trunk (SLT) ratio in canopy landscapes. *Landsc Urban Plan.* 2023; 234: 104730.
50. Li H, Dong W, Wang Z, Chen N, Wu J, Wang G, et al. Effect of a virtual reality-based restorative environment on the emotional and cognitive recovery of individuals with mild-to-moderate anxiety and depression. *Int J Environ Res Public Health.* 2021; 18: 9053.
51. D'Errico F, Leone G, Schmid M, D'Anna C. Prosocial virtual reality, empathy, and EEG measures: A pilot study aimed at monitoring emotional processes in intergroup helping behaviors. *Appl Sci.* 2020; 10: 1196.
52. Natalizio A, Sieghartsleitner S, Schreiner L, Walchshofer M, Esposito A, Scharinger J, et al. Real-time estimation of EEG-based engagement in different tasks. *J Neural Eng.* 2024; 21: 016014.
53. Gruzelier JH, Holmes P, Hirst L, Bulpin K, Rahman S, Van Run C, et al. Replication of elite music performance enhancement following alpha/theta neurofeedback and application to novice performance and improvisation with SMR benefits. *Biol Psychol.* 2014; 95: 96-107.
54. Hassan A, Qibing C, Tao J. Physiological and psychological effects of gardening activity in older adults. *Geriatr Gerontol Int.* 2018; 18: 1147-1152.
55. Hankins TC, Wilson GF. A comparison of heart rate, eye activity, EEG and subjective measures of pilot mental workload during flight. *Aviation Space Environ Med.* 1998; 69: 360-367.
56. Evans G, Hygge S. Noise and cognitive performance in children and adults. *Noise and its effects.* Chichester, England: Wiley; 2007.