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Research Article

Keywords: Bamboo forest, Forest recreation, Cultural ecosystem services, Soundscape, Traffic noise, Electroencephalography

Posted Date: August 14th, 2026

DOI: <https://doi.org/10.21203/rs.3.rs-10620508/v1>

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Additional Declarations: No competing interests reported.

Soundscape categories shape recreational responses across independently characterized bamboo forest settings: a two-phase audio–visual experiment

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Abstract

Bamboo forests provide ecological, production, and recreational functions, yet the quality of their cultural ecosystem services may depend on both stand structure and acoustic conditions. Visual context can influence soundscape evaluation but is often insufficiently characterized in controlled audio–visual experiments. We used a two-phase design with independent participant samples to compare responses to natural sounds (NAT), human-activity sounds (HUM), and traffic noise (TRA) across independently characterized bamboo-space visual contexts. Phase 1 derived block-level visual restorative potential, vertical stratification, and groundcover coverage from 50 matched photograph–plot units. In Phase 2, 113 adults completed six 50-s exposures, yielding 678 observations across 10 visual blocks and 18 soundtracks. Outcomes were relaxation, pleasure, preference, and EEG $\Delta(\beta/\alpha)$. Mixed-effects models adjusted for trial position and visual context, with sensitivity analyses addressing alternative visual specifications, stimulus omission, soundtrack reuse, participant heterogeneity, bootstrap inference, and participant-clustered CR2 inference. Subjective responses decreased from NAT to HUM to TRA, whereas EEG showed the reverse ordering. Relative to NAT, HUM reduced relaxation, pleasure, and preference by 17.47, 18.14,

and 22.36 points, while TRA reduced them by 41.52, 41.51, and 46.64 points; EEG contrasts were 0.318 for HUM–NAT and 0.494 for TRA–NAT. All eight contrasts remained significant after Holm adjustment. Joint adjustment for pleasantness and annoyance attenuated HUM–NAT contrasts by 95.2%–99.6% and TRA–NAT contrasts by 81.3%–90.0%. EEG–subjective correspondence was weak, and neither age nor pre-exposure STAI-S showed multiplicity-adjusted evidence of moderation. These findings indicate that acoustic conditions represent a distinct component of recreational quality in bamboo forests and should be considered alongside stand structure in the assessment and management of forest cultural ecosystem services.

Keywords

Bamboo forest; Forest recreation; Cultural ecosystem services; Soundscape; Traffic noise; Electroencephalography

1 Introduction

Forests are increasingly managed for multiple functions extending beyond timber production and biodiversity conservation. Recreation, aesthetic experience, psychological well-being, and opportunities for contact with nature constitute important cultural ecosystem services, particularly in peri-urban and multifunctional forests. The quality of these services depends not only on visible stand characteristics but also on the acoustic conditions encountered by visitors. Biological sounds, recreational activity, and external transportation noise may therefore represent distinct components of forest recreational quality. However, acoustic conditions remain less explicitly incorporated than visual stand characteristics in assessments of forest experience and management.

1.1 Acoustic quality within forest recreation and multisensory experience

Restorative environments are experienced through multiple senses, although experimental research has relied heavily on photographs, videos, and landscape views. Exposure to natural settings can influence affect, perceived stress, autonomic activity,

and attention, but the magnitude and direction of these responses vary across settings, exposure modes, populations, and outcome measures [1-5]. Visual stimuli provide useful experimental control, but they represent only part of an environmental encounter [4-6]. In audio–visual research, vision and sound are the two channels most directly manipulated and most likely to interact.

Sound can remain perceptually salient even when attention is directed elsewhere. It also conveys information about ecological activity, human presence, movement, safety, and intrusion [7, 8]. Soundscape research therefore treats the acoustic environment as perceived and interpreted in context, rather than as a set of physical signals alone [9]. Responses depend not only on acoustic properties but also on source recognition, temporal pattern, expectation, prior experience, current activity, and contextual appropriateness [10]. Accordingly, perceived acoustic quality often relates more closely to pleasantness, annoyance, calmness, and restorative potential than sound level alone [11-13].

Birdsong, flowing water, and vegetation sounds are generally rated as more pleasant and less annoying than traffic or other mechanical noise [14-18]. Traffic-dominated soundscapes, by contrast, are commonly associated with poorer affective appraisal and greater disturbance [19-22]. These patterns are not universal. Natural sounds differ in loudness, spectral content, temporal structure, familiarity, and meaning, and some water or animal sounds may be neutral, activating, or unpleasant [20, 23, 24]. Human-activity sounds are even more context-dependent. Conversation, footsteps, and recreational activity may indicate sociability and appropriate use, but they may become intrusive when dominant, unpredictable, or inconsistent with expectations for a natural setting [25-27].

Natural, human-activity, and traffic sounds therefore provide useful experimental

contrasts, but none should be treated as an internally uniform category [24, 27, 28]. Their effects depend on both the composition of the soundtrack and the setting in which it is presented. Natural sounds can improve evaluations of visually urban environments, whereas anthropogenic noise can reduce the perceived quality of natural scenes [29]. Audio–visual incongruence may also produce uneven or asymmetric responses across sensory combinations [11, 26, 30]. Soundscape effects must therefore be interpreted in relation to their visual context.

1.2 Separating soundscape responses from forest visual heterogeneity

Visual context clearly influences soundscape evaluation. The key methodological question is whether that context is characterized precisely enough to support valid attribution. Visible naturalness, spatial form, source visibility, and landscape quality can alter responses to similar acoustic stimuli [3, 31, 32]. Audio–visual congruence can also affect perceived appropriateness and environmental quality [9, 29, 33, 34]. Acoustic information may, in turn, reshape evaluations of landscape satisfaction and restorative potential [19, 35, 36]. Vision is therefore part of experimental exposure rather than a neutral background for sound presentation.

Field studies preserve the sensory, spatial, and social conditions in which soundscapes are normally experienced. However, vegetation structure, road visibility, visitor density, season, site use, sound level, and sound-source composition often vary together [9, 19, 33, 36]. A favourable response at one site may therefore reflect better visual quality, lower traffic exposure, richer biological sound, different patterns of use, or several of these factors at the same time [10, 37-39]. Statistical adjustment can account for measured covariates, but it cannot fully separate auditory and visual contributions when both are assessed concurrently or represented only by broad site categories [20, 40-42].

Laboratory and virtual-reality studies offer greater control by standardizing playback and pairing sounds systematically with photographs, videos, or simulated environments [29, 31, 34, 35]. Yet controlling sound presentation does not control visual heterogeneity. Many studies use a single scene, a small set of selected images, or broad natural–built contrasts [37, 43–45]. Others combine several sounds and scenes without independently quantifying the baseline quality or structural properties of each visual stimulus [10–12, 30, 46]. Estimated soundscape effects may therefore remain dependent on the selected scenes, perceived source plausibility, cross-modal congruence, or reproduction fidelity [13, 47–49].

A stronger design should test each soundscape condition across multiple visual backgrounds and characterize those backgrounds independently of the audio–visual outcomes. It should also distinguish repeated participant responses from stable differences among visual blocks and specific soundtracks. Repeated responses to the same soundtrack do not constitute independent samples of the wider sound category. The analysis should therefore test whether the main estimates remain stable under alternative visual specifications and after variation among specific soundtracks and participants has been considered.

1.3 Bamboo forest context, aims, and hypotheses

Bamboo-dominant green spaces provided a visually coherent but structurally heterogeneous setting for this study. Previous research has reported short-term affective and physiological responses to bamboo environments and shown that these responses vary with spatial structure and exposure conditions [50–52]. Bamboo forests provided a suitable model system because they combine a coherent vegetation identity with substantial variation in stand structure, understory condition, management function, and recreational use. This combination allowed acoustic responses to be examined within a

defined forest system while accounting for measured visual heterogeneity among forest settings.

The study used a two-phase design with independent participant samples. Phase 1 characterized visual variation using matched photographs, field measurements, and subjective ratings. Phase 2 examined responses to soundtracks paired with videos recorded at the same locations. Visual restorative potential, vertical stratification, and groundcover coverage derived from Phase 1 were introduced as external descriptors of the Phase 2 visual context. This design reduced dependence between visual-context measures and audio–visual outcomes and allowed soundscape effects to be evaluated after visual heterogeneity had been considered.

The study first tested whether natural sounds (NAT), human-activity sounds (HUM), and traffic noise (TRA), each represented by six soundtracks, produced the expected differences in auditory pleasantness and annoyance. The primary analyses then compared relaxation, pleasure, preference, and EEG $\Delta(\beta/\alpha)$ across the three categories. We hypothesized that subjective responses would follow a NAT>HUM>TRA pattern, whereas $\Delta(\beta/\alpha)$ would show the reverse ordering. We further examined whether the HUM–NAT and TRA–NAT contrasts remained stable across alternative representations of visual context and stimulus-level sensitivity analyses.

An additional hierarchical sensitivity analysis tested whether the primary contrasts remained stable after repeated use of specific soundtracks and participant-specific variation in category responses were modelled directly. This analysis was used to assess the robustness of the primary estimates rather than to test an additional directional hypothesis.

Secondary analyses assessed the statistical overlap between the subjective contrasts and concurrent auditory appraisal, as well as the correspondence between

EEG and subjective responses. Age and pre-exposure STAI-S were examined as exploratory moderators without directional hypotheses. Inference was limited to the tested soundtracks, visual materials, and participant sample. From a forest-management perspective, the design tested whether differences among acoustic conditions persisted after measurable variation in bamboo stand structure and visual quality had been considered.

2 Materials and methods

2.1 Overall two-phase study design

Two independent experiments were linked through visual materials collected at the same 50 bamboo-space locations. Phase 1 characterized visual context using photographs, participant ratings, and field-measured spatial indicators. Phase 2 used videos recorded from matched viewpoints to examine responses to three soundscape categories—natural sounds (NAT), human-activity sounds (HUM), and traffic noise (TRA)—each represented by six specific soundtracks. The participant samples did not overlap. The 50 videos were organized into 10 visual blocks, each containing one clip from each of the five bamboo-space types. Phase 1- derived measures were linked to these blocks as external descriptors of visual context. Phase 2 followed a laboratory-based incomplete repeated-measures design: each participant completed six audio–visual exposures, including two from each soundscape category, with subjective and EEG outcomes obtained for each trial (**Figure 1**). The study sites comprised managed bamboo forest stands representing ecological conservation, production, protective-greenbelt, recreational, and understory-composite functions. Although the stands shared bamboo dominance, they differed in vertical layering, groundcover development, canopy and culm structure, and intended management use. These attributes provided a defined forest context in which acoustic responses could be assessed while accounting

for variation in stand-level visual conditions.

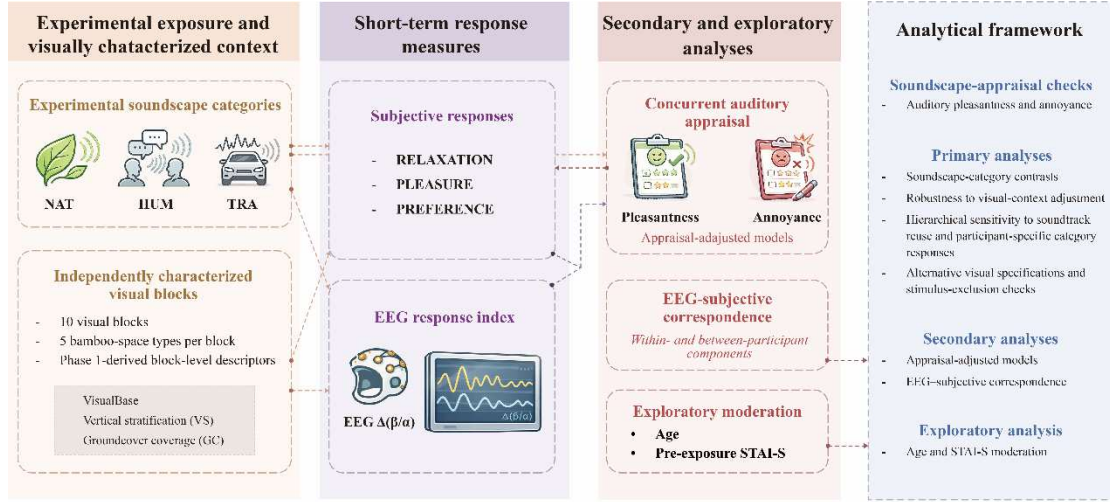


Figure 1 Overall design and analytical linkage of the two-phase study.

2.2 Phase 1 source study and derivation of block-level visual covariates

Phase 1 provided external measures of visual context for the Phase 2 experiment. It comprised 50 photograph–plot units, with 10 representing each bamboo-space type. Each photograph was recorded at the same location and from the same viewpoint as its corresponding Phase 2 video, and each location was associated with an independently measured field plot. During visual-only exposure, participants rated relaxation, pleasure, and preference, while nine visual and structural indicators were obtained from the matched plots [50] [65].

Based on the independently obtained Phase 1 findings, vertical stratification (VS) and groundcover coverage (GC) were retained because they showed the most consistent associations with the three subjective ratings [50] [65]. The number of block-level adjustment variables was restricted because Phase 2 contained only 10 visual blocks. For each block, the five matched photograph–video–plot units were summarized using VisualBase, mean VS, and mean GC:

$$\text{VisualBase}_b = \frac{1}{5} \sum_{j=1}^5 \bar{R}_{bj} \quad (1)$$

$$VS_b = \frac{1}{5} \sum_{j=1}^5 VS_{bj}, GC_b = \frac{1}{5} \sum_{j=1}^5 GC_{bj} \quad (2)$$

where $b = 1, \dots, 10$ denotes the visual block and $j = 1, \dots, 5$ denotes the matched unit within that block. $\bar{R}_{bj}$ is the Phase 1 participant-averaged relaxation rating for photograph j , whereas VS_{bj} and GC_{bj} are the corresponding plot-level measurements. The resulting block-level values are reported in **Table S1**.

VisualBase was defined using the Phase 1 relaxation ratings, while alternative definitions based on pleasure, preference, and their composite were examined in sensitivity analyses. All three variables varied only between visual blocks and were used to adjust for visual-context heterogeneity rather than to estimate within-block effects. Because VS and GC were strongly correlated, their coefficients were not interpreted as independent structural effects. VisualBase was likewise treated as an external proxy for the matched visual context, not as a direct rating of the Phase 2 videos.

2.3 Participants and analytical sample

Participants were adults aged 18–70 years with normal or corrected-to-normal vision and no self-reported severe hearing impairment, neurological disorder, or recent use of psychotropic medication. Exclusion criteria were failure to complete the procedure, substantial missing questionnaire data, or EEG recordings that did not meet the study quality-control criteria.

EEG quality control was evaluated at the trial level, but participants were included in the analytical sample only if all six trials met the prespecified criteria; no individual trials were deleted from retained participants. The final sample comprised 113 participants, each contributing six valid exposures. All 678 block observations were retained for both subjective and EEG analyses. Participant characteristics and realized exposure allocation are reported in **Table 1**.

The study was approved by the Academic Ethics Committee of Sichuan Agricultural University (Approval No. H20260004). All participants provided verbal informed consent before taking part in the study.

Table 1 Participant characteristics and exposure allocation.

Panel A. Participant characteristics

Characteristic	Value
Final analytical sample, n	113
Age, mean $\pm$ SD (years)	40.20 $\pm$ 14.89
Age range (years)	18–70
Female, n (%)	58 (51.3%)
Male, n (%)	55 (48.7%)
Pre-exposure STAI-S total, mean $\pm$ SD	38.48 $\pm$ 7.86
STAI-S range	26–64

Panel B. Exposure allocation and design balance

Item	Overall
Predefined visual blocks, n	10 (B01–B10)
Blocks per participant, n	6
Total observations (block exposures), n	678 (=113 $\times$ 6)
Trial order (1–6), n per position	113 each
Soundscape exposures, n (%)	NAT 226 (33.3%) HUM 226 (33.3%) TRA 226 (33.3%)
Specific soundtracks, n	18 total; 6 per category
Observations per specific soundtrack, range	36–41
Visual-sequence assignment, n	S1–S6: 12 each S7: 11 S8–S10: 10 each
Realized soundscape-category order, n (%)	O1: 38 (33.6%) O2: 38 (33.6%) O3: 37 (32.7%)

Notes: Panel A summarizes participant-level characteristics. Panel B reports the realized distribution of block exposures under the prespecified incomplete repeated-measures allocation. Each participant contributed six valid block observations, and all 678 observations were included in both the subjective and EEG analyses. Values are presented as mean $\pm$ SD unless otherwise stated.

2.4 Audio–visual stimuli and block construction

The visual stimulus set comprised 50 distinct 10-s video clips recorded at the locations used in Phase 1 and from matched viewpoints. Five bamboo-space types were represented: ecological conservation (EC), productive–economic (PE), protective–greenbelt (PG), landscape–recreational (LR), and understory–composite (UC), with 10 clips per type. Recording was conducted in May 2025 between 10:00 and 15:00 under clear weather conditions. Camera height, viewing direction, upward tilt, and exposure settings were held constant across locations.

The clips were organized into 10 visual blocks (B01–B10). Each 50-s block

contained one clip from each bamboo-space type, presented in the fixed order EC–PE–PG–LR–UC. Each clip appeared in only one block. Because responses were collected after the complete block, the audio–visual block was the unit of exposure and analysis; effects of individual bamboo-space types were not estimated.

The acoustic stimuli comprised three soundscape categories: natural sounds (NAT), human-activity sounds (HUM), and traffic noise (TRA). Each category was represented by six distinct 50-s soundtracks, yielding 18 soundtracks in total. NAT included combinations of birdsong, insect sounds, wind, and vegetation movement; HUM included conversation, footsteps, and recreational activity; and TRA included road traffic, vehicle pass-bys, horns, and railway-related sounds.

The soundtracks were added as experimental overlays rather than recorded concurrently with the videos. Original video audio was removed, and one 50-s soundtrack was paired with each visual block and played continuously across its five clips. Audio normalization, audio–visual alignment, and fade-in and fade-out procedures were standardized across stimuli. All exposures were presented using the same headphones and fixed system-volume setting.

2.5 Exposure allocation and experimental procedure

Phase 2 used a laboratory-based incomplete repeated-measures design. Each participant completed six audio–visual trials involving six different visual blocks and six different specific soundtracks. Two trials were assigned to each soundscape category, so that every participant received two NAT, two HUM, and two TRA exposures. Soundtrack numbers 1–6 were each presented once, yielding six distinct soundtracks per participant.

Visual blocks were assigned through 10 cyclic six-block sequences. Each successive sequence began one block later in the B01–B10 cycle, allowing the blocks

to be distributed across participants without requiring every participant to view all 10.

Soundscape category followed one of three cyclic orders:

O1: NAT – HUM – TRA – NAT – HUM – TRA

O2: HUM – TRA – NAT – HUM – TRA – NAT

O3: TRA – NAT – HUM – TRA – NAT – HUM

These orders balanced the three categories approximately across the six trial positions. Within-category soundtrack numbers followed six cyclic rotations. Visual-block sequence, category order, and soundtrack-number rotation were combined across participants, and the specific stimulus in each trial was determined jointly by the assigned category and soundtrack number. The resulting design was partially crossed: each participant encountered multiple blocks and soundtracks, but every soundtrack was not paired with every visual block. The predefined and realized allocations are summarized in **Figure 2**.

Before the exposure trials, participants completed demographic questions and the State Anxiety Inventory–State version. The EEG system was then fitted, and signal quality was checked. Each trial comprised a 20-s resting EEG baseline, a 50-s audio–visual exposure, and post-exposure ratings of relaxation, pleasure, preference, auditory pleasantness, and annoyance. The experiment ended after all six trials had been completed.

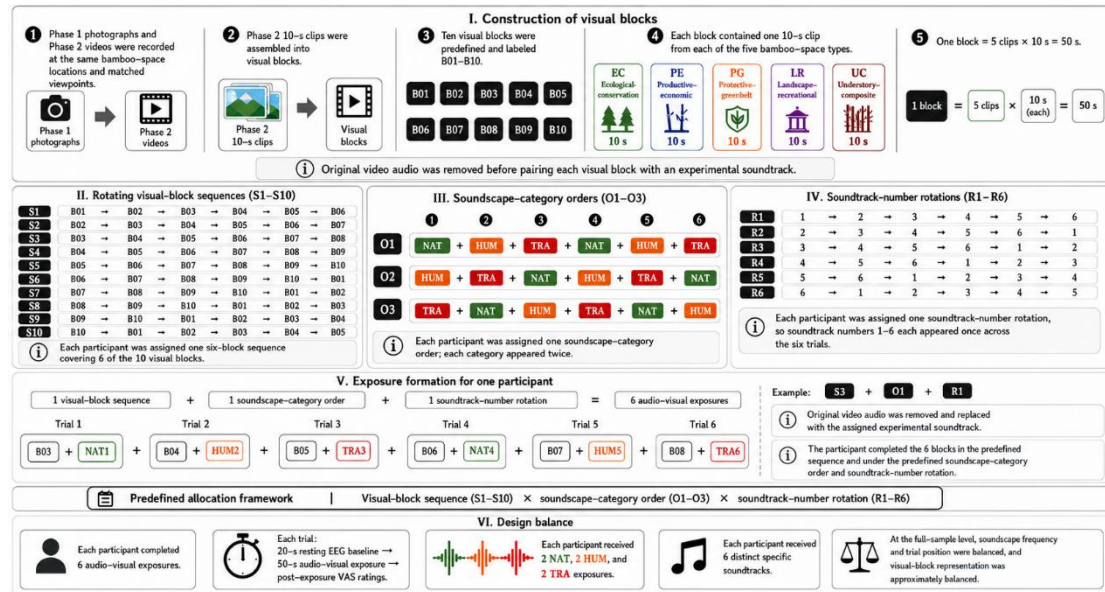


Figure 2 Experimental design and predefined sequential allocation for the Phase 2 audio-visual block experiment.

2.6 Outcome measures

2.6.1 Subjective responses

Immediately after each block, participants rated relaxation, pleasure, and preference on separate 0–100 visual analogue scales (VAS). Relaxation represented tension relief and mental or bodily ease; pleasure captured positive affective valence; and preference reflected overall liking of the audio-visual environment. The outcomes were analysed separately, with higher scores indicating more positive responses.

Ratings referred to the complete video-soundtrack combination rather than either modality in isolation. The continuous VAS format provided fine-grained trial-level responses while limiting burden during repeated assessment [53].

Participants also rated auditory pleasantness and annoyance on separate 0–100 VAS items. Higher scores indicated greater pleasantness or annoyance, respectively. These variables were treated as concurrent soundscape appraisals rather than primary restorative-affective outcomes [13, 37, 54, 55].

2.6.2 EEG acquisition and outcome

EEG was recorded continuously using a mobile 16-channel system (MB8600, BoYing BI, China), with electrodes positioned according to the international 10–20

system and referenced to the earlobes (A1/A2). Analyses included 10 frontal, temporal, and occipital channels: F3, F4, F7, F8, T3, T4, T5, T6, O1, and O2. Signals were sampled at 250 Hz, band-pass filtered from 1 to 40 Hz, and notch-filtered at 50 Hz.

Ocular- and muscle-related components were removed using independent component analysis [56]. Residual segments with peak-to-peak amplitudes exceeding 100 μ V were rejected, and power spectral density was estimated using Welch's method [57]. Alpha and beta power were defined over 8–13 Hz and 13–30 Hz, respectively. The β/α ratio was treated as a complementary index of relative cortical activation rather than a direct measure of relaxation [58, 59].

For each trial, β/α was calculated for the 20-s pre-exposure baseline and the corresponding 50-s exposure. The primary EEG outcome was:

$$\Delta(\beta/\alpha) = (\beta/\alpha)_{\text{exposure}} - (\beta/\alpha)_{\text{baseline}}. \quad (3)$$

Positive values indicated an increase in beta power relative to alpha power during exposure; negative values indicated a decrease from baseline. A trial was retained only when both segments were available and met the EEG quality-control criteria.

2.7 Statistical analysis

Analyses were conducted at the audio–visual block level using 678 observations from 113 participants. Linear mixed-effects models were used to account for the repeated and partially crossed data structure [60]. Subjective-outcome models included crossed random intercepts for participant and visual block, with NAT as the reference category and trial position as a covariate. Models for relaxation, pleasure, preference, and EEG $\Delta(\beta/\alpha)$ additionally adjusted for VisualBase, vertical stratification (VS), and groundcover coverage (GC). The prespecified participant-and-block EEG model was singular because the estimated visual-block variance was effectively zero; the reported EEG model therefore included random intercepts for participant and specific

soundtrack.

Auditory pleasantness and annoyance were analysed as soundscape-appraisal checks. Estimated marginal means and pairwise category contrasts were obtained with Tukey adjustment [61] . The primary tests comprised the HUM–NAT and TRA–NAT contrasts for the three subjective outcomes and EEG $\Delta(\beta/\alpha)$; Holm correction was applied across these eight contrasts [62] .

Robustness analyses examined models without the visual covariates, alternative Phase 1 visual baselines, categorical block fixed effects, soundscape-category-by-visual-context interactions, sequential omission of individual soundtracks and visual blocks, first-trial-only data, parametric bootstrap inference [63], and participant-clustered CR2 fixed-effects inference [64] . Holm correction was applied across the 24 visual-context interaction tests. Singular sensitivity models, if encountered, were simplified according to a prespecified sequence while retaining the fixed-effects specification.

Hierarchical sensitivity analyses further considered a specific-soundtrack random intercept and independent participant-level HUM and TRA slopes. For each subjective outcome, the richest converged, non-singular candidate structure was retained according to a fixed simplification sequence[65, 66].

Secondary models added concurrent auditory pleasantness, annoyance, or both to the subjective-outcome models. Within each outcome, the matched baseline and adjusted models used identical observations and random-effects structures. Contrast attenuation was calculated as:

$$\text{Attenuation} = \frac{|B_{\text{baseline}}| - |B_{\text{adjusted}}|}{|B_{\text{baseline}}|} \times 100\%. \quad (4)$$

Because appraisal and subjective outcomes were measured after the same exposure, attenuation was interpreted as concurrent statistical overlap rather than

mediation [67].

EEG–subjective correspondence was examined by simultaneously entering participant-mean-centred EEG deviations and participant-level EEG means, thereby separating within- and between-participant associations[68]. Exploratory models tested interactions with standardized age and pre-exposure STAI-S. Holm correction was applied across the three within-participant EEG associations, separately within each eight-test moderator family, and across all 16 moderation tests [86].

Convergence, singularity, residual behaviour, and collinearity were assessed. Results are reported as unstandardized coefficients with 95% confidence intervals, with statistical significance evaluated at $p < 0.05$ after the specified multiplicity adjustment.

3 Results

3.1 Analytical sample and soundscape-appraisal checks

The final analytical sample comprised 113 participants contributing 678 valid audio–visual block observations. Participant characteristics and the achieved balance across soundscape categories, trial positions, specific soundtracks, and allocation sequences are summarized in **Table 1** and **Table S2**.

Concurrent soundscape appraisal showed the expected ordering across categories (**Table 2; Figure 3**). Estimated marginal mean pleasantness decreased from NAT (80.37, 95% CI [77.71, 83.02]) to HUM (54.01, 95% CI [50.46, 57.57]) and TRA (30.32, 95% CI [26.17, 34.48]), whereas annoyance increased from NAT (15.05, 95% CI [12.31, 17.79]) to HUM (41.54, 95% CI [38.38, 44.70]) and TRA (69.22, 95% CI [65.37, 73.06]). All pairwise contrasts were significant after Tukey adjustment for both outcomes (all $p < 0.001$), indicating clear perceptual differentiation among the tested soundtrack sets.

Table 2 Tukey-adjusted pairwise contrasts in soundscape appraisal across the three soundscape categories.

Outcome	Contrast	B	SE	95% CI	p
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Pleasantness	HUM–NAT	–26.35	1.67	[–30.32, –22.39]	<0.001
	TRA–NAT	–50.04	2.00	[–54.78, –45.31]	<0.001
	TRA–HUM	–23.69	2.33	[–29.20, –18.18]	<0.001
Annoyance	HUM–NAT	26.49	1.69	[22.49, 30.49]	<0.001
	TRA–NAT	54.17	2.02	[49.39, 58.95]	<0.001
	TRA–HUM	27.68	2.17	[22.54, 32.81]	<0.001

Note: Positive coefficients indicate higher scores in the first-named category relative to the second-named category. Estimated marginal means and contrasts were obtained from the final mixed-effects models adjusted for trial position. Confidence intervals and p values for pairwise contrasts were Tukey-adjusted.

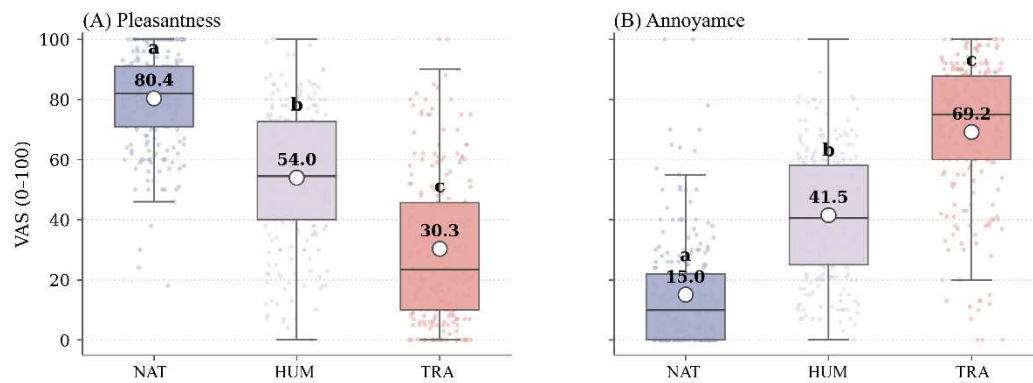


Figure 3 Soundscape appraisal across NAT, HUM, and TRA. Jittered points and boxplots show trial-level VAS ratings, whereas white circles indicate mixed-model estimated marginal means; different lowercase letters denote significant Tukey-adjusted pairwise differences (all $p < 0.001$).

3.2 Soundscape-category effects on recreational-affective responses and EEG

Estimated marginal means for relaxation, pleasure, and preference followed a NAT>HUM>TRA ordering, whereas EEG $\Delta(\beta/\alpha)$ showed the reverse NAT<HUM<TRA pattern (Table 3; Figure 4). Compared with NAT, HUM was associated with lower relaxation ($B = -17.47$, 95% CI [–20.04, –14.91]), pleasure ($B = -18.14$, 95% CI [–20.70, –15.58]), and preference ($B = -22.36$, 95% CI [–25.35, –19.37]). The corresponding TRA–NAT contrasts were larger for relaxation ($B = -41.52$, 95% CI [–44.09, –38.96]), pleasure ($B = -41.51$, 95% CI [–44.07, –38.95]), and preference ($B = -46.64$, 95% CI [–49.63, –43.64]).

For EEG, the visual-block random-intercept variance was effectively zero, and the reported final model therefore retained random intercepts for participant and specific soundtrack (Table S4, Panels A and C). EEG $\Delta(\beta/\alpha)$ was higher under HUM than under NAT ($B = 0.318$, 95% CI [0.221, 0.415]) and higher under TRA than under NAT ($B = 0.494$, 95% CI [0.398, 0.591]). These positive contrasts corresponded to progressively

less negative estimated means from NAT to HUM to TRA. All reported final models converged without singularity, and all eight prespecified contrasts remained significant after Holm correction (all Holm-adjusted $p < 0.001$).

Table 3 Prespecified soundscape-category contrasts from the final outcome models.

Outcome	HUM–NAT,		TRA–NAT	
	B (95% CI)	Holm (p)	B (95% CI)	Holm (p)
Relaxation	–17.47 [–20.04, –14.91]	<0.001	–41.52 [–44.09, –38.96]	<0.001
Pleasure	–18.14 [–20.70, –15.58]	<0.001	–41.51 [–44.07, –38.95]	<0.001
Preference	–22.36 [–25.35, –19.37]	<0.001	–46.64 [–49.63, –43.64]	<0.001
EEG $\Delta(\beta/\alpha)$	0.318 [0.221, 0.415]	<0.001	0.494 [0.398, 0.591]	<0.001

Note: Subjective models included crossed random intercepts for participant and visual block. Because the visual-block variance for EEG was effectively zero, the reported final EEG model included random intercepts for participant and specific soundtrack. p values were Holm-adjusted across the eight prespecified contrasts.

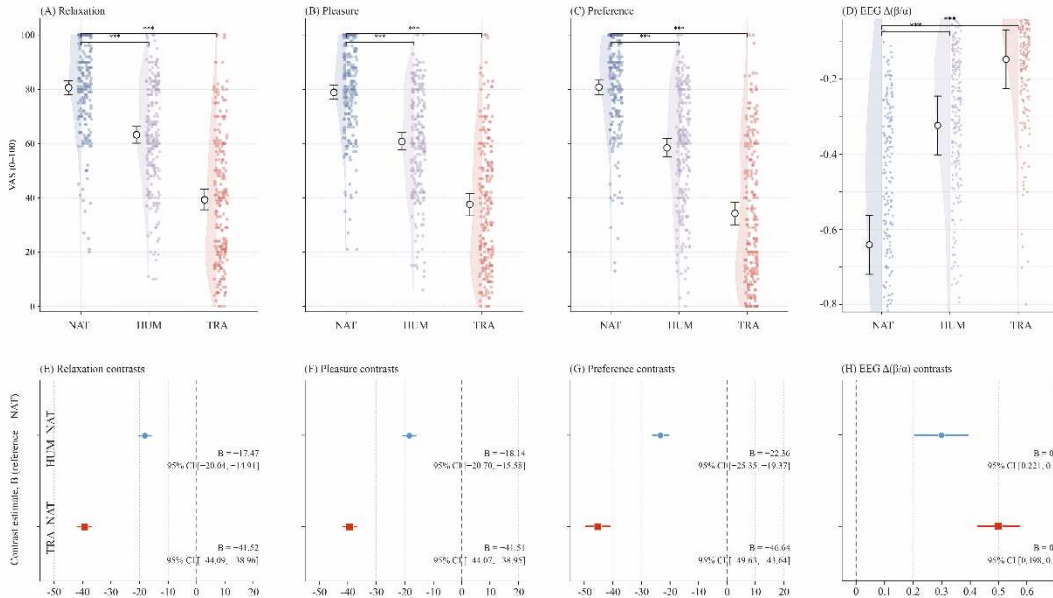


Figure 4 Primary subjective and EEG responses across the three tested soundscape categories. Panels (A–D) show trial-level distributions and model-based estimated marginal means with 95% confidence intervals. Panels (E–H) show the prespecified HUM–NAT and TRA–NAT contrasts with 95% confidence intervals; dashed vertical lines indicate zero, and all eight contrasts remained significant after Holm adjustment (all adjusted $p < 0.001$).

3.3 Robustness across bamboo forest visual contexts, stimuli, and analytical specifications

The reported soundscape contrasts were highly stable across visual specifications (Table 4; Figure 5). Comparing the visually adjusted reference models with models omitting VisualBase, VS, and GC showed changes of only 0.02%–0.16% across the eight contrasts, without altering their directions or inferential conclusions. Replacing VisualBase with alternative Phase 1 visual baselines changed the estimates by no more

than 0.14%, whereas substituting categorical block fixed effects for the continuous visual descriptors changed them by at most 0.98%. None of the 24 soundscape-category-by-visual-context interactions remained significant after Holm correction (minimum adjusted $p = 0.187$; **Table S3**). Because VS and GC showed elevated collinearity ($VIF = 5.66\text{--}6.51$), their coefficients were treated as adjustment terms rather than interpreted as independent visual effects.

The contrasts also remained stable when individual soundtracks or visual blocks were omitted in turn. All 72 leave-one-soundtrack-out and 40 leave-one-block-out models were estimable using the full specified random-effects structures, without requiring random-effects simplification. Every derived contrast retained the direction of its reference estimate, and all corresponding 95% CIs excluded zero. For the subjective outcomes, the largest absolute departures from the reference estimates were 1.37 VAS points under soundtrack omission and 1.28 VAS points under block omission. The corresponding maximum departures for EEG $\Delta(\beta/\alpha)$ were 0.043 and 0.036, respectively.

Additional hierarchical sensitivity models directly accounted for repeated use of the specific soundtracks and participant-level variation in category responses. Across the six subjective contrasts, the selected non-singular models changed the point estimates by no more than 0.35%; all contrasts retained their original directions, their 95% CIs excluded zero, and their Holm-adjusted conclusions were unchanged (**Table S4**, Panel B). The EEG contrasts were likewise insensitive to random-effects specification: the reported participant-and-soundtrack model was non-singular, and its estimates differed by less than 0.2% from those obtained under the prespecified participant-and-block specification, with unchanged directions and inferential conclusions (**Table S4**, Panel C).

In the first-trial-only analysis, all eight estimates retained their original directions. The HUM–NAT contrast for pleasure was less precise and its confidence interval included zero ($B = -9.92$, 95% CI $[-21.06, 1.22]$), whereas the remaining seven intervals excluded zero. All 1,000 parametric-bootstrap simulations were successful for each final model, and every bootstrap interval excluded zero. Estimates from the participant-clustered CR2 fixed-effects analyses differed from the reference mixed-model estimates by no more than 0.11 VAS points for the subjective outcomes and 0.004 units for EEG $\Delta(\beta/\alpha)$, with unchanged inferential conclusions.

Table 4 Robustness of the reported soundscape-category contrasts

Panel A. Visual and omission analyses

Outcome	Contrast	Reference B	Visual-specification B range			Omission analysis		
			No covariates	Alternative baseline	Block fixed effects	Soundtrack omission	Block omission	
Relaxation	HUM–NAT	–17.47	–17.45	–17.45 to –17.40	to 8	–18.21 to –16.22	to	–17.98 to –16.16
	TRA–NAT	–41.52	–41.50	–41.50 to –41.37	to 3	–42.09 to –40.08	to	–42.00 to –40.84
Pleasure	HUM–NAT	–18.14	–18.14	–18.17 to –18.10	to 9	–18.84 to –17.62	to	–19.03 to –17.21
	TRA–NAT	–41.51	–41.47	–41.50 to –41.40	to 8	–41.95 to –40.64	to	–42.05 to –41.02
Preference	HUM–NAT	–22.36	–22.34	–22.41 to –22.21	to 0	–23.64 to –21.45	to	–23.37 to –21.72
	TRA–NAT	–46.64	–46.62	–46.58 to –46.51	to 3	–47.22 to –45.96	to	–47.52 to –45.90
EEG $\Delta(\beta/\alpha)$	HUM–NAT	0.318	0.3179	0.318 to 0.321	to 0.3212	0.275 to 0.349	to	0.282 to 0.336
	TRA–NAT	0.494	0.4952	0.494 to 0.497	to 0.4973	0.452 to 0.526	to	0.462 to 0.515

Panel B. Sample and inferential analyses

Outcome	Contrast	First-trial model	Bootstrap 95% CI	CR2 model
Relaxation	HUM–NAT	–10.38 $[-19.68, -1.08]$	$[-20.03, -15.05]$	–17.48 $[-20.11, -14.86]$
	TRA–NAT	–31.61 $[-40.98, -22.24]$	$[-44.23, -38.94]$	–41.63 $[-45.28, -37.98]$
Pleasure	HUM–NAT	–9.92 $[-21.06, 1.22]$	$[-20.58, -15.68]$	–18.09 $[-20.81, -15.38]$

Preference	TRA–NAT	–34.24 [–45.37, –23.12]	[–44.14, –39.13]	–41.58 [–45.34, –37.82]
	HUM–NAT	–18.03 [–32.22, –3.84]	[–25.17, –19.21]	–22.30 [–25.65, –18.94]
	TRA–NAT	–45.72 [–59.90, –31.53]	[–49.60, –43.50]	–46.73 [–51.00, –42.46]
EEG $\Delta(\beta/\alpha)$	HUM–NAT	0.300 [0.185, 0.416]	[0.232, 0.405]	0.322 [0.252, 0.392]
	TRA–NAT	0.469 [0.353, 0.586]	[0.411, 0.580]	0.498 [0.416, 0.581]

Note: Reference estimates are those reported in Table 3. “Without visual covariates” refers to models omitting VisualBase, VS, and GC. Alternative visual-baseline ranges summarize the non-singular models replacing VisualBase with the Phase 1 pleasure, preference, or composite baseline. Block fixed-effects models replaced the continuous visual descriptors and visual-block random intercept with categorical block fixed effects. All 72 leave-one-soundtrack-out and 40 leave-one-block-out models were estimable using the full specified random-effects structures. Parametric-bootstrap intervals are percentile intervals from 1,000 successful simulations per final model. CR2 estimates were obtained from participant-clustered fixed-effects analyses. Subjective coefficients are expressed in VAS points; EEG coefficients are expressed in $\Delta(\beta/\alpha)$ units.

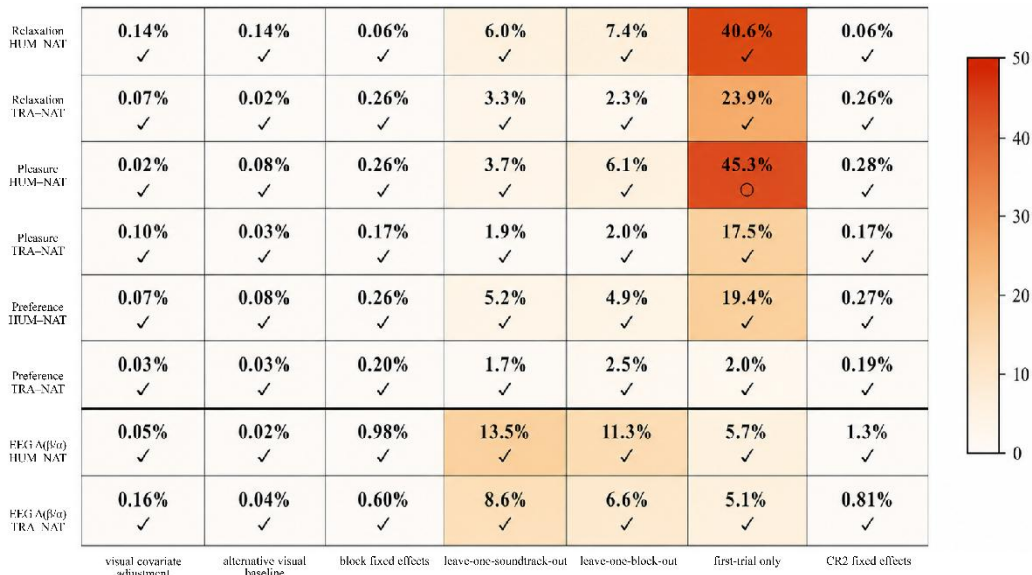


Figure 5 Stability of the eight reported soundscape contrasts across visual, stimulus-omission, restricted-sample, and inferential sensitivity analyses. Cell values indicate the absolute percentage change from the corresponding reference estimate in Table 3. Check marks indicate that the original direction was retained and the 95% confidence interval excluded zero; the open circle indicates that the direction was retained but the confidence interval included zero.

3.4 Secondary associations of subjective responses with auditory appraisal and EEG

3.4.1 Concurrent auditory-appraisal overlap with subjective soundscape contrasts

The subjective soundscape contrasts decreased substantially after concurrent pleasantness and annoyance ratings were added to the matched models (**Table 5; Figure 6**). Adjustment for pleasantness alone attenuated the HUM–NAT coefficients by 91.1%–98.1% and the TRA–NAT coefficients by 73.1%–84.1%. Adjustment for annoyance produced smaller reductions of 57.1%–61.9% for HUM–NAT and 49.9%–

56.3% for TRA–NAT. When pleasantness and annoyance were entered jointly, the HUM–NAT coefficients were attenuated by 95.2%–99.6%, and all three confidence intervals included zero: relaxation ($B = -0.06$, 95% CI $[-3.53, 3.41]$), pleasure ($B = -0.87$, 95% CI $[-1.38, 3.13]$), and preference ($B = -0.58$, 95% CI $[-3.19, 2.04]$). The TRA–NAT coefficients were attenuated by 81.3%–90.0% but remained negative, with confidence intervals excluding zero for relaxation ($B = -7.75$, 95% CI $[-12.02, -3.48]$), pleasure ($B = -4.77$, 95% CI $[-7.94, -1.60]$), and preference ($B = -4.65$, 95% CI $[-8.26, -1.04]$). Because soundscape appraisal and subjective responses were assessed after the same exposure, these patterns indicate concurrent statistical overlap rather than mediation or causal ordering.

Table 5 Subjective soundscape contrasts before and after adjustment for concurrent pleasantness and annoyance.

Outcome	Contrast	Matched baseline B	+ Pleasantness	+ Annoyance	+ Both B	Joint attenuation
Relaxation	HUM–NAT	–17.42 [–20.74, –14.11]	–1.55 [–4.92, 1.83]	–7.33 [–11.02, –3.64]	–0.06 [–3.53, 3.41]	99.6%
	TRA–NAT	–41.37 [–45.37, –37.37]	–11.11 [–15.18, –7.04]	–20.71 [–25.39, –16.03]	–7.75 [–12.02, –3.48]	81.3%
Pleasure	HUM–NAT	–18.14 [–20.70, –15.58]	–0.35 [–2.58, 1.88]	–6.91 [–9.54, –4.28]	0.87 [–1.38, 3.13]	95.2%
	TRA–NAT	–41.51 [–44.07, –38.95]	–7.59 [–10.56, –4.62]	–18.42 [–22.07, –14.78]	–4.77 [–7.94, –1.60]	88.5%
Preference	HUM–NAT	–22.36 [–25.35, –19.37]	–1.79 [–4.36, 0.78]	–9.60 [–12.68, –6.51]	–0.58 [–3.19, 2.04]	97.4%
	TRA–NAT	–46.64 [–49.63, –43.64]	–7.44 [–10.80, –4.08]	–20.40 [–24.66, –16.14]	–4.65 [–8.26, –1.04]	90.0%

Note: Values are model-based unstandardized coefficients with 95% confidence intervals. Joint attenuation was calculated as $100 \times [1 - |B_{\text{both}}| / |B_{\text{baseline}}|]$. Because soundscape appraisal and subjective outcomes were assessed concurrently, the adjusted models quantify statistical overlap rather than mediation.

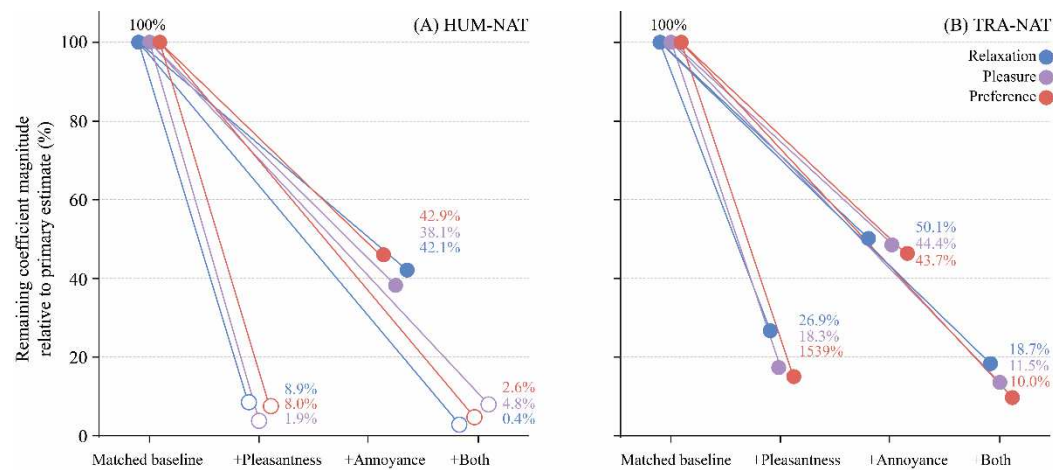


Figure 6 Remaining magnitude of subjective soundscape contrasts after adjustment for concurrent soundscape appraisal. Values represent the absolute adjusted coefficient as a percentage of the corresponding matched baseline estimate; solid and hollow points indicate 95% confidence intervals excluding and including zero, respectively.

3.4.2 Within- and between-participant EEG–subjective correspondence

After decomposing EEG $\Delta(\beta/\alpha)$ into trial-specific deviations from each participant's mean and participant-level mean values, its correspondence with subjective responses was limited (**Table 6**). Higher within-participant EEG $\Delta(\beta/\alpha)$ was associated with lower pleasure before multiplicity adjustment ($B = -3.57$, 95% CI $[-6.64, -0.49]$, raw $p=0.023$), but the association did not remain significant after Holm correction across the three within-participant tests (adjusted $p=0.069$). The within-participant estimates for relaxation ($B = -2.50$, 95% CI $[-5.78, 0.78]$) and preference ($B = -1.25$, 95% CI $[-5.02, 2.52]$) were also negative, but their confidence intervals included zero. No between-participant association was supported for relaxation, pleasure, or preference; all confidence intervals included zero and all raw p values were ≥ 0.415 .

Table 6 Within- and between-participant associations between EEG $\Delta(\beta/\alpha)$ and subjective outcomes.

Outcome	EEG component	B	95% CI	Raw p	Holm-adjusted p
Relaxation	Within-participant	-2.497	[-5.776, 0.783]	0.135	0.271
	Between-participant	4.182	[-5.944, 14.309]	0.415	—
Pleasure	Within-participant	-3.568	[-6.644, -0.491]	0.023	0.069
	Between-participant	3.666	[-6.345, 13.677]	0.470	—
Preference	Within-participant	-1.247	[-5.019, 2.524]	0.516	0.516
	Between-participant	1.022	[-9.046, 11.090]	0.841	—

Note: Within-participant EEG represents each trial's $\Delta(\beta/\alpha)$ deviation from the participant-specific mean, whereas between-participant EEG represents the participant mean; both components were entered simultaneously into each outcome model. Holm correction was applied across the three

within-participant associations, which constituted the prespecified EEG–subjective test family.

3.5 Exploratory moderation by age and pre-exposure STAI-S

Four age interactions had raw p values below 0.05: TRA×Age for pleasure, HUM×Age and TRA×Age for preference, and TRA×Age for EEG $\Delta(\beta/\alpha)$ (**Table 7**). For the subjective outcomes, the positive interaction estimates indicated a tendency for the negative HUM–NAT or TRA–NAT contrasts to become smaller at higher ages, whereas the negative TRA×Age estimate for EEG indicated a tendency for the positive EEG contrast to decrease with age. However, none of the eight age interactions remained significant after Holm correction within the age family (minimum adjusted $p=0.109$), and none survived correction across all 16 moderation tests (minimum adjusted $p=0.219$; **Figure 7**).

No interaction with pre-exposure STAI-S had a raw p value below 0.05 (all raw $p\geq 0.278$), and all corresponding Holm-adjusted p values were 1.000. These exploratory analyses therefore provided no multiplicity-adjusted evidence that either age or pre-exposure STAI-S moderated the soundscape contrasts.

Table 7 Exploratory moderation of soundscape contrasts by age and pre-exposure STAI-S.

Moderator	Outcome	HUM×moderator, B (95% CI)	Holm- adjust ed p	TRA×moderator, B (95% CI)	Holm- adjuste d p
Age	Relaxation	2.17 [−0.39, 4.73]	0.343	3.24 [−0.46, 6.95]	0.343
	Pleasure	1.75 [−0.82, 4.31]	0.343	3.76 [0.31, 7.21]	0.196
	Preference	3.40 [0.18, 6.63]	0.196	5.46 [1.14, 9.79]	0.109
	EEG $\Delta(\beta/\alpha)$	−0.045 [−0.107, 0.016]	0.343	−0.069 [−0.131, −0.008]	0.193
STAI-S	Relaxation	−0.05 [−2.66, 2.56]	1.000	−1.92 [−5.66, 1.82]	1.000
	Pleasure	1.42 [−1.16, 4.00]	1.000	−1.37 [−4.88, 2.13]	1.000
	Preference	1.35 [−1.95, 4.65]	1.000	−0.05 [−4.49, 4.39]	1.000
	EEG $\Delta(\beta/\alpha)$	0.001 [−0.062, 0.064]	1.000	0.011 [−0.051, 0.074]	1.000

Note: Age and pre-exposure STAI-S were standardized, and NAT was the reference category. Interaction coefficients represent the change in the corresponding HUM–NAT or TRA–NAT contrast per 1-SD increase in the moderator; p values were Holm-adjusted separately across the eight age and eight STAI-S interactions.

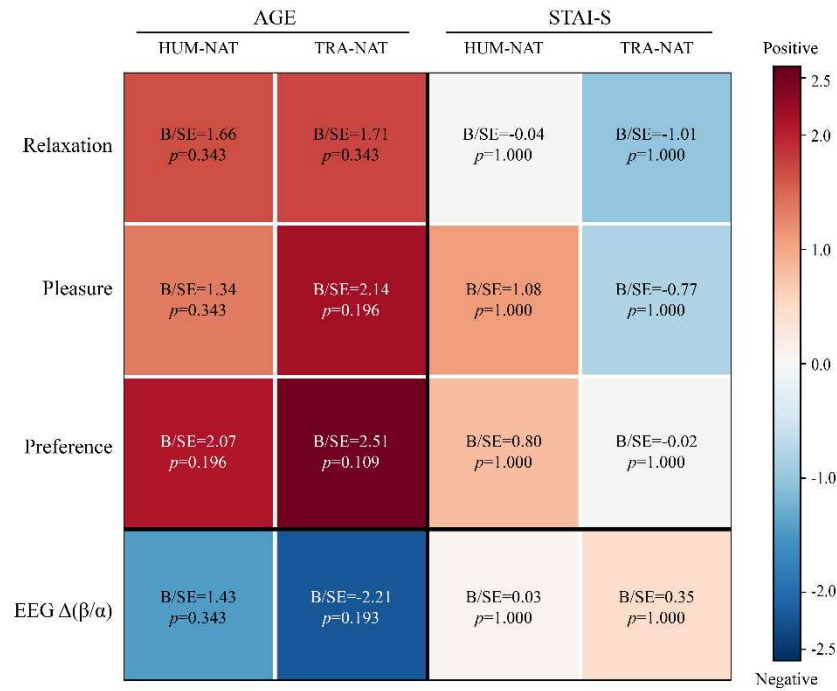


Figure 7 Direction and strength of exploratory soundscape moderation by standardized age and pre-exposure STAI-S. Cell colours indicate the direction and magnitude of the standardized interaction statistic (B/SE), and numerical labels report Holm-adjusted p values within the corresponding moderator family. None of the 16 interactions remained significant after multiplicity adjustment.

4 Discussion

Natural sounds produced the most favourable subjective responses, human-activity sounds an intermediate profile, and traffic noise the least favourable responses; EEG $\Delta(\beta/\alpha)$ showed the opposite category-level ordering. These contrasts were robust across visual and stimulus specifications, while subjective differences overlapped strongly with concurrent auditory appraisal; EEG–subjective correspondence was weak, and neither age nor pre-exposure STAI-S showed moderation after multiplicity correction. Together, these findings identify acoustic conditions as a component of recreational quality within bamboo forests rather than as a response that can be inferred from visual stand quality alone.

4.1 Soundscape-category response patterns

Relaxation, pleasure, and preference followed a consistent NAT > HUM > TRA ordering, whereas EEG $\Delta(\beta/\alpha)$ showed the reverse NAT < HUM < TRA pattern. This ordering remained stable after accounting for repeated soundtrack use, participant-

specific category responses, and the omission of individual soundtracks or visual blocks. The results therefore indicate a robust distinction among the tested soundtrack sets rather than an effect driven by a single stimulus, visual context, or participant subgroup.

The favourable NAT profile is consistent with evidence that natural sounds can support more positive affective, restorative, and physiological responses than traffic or mechanical noise. Alvarsson et al. reported faster sympathetic recovery during natural-sound exposure [69], while Ratcliffe et al. showed that the restorative value of birdsong depends on its acoustic properties and associated meanings [70]. Subsequent studies have likewise linked audible natural sounds and natural audio–visual combinations with lower anxiety and more favourable environmental evaluations [17]. The present study extends this evidence by distinguishing human-activity sounds from traffic noise: HUM formed a stable intermediate category rather than a weaker version of TRA.

The ordering may partly reflect the environmental meanings conveyed by the three soundtrack sets. Birdsong, insects, wind, and vegetation movement were consistent with the ecological character of the bamboo setting, whereas traffic sounds indicated mechanical activity and intrusion from outside the visible scene. NAT may therefore have required less monitoring of disruptive events, while TRA may have directed attention towards dominant or contextually unsuitable sources. Different affective and neural responses to natural and urban soundscapes support this interpretation [71, 72], although attention, perceived threat, and monitoring demand were not measured directly.

Audio–visual compatibility provides a related explanation. Soundscape quality depends partly on whether acoustic sources fit the visible setting and expected activities [73, 74], and auditory and visual information can jointly shape pleasantness and environmental satisfaction [44, 45]. Anthropogenic sound may also reduce the

restorative value of natural scenery more strongly than natural sound improves an urban scene [30]. In this experiment, NAT soundtracks were semantically compatible with the bamboo videos, whereas vehicles, horns, and railway sounds lacked corresponding visible sources. Their adverse effects may therefore have reflected both acoustic properties and cross-modal mismatch, although perceived appropriateness, source visibility, and audio–visual congruence were not assessed.

The NAT advantage should not be generalized to all natural sounds. Responses vary with source type, temporal pattern, familiarity, audibility, preference, and the surrounding acoustic environment [70]. Natural-sound augmentation is also most effective when introduced sounds remain audible and fit existing noise conditions [14]. Naturalness and quietness are related but distinct qualities: natural sounds may be activating or unwanted, while quiet settings may contain little salient biological sound. The conclusions therefore apply to the six NAT, six HUM, and six TRA soundtracks paired with the tested bamboo videos, rather than to all sounds within these categories or all green-space settings.

The intermediate HUM profile is important because human sounds convey mixed social meanings. Conversation, footsteps, and recreational activity may signal legitimate use and social presence, but dominant activity can reduce tranquillity, privacy, and acoustic comfort [75-77]. Natural sounds may support social interaction without producing a human-dominated acoustic environment [78]. HUM may therefore have represented a trade-off: less mechanically intrusive and contextually discordant than TRA, but offering less acoustic refuge than NAT. Because social presence, privacy, expected activity, and perceived suitability were not measured, this interpretation remains provisional.

4.2 Stability across bamboo forest visual contexts

The HUM–NAT and TRA–NAT contrasts changed little after adjustment for VisualBase, vertical stratification, and groundcover coverage. Their stability under alternative visual baselines, block fixed effects, and soundtrack and block exclusions indicates that the category ordering was not driven by one visual specification or individual stimulus.

This stability does not mean that visual context was unimportant. Early experiments showed that visual settings can alter ratings of the same sound[79-82]. Later studies identified scene congruence, source visibility, and perceived appropriateness as key influences on soundscape evaluation[31, 73, 83, 84]. Research in parks, residential areas, and protected landscapes also showed that visual and contextual perceptions can affect pleasantness, satisfaction, and overall soundscape quality [35, 36, 85, 86] . The present findings refine this evidence. Visual differences may have changed the absolute experience of individual blocks without materially changing the relative gaps among NAT, HUM, and TRA.

The independent characterization of visual context strengthens this interpretation. Phase 1 ratings and field measurements came from a separate participant sample, and each photograph, video, and plot was linked by location and viewpoint [50]. VisualBase, VS, and GC therefore served as external block-level descriptors rather than concurrent visual ratings from the Phase 2 outcome sample. This design reduces common-source dependence and provides a stronger test of whether soundscape contrasts persist after measured visual heterogeneity is considered. It does not separate sound from the wider multisensory experience, but it improves confidence that uneven visual quality did not drive the category contrasts.

Two factors may explain the limited effect of visual adjustment. All 10 blocks represented bamboo-dominant green spaces, so their visual and semantic range was

narrower than that of studies comparing residential, commercial, waterfront, urban, and natural settings. Studies with broader scene variation have found stronger effects of greenery, architectural quality, viewing cues, and scene type on soundscape evaluation [38, 43-45, 87, 88]. The auditory differences among NAT, HUM, and TRA may also have been stronger than the visual differences among blocks. Experimental studies show that strong anthropogenic sounds may outweigh some benefits of favourable visual settings[11, 13, 30, 47, 89]. The present result therefore supports robustness within a visually coherent landscape class, not visual invariance across environments.

The absence of Holm-adjusted soundscape-by-visual-context interactions also requires caution. VisualBase, VS, and GC varied across only 10 blocks, so the moderation tests relied mainly on between-block information rather than 678 independent visual contexts. The partially crossed design supported category-level interaction tests and stimulus-exclusion analyses, but it could not fully estimate specific-soundtrack-by-specific-scene interactions. Stability across the tested stimuli strengthens internal robustness, but it does not support unrestricted generalization to wider sound and scene populations [90, 91]. For recreational forest management, this stability suggests that favourable visual stand conditions cannot be assumed to compensate for unfavourable acoustic exposure. Vertical layering, groundcover development, and visually restorative stand characteristics remain relevant components of forest experience, but the adverse contrasts associated with traffic sounds persisted after these measured attributes were considered. Visual stand management and acoustic management should therefore be treated as complementary rather than interchangeable components of recreational forest quality.

4.3 Concurrent appraisal and subjective responses

The matched-model analyses showed substantial overlap between soundscape-

category contrasts and concurrent auditory appraisal. Because the baseline and appraisal-adjusted models used the same observations and random-effects structure, the observed attenuation reflected the addition of pleasantness and annoyance rather than changes in model specification. Joint adjustment reduced the HUM–NAT contrasts by 95.2%–99.6%, after which none differed from zero. The TRA–NAT contrasts were reduced by 81.3%–90.0% but remained negative, indicating substantial yet incomplete overlap with concurrent appraisal.

These findings shift interpretation from sound-source category alone towards person-in-context evaluation. Soundscape research emphasizes that responses depend not only on the physical source but also on how sounds are perceived and understood within a particular setting, with pleasantness and contextual appropriateness forming central dimensions of soundscape quality[73, 83, 92, 93]. In the present study, NAT, HUM, and TRA were associated with different relaxation, pleasure, and preference ratings partly because participants evaluated the soundtrack sets differently within the bamboo scenes. The adjusted models therefore do not invalidate the original category contrasts; instead, they clarify how strongly those contrasts coincided with immediate auditory appraisal.

Pleasantness accounted for more of the coefficient reduction than annoyance. Adjustment for pleasantness alone attenuated the HUM–NAT contrasts by 91.1%–98.1% and the TRA–NAT contrasts by 73.1%–84.1%, whereas the corresponding reductions after adjustment for annoyance were 57.1%–61.9% and 49.9%–56.3%. This difference is plausible because pleasantness represents broad affective valence and is conceptually close to pleasure, preference, and perceived relaxation, whereas annoyance more specifically reflects unwanted disturbance[92]. Nevertheless, pleasantness, annoyance, and the three subjective outcomes were collected after the same exposure using the

same response format. Their associations may therefore also reflect overlapping item content and common-method variance [94].

The contrasting residual patterns for HUM and TRA are informative. After joint adjustment, the HUM–NAT coefficients were close to zero, suggesting that their subjective distinction statistically overlapped almost completely with concurrent pleasantness and annoyance. By contrast, the remaining TRA–NAT coefficients indicate that these two appraisal dimensions did not capture all of the adverse subjective response associated with traffic noise. Source dominance, perceived intrusion, contextual inappropriateness, or the absence of a visible source may have contributed additional information [25, 73, 95]. These possibilities remain tentative because they were not measured directly.

These analyses should not be interpreted as evidence of mediation. Pleasantness, annoyance, relaxation, pleasure, and preference were all assessed after the same 50-s exposure, so their temporal ordering cannot be established. Concurrent covariate adjustment may quantify shared variation but cannot determine whether pleasantness or annoyance transmitted the effect of soundscape category. The attenuation percentages therefore describe statistical overlap, not the proportion of a causal mechanism explained. Overall, soundscape category and immediate appraisal jointly organized subjective responses, but their causal relationships require designs with temporally separated or experimentally manipulated appraisal measures.

4.4 EEG–subjective correspondence

EEG and subjective responses showed corresponding category-level orderings but limited correspondence within or between participants. EEG $\Delta(\beta/\alpha)$ increased from NAT to HUM to TRA, whereas relaxation, pleasure, and preference decreased across the same categories. This EEG ordering remained stable after repeated use of specific

soundtracks was modelled directly: the reduced participant-and-soundtrack model converged without singularity, and the HUM–NAT and TRA–NAT estimates changed by less than 0.2%. At the finer response level, however, higher within-participant EEG $\Delta(\beta/\alpha)$ was associated with lower pleasure only before multiplicity correction (raw $p=0.023$; Holm-adjusted $p=0.069$). No corrected within-participant association or between-participant association was supported.

These analyses address distinct levels of association. The category contrasts tested whether the three soundtrack sets shifted average EEG and subjective responses in corresponding directions. The within-participant models instead examined whether trial-specific EEG deviations tracked changes in each participant's ratings, while the between-participant component tested whether participants with higher mean EEG responses also reported less favourable experiences overall. Experimental conditions can shift two outcomes in parallel without producing strong covariance across trials or individuals. The weak finer-level correspondence therefore does not contradict the category effects, but it indicates that EEG $\Delta(\beta/\alpha)$ was not a reliable proxy for subjective response.

This distinction is consistent with previous soundscape research. Reviews have reported substantial heterogeneity in associations between perceptual and physiological responses across measures, stimuli, and analytical designs [96]. Experimental studies have identified neural differences between natural and urban soundscapes and among different natural sounds, but the observed patterns vary by frequency band, electrode region, exposure context, and analysis method [20, 23, 71]. Virtual-reality studies have likewise detected psychophysiological differences through EEG connectivity or autonomic measures rather than a single common physiological index[47, 48]. Multivariate associations between subjective perception and EEG features have also

been reported [72], suggesting that broader neural patterns may capture response variation better than one summary ratio.

Self-report and EEG may also reflect different processes and timescales. The VAS ratings summarized the entire exposure and may have integrated affective valence, source meaning, familiarity, and contextual fit. EEG recorded continuous cortical activity that may additionally reflect attention, arousal, sensory processing, and environmental monitoring. Pleasure showed the strongest nominal within-participant association, possibly because it more directly represents immediate affective valence than relaxation or preference. However, this interpretation remains tentative because the association did not survive multiplicity correction.

Finally, EEG $\Delta(\beta/\alpha)$ combines changes in two frequency bands. A change in the ratio may result from increased beta activity, decreased alpha activity, or both, and its meaning depends on electrode selection, referencing, preprocessing, exposure context, and the ratio definition [97]. In the present study, EEG $\Delta(\beta/\alpha)$ provides complementary evidence of category-level differences in relative cortical activation. It should not be interpreted as an objective confirmation, direct neural equivalent, or biomarker of subjective restoration.

4.5 Participant variation and implications for recreational forest management

Several age interactions showed nominal directional patterns, but none remained significant after Holm correction within the age family or across all 16 moderation tests. Pre-exposure STAI-S likewise did not moderate the HUM–NAT or TRA–NAT contrasts. The present results therefore provide no multiplicity-adjusted evidence that the relative responses to the three tested soundscape categories differed systematically according to age or pre-exposure state anxiety. The unadjusted age patterns should be treated as hypotheses for future investigation rather than as evidence supporting age-specific

management recommendations.

This interpretation should remain narrow. Age and state anxiety represent only part of the individual variation that may influence forest soundscape experience [26, 37, 98]. Hearing ability, noise sensitivity, familiarity with forest environments, intended activity, prior exposure, and expectations regarding tranquillity or social use were not measured comprehensively [99, 100]. The absence of significant moderation therefore does not imply uniform responses across all visitor groups [101, 102]. Future studies should recruit populations with broader variation in hearing status, recreational purpose, forest-use experience, and sound-source expectations, with sufficient power to estimate participant-by-soundscape interactions directly.

Management implications should instead be based on the robust category-level findings. Traffic sounds produced the least favourable subjective responses and the highest EEG $\Delta(\beta/\alpha)$, whereas natural sounds produced the most favourable profile. These contrasts remained largely unchanged after adjustment for VisualBase, vertical stratification, and groundcover coverage. Within the range of bamboo forest settings examined, favourable visual conditions therefore did not remove the adverse responses associated with traffic sounds. This result suggests that visual stand quality and acoustic quality should be treated as complementary components of recreational forest experience. Improvements in stand structure, understory condition, or visual restorative potential cannot be assumed to compensate for persistent mechanical noise from surrounding transportation infrastructure.

Human-activity sounds require a different management interpretation. Their effects were consistently less favourable than those of natural sounds but substantially less adverse than those of traffic noise. Conversation, footsteps, and recreational activity may reduce perceived tranquillity, yet they can also indicate legitimate forest

use, social presence, and accessibility [34, 75, 84, 103, 104]. Human-generated sounds should therefore not be managed as equivalent to external mechanical noise [54, 95, 105]. In multifunctional bamboo forests, differentiated spatial management may be more appropriate: socially active areas can accommodate ordinary visitor sounds, whereas quieter zones should be protected for visitors seeking solitude, attentional recovery, or low-disturbance nature contact [44, 83, 106].

Taken together, the results indicate that acoustic conditions contribute independently to the recreational quality and cultural ecosystem services of bamboo forests. Forest assessment and management should distinguish natural biological sounds, visitor-related activity, and external transportation noise rather than treating all non-natural sounds as a single disturbance category. The present findings do not support age-specific standards, but they do support incorporating acoustic-source composition into the evaluation and management of recreational bamboo forests.

4.6 Strengths and limitations

Several features strengthen the study. Phase 1 characterized visual context in an independent participant sample, with photographs, videos, and field plots matched by location and viewpoint. Phase 2 tested three soundscape categories, each represented by six specific soundtracks, across 10 independently characterized visual blocks. Robustness was examined using alternative visual specifications, stimulus-exclusion analyses, first-trial restriction, bootstrap intervals, and participant-clustered CR2 inference. Additional hierarchical models accounted directly for repeated soundtrack use and participant-level variation in category responses; the subjective contrasts changed by no more than 0.35%, and the reduced participant-and-soundtrack EEG model produced nearly identical estimates. The appraisal analyses also used matched observations and random-effects structures, ensuring that coefficient attenuation

reflected the addition of pleasantness and annoyance rather than changes in model specification.

The study nevertheless remains limited by stimulus sampling. The soundtracks were selected purposively rather than randomly sampled from defined populations of natural, human-activity, and traffic sounds, and the partially crossed design did not pair every soundtrack with every visual block. Soundtrack- and block-omission analyses showed that no single stimulus drove the main contrasts, while soundtrack-level random effects accounted statistically for repeated use of the tested recordings. These procedures, however, cannot make six soundtracks per category representative of all sounds within that category or identify the full range of soundtrack-by-scene interactions. Larger participant samples cannot fully compensate for restricted stimulus sampling [110-112]. Future studies should use broader and more systematically sampled sets of sounds and scenes, cross them more completely, and estimate participant-, soundtrack-, visual-context-, and soundtrack-by-scene variation where the design permits [113].

The visual and exposure conditions also constrain inference. VisualBase was derived from matched photographs rather than visual-only ratings of the Phase 2 videos and therefore did not capture movement, source visibility, or moment-to-moment audio–visual compatibility [7, 49, 114]. Fixed playback improved experimental consistency, but sound pressure level at the ear was not calibrated to matched field exposure. The 50-s seated trials further excluded movement, thermal conditions, odour, and naturally occurring social interaction. Reproduction method, presentation level, and immersion can influence agreement between laboratory and field responses [1, 115-118]. Future work should compare calibrated audio–visual simulations with matched field observations and longer exposures, following standardized soundscape and

contextual-reporting frameworks [115, 116, 119].

Measurement timing limits causal interpretation. Pleasantness, annoyance, relaxation, pleasure, and preference were assessed after the same exposure; even under matched model specifications, their coefficient overlap cannot establish mediation or temporal ordering [120]. EEG $\Delta(\beta/\alpha)$ also has limited physiological specificity. Although the category contrasts remained stable after the negligible visual-block variance was removed and specific soundtrack variation was modelled, the ratio cannot distinguish whether changes arose from beta activity, alpha activity, or both. The weak within- and between-participant EEG–subjective correspondence further indicates that it should not be treated as a direct neural proxy for subjective restoration [8, 97, 121, 122]. Future studies should separate appraisal and outcome measurement in time and combine multiple EEG features, autonomic indicators, and subjective measures.

Finally, the moderation analyses were exploratory, and none remained significant after multiplicity correction. Participants were recruited from one region, and hearing status, noise sensitivity, familiarity, intended activity, and related personal characteristics were not comprehensively assessed. Detecting participant-by-soundscape interactions requires targeted statistical power and broader population sampling [113, 123].

The study therefore does not establish a universal ranking of all natural, human-activity, and traffic sounds. Its main contribution is evidence that the contrasts among the tested soundtrack sets remained stable across independently characterized bamboo-space visual contexts, individual soundtrack and block omissions, hierarchical random-effects specifications, and alternative inferential procedures. Broader samples of sounds, settings, exposure conditions, and populations are needed to define the generalizability of this two-phase framework.

5 Conclusion

Across the tested bamboo-space videos and soundtrack sets, relaxation, pleasure, and preference followed a consistent NAT > HUM > TRA ordering, whereas EEG $\Delta(\beta/\alpha)$ showed the reverse NAT < HUM < TRA pattern. The contrasts remained stable after adjustment for independently derived visual-context measures, alternative visual specifications, individual soundtrack and block omissions, participant-level category variation, repeated soundtrack use, sample restriction, and alternative inferential procedures. The observed ordering was therefore unlikely to be explained by any single visual block or soundtrack or by the evaluated repeated-measures specifications.

Concurrent soundscape appraisal substantially qualified the category differences. Pleasantness and annoyance jointly overlapped statistically with nearly all of the HUM–NAT subjective contrasts, whereas the TRA–NAT contrasts retained smaller but consistently negative residual associations. These results indicate that immediate person-in-context appraisal was closely intertwined with subjective response, but they do not establish mediation because appraisal and outcomes were measured after the same exposure. EEG differentiated the soundtrack categories but showed little consistent correspondence with subjective ratings within or between participants, supporting its interpretation as complementary physiological evidence rather than an objective measure of subjective restoration. Neither age nor pre-exposure STAI-S provided multiplicity-adjusted evidence of moderation.

These findings have implications for the recreational management of bamboo forests. Acoustic conditions should be assessed alongside stand structure when evaluating the cultural ecosystem services provided by multifunctional and peri-urban forests. In the tested settings, favourable visual conditions did not remove the adverse subjective and EEG contrasts associated with traffic sounds, indicating that visual stand

management cannot substitute for acoustic source control. Human-activity sounds produced an intermediate profile and should not be managed as equivalent to transportation noise, because they may also indicate legitimate recreational use and social presence.

Author Contributions:

H.L.: Writing—original draft, Visualization, Software, Investigation, Data curation, Formal analysis, Methodology. Z.L.: Validation, Methodology, Investigation, Data curation. Y.P.: Writing—review and editing, Resources, Methodology. Conceptualization. C.J.: Writing—original draft, Investigation. X.D.: Investigation, Funding acquisition, Data curation. Q.C.: Supervision, Project administration, Funding acquisition, Conceptualization. B.L.: Supervision, Methodology. C.M.: Methodology, Investigation. All authors have read and agreed to the published version of the manuscript.

Funding:

This research was funded by the National Natural Science Foundation of China (Nos. 32271944), the Ya'an Yucheng District and University Cooperation Program (2024QXHZ05), and the Sichuan Office of Philosophy and Social Science (Nos. SCJJ24ND261).

Data Availability Statement:

The original contributions presented in this study are included in the article and Supplementary Materials. Further inquiries can be directed to the corresponding author.

Conflicts of Interest:

We declare that this manuscript is original, has not been published before and is not currently being considered for publication elsewhere. We confirm that the

manuscript has been read and approved by all named authors and that there are no other persons who satisfied the criteria for authorship but are not listed. We further confirm that the order of authors listed in the manuscript has been approved by all of us.

Acknowledgments:

This research was financially supported by the National Key Research and Development Program of China during the 14th Five-Year Plan period: “Urban and Rural Bamboo Forest Layout and Adaptive Management Technologies under Climate Change”, under the project “Multi-objective Precision and Efficient Cultivation Technologies for Bamboo and Rattan Resources” (Grant No. 2023YFD2201204).

Conflicts of Interest:

The authors declare no conflicts of interest.

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