

Article

Materials Selection in Biophilic Building Design: Multisensory Perception and Psycho-Physical Mapping of Wood Materials

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Abstract

The selection of building materials increasingly prioritizes aesthetic and comfort-related experiences, yet the perceptual pathways linking physical properties to emotional judgments remain underexplored, particularly among Chinese users. This study aimed to clarify how different sensory modalities contribute to the perceptual pathways linking physical properties of wood to emotional judgments under multisensory conditions. Sixty young Chinese adults evaluated wood samples under visual, tactile, auditory, and multisensory conditions. Multivariate modeling approaches were applied to identify perceptual structures, mediating pathways to aesthetic judgments, and associations between subjective impressions and physical parameters. A three-factor perceptual structure was identified, comprising surface qualities, internal qualities, and emotional judgment. Path analyses showed that perceived cleanliness acted as the primary mediator from low-level perceptions to emotional responses, whereas naturalness played a limited role. Multisensory integration was vision-dominant (relative sensory weights from Bayesian weighted regression > 0.50), with touch providing secondary contributions (weights > 0.30) and audition exerting minimal influence. Lightness strongly predicted surface qualities, while density predicted internal qualities, with both achieving conditional and marginal R^2 values above 0.50. In contrast, higher-order impressions showed strong between-group but weak individual-level explanatory power (marginal $R^2 < 0.30$), indicating that physical parameters capture group-level tendencies but offer limited precision for individual emotional responses. These results inform culturally sensitive, multisensory design strategies for wood in biophilic and human-oriented environments and highlight the need to incorporate non-physical factors for precise personalization.



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1. Introduction

The selection of construction materials traditionally prioritizes structural performance, with functional requirements and user experience considered secondary. With increasing urbanization, humans now spend nearly 80% of their time indoors, shifting attention toward health-oriented and human-centered design [1,2]. This shift has heightened interest

in the psychological and physiological effects of materials and in how they shape lived experience within built spaces.

Human experience of built environments arises from multisensory interactions with materials through vision, touch, audition, and olfaction [3]. Understanding these cross-modal processes is essential for explaining how spaces are perceived and evaluated [4]. Within this context, wood is distinguished from inorganic materials by its strong multisensory appeal. Its warm color tones and natural grain patterns convey organic beauty [5], whereas low thermal conductivity delivers a softer, warmer tactile sensation [6]. Exposure to wooden interiors has been consistently linked to reduced blood pressure, lower stress levels, and improved emotional well-being. According to the biophilia hypothesis, these effects are attributed to naturalness, comfort, and aesthetic pleasure evoked by wood through its visual, tactile, and thermal properties [7–9]. Consequently, the strategic selection and multisensory optimization of wood in architecture and interior design have attracted growing research and practical interest.

Aesthetic experience and comfort impressions depend not only on complex multi-modal interactions between physiological sensors and material properties, but also on perceptual and cognitive processes that integrate subjective impressions derived from objective physical attributes—such as brightness, softness, and warmth—with emotional and semantic evaluations [10]. These impressions arise as physical stimulus properties are first transduced by sensory receptors and encoded along modality-specific neural pathways, then integrated within cortical perceptual networks responsible for constructing coherent material impressions, and finally linked to affective and evaluative systems associated with emotional and semantic appraisal [11,12].

Previous studies have demonstrated that, under visual conditions, perceived warmth, harmony, and lightness account for approximately 60% of the variance in aesthetic evaluations [13], whereas smoothness and naturalness reliably elicit positive emotional responses under tactile conditions [14]. However, the mechanisms underlying how low-level sensory features that are closely tied to physical stimulus properties, such as roughness and hardness, are transformed into intermediate perceptual impressions, which in turn mediate the formation of high-level aesthetic and comfort-related evaluations, remain poorly understood. These processing pathways and their key mediators therefore warrant further exploration.

Many existing studies have examined material perception within a single sensory, even though everyday interactions involve simultaneous inputs from multiple senses [5,15]. Rather than a mere sum of inputs, multisensory perception involves dynamic cross-modal integration and cognitive reinterpretation [16]. For instance, matching a visual appearance of glass with the sound of a struck pepper causes participants to perceive it as transparent plastic [3], and high-frequency auditory feedback during touch can induce the “parchment-skin illusion,” making the skin feel dry and paper-like [17]. These examples illustrate how multisensory cues can reshape the perception of physical attributes and, consequently, aesthetic and emotional responses. Advancing architectural and interior materials research therefore requires a deeper understanding of cross-modal interactions, their relative weighting across senses, and the mechanisms that govern multisensory integration.

Cultural and experiential factors also strongly shape material perception and aesthetic judgment. Cross-cultural studies reveal divergent attitudes toward natural elements: participants from Germany and Sweden tend to perceive riverscapes with woody debris as more natural and aesthetically positive, whereas those from China and India often view them as disordered or unsafe [18]. These differences underscore how cultural background can reshape preferences for “naturalness” versus “order and cleanliness.” Yet much of existing work has focused on populations from Japan, Northern Europe, and Canada, which

may limit its applicability to Chinese contexts, where perceptual norms and emotional priorities may differ [19].

For young Chinese adults, typically in their early to mid-20s, who commonly experience substantial academic and career pressure [20], everyday settings such as offices, dormitories, and public spaces become important sites for psychological restoration. Evidence-based material selection and multisensory optimization of wood in these environments therefore offer practical value as a cost-effective strategy to boost comfort, alleviate stress, and foster emotional well-being through targeted architectural and interior design choices.

The present study addressed this gap by examining how young Chinese adults perceive and evaluate wood under controlled visual, tactile, auditory, and multisensory conditions. Sensory evaluations, exploratory structural equation modeling, Bayesian cue-combination analyses, and linear mixed-effects models were used to identify the latent perceptual structure of wood, trace pathways to aesthetic and emotional judgments, characterize cross-modal cue integration, and quantify how subjective evaluations map onto physical properties.

Based on this framework, three research hypotheses were proposed.

H1. *Wood perception under multisensory conditions was expected to be structured into a limited set of latent perceptual dimensions linking sensory inputs to emotional judgments.*

H2. *Emotional evaluations were expected to depend primarily on these perceptual mediators rather than being directly predicted by physical properties alone.*

H3. *Sensory modalities were expected to contribute unequally to multisensory evaluations, consistent with reliability-weighted integration patterns.*

The results provide the first culturally specific evidence on multisensory wood perception in Chinese young adults and establish a mechanistic framework linking physical parameters to perceptual and emotional outcomes. The findings are expected to provide practical design guidance for architects and material developers by clarifying how visual, tactile, and auditory cues may be strategically optimized to enhance comfort, psychological restoration, and emotional well-being in health-oriented built environments.

2. Materials and Methods

2.1. Participants

33 male and 27 female Chinese university students ($n = 60$) were recruited online to participate in this study. All were from a Chinese cultural background. G*Power (version 3.1) was used to validate statistical power for the repeated-measures ANOVA, with parameters set as repeated-measures correlation = 0.5, $f = 0.25$, $\alpha = 0.05$, confirming that this sample achieves a statistical power above 0.95. The mean age \pm standard deviation of the participants was 23.5 ± 2.8 years. All participants self-reported normal or corrected-to-normal vision and hearing and no known sensitivities to wood materials. Written informed consent was obtained after the study procedures had been fully explained. This study did not involve the collection of any private or commercial information and posed no risk to participants' health.

2.2. Selection of Materials

Eight clear wood species, free from knots, cracks, deformation, or discoloration, together with two wood-based boards were used as stimuli, as shown in Figure 1. The selection included common softwoods and hardwoods applied in flooring, furniture, and construction, thereby covering a wide range of physical properties such as color and density. The two artificial boards, consisting of veneered plywood with natural wood veneer and

decorative particleboard laminated with impregnated paper printed to resemble black walnut, were included to broaden the range of surface characteristics and to better reflect commonly used wood-related materials in interior applications.



Figure 1. Wooden materials used in this study: (a) Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco); (b) Chinese fir (*Cunninghamia lanceolata* (Lamb.) Hook.); (c) Japanese cypress (*Chamaecyparis obtusa* (Siebold & Zucc.) Endl.); (d) Japanese cedar (*Cryptomeria japonica* (Thunb. ex L.f.) D.Don); (e) Norway spruce (*Picea abies* (L.) H. Karst.); (f) Northern red oak (*Quercus rubra* L.); (g) American ash (*Fraxinus americana* L.); (h) Black walnut (*Juglans nigra* L.); (i) Veneered plywood; (j) Decorative particleboard.

All wood samples were cut to 400 mm (length) × 90 mm (width) using a circular saw and planed to a uniform thickness of 18 mm, matching standard artificial board dimensions. Specimens were then conditioned at room temperature for 30 days to stabilize moisture content and minimize odor emissions. Dimensions and weight were measured using a digital caliper and electronic balance to calculate density, and moisture content was measured with a moisture meter. The resulting values are listed in Table 1.

Table 1. Density and moisture content of wooden materials used in this study.

| Labels | Specimens | Density (g/cm ³) | Moisture Content (%) |
|--------|--------------------------|------------------------------|----------------------|
| (a) | Douglas-fir | 0.61 | 12.1 |
| (b) | Chinese fir | 0.36 | 12.5 |
| (c) | Japanese cypress | 0.44 | 12.7 |
| (d) | Japanese cedar | 0.36 | 11.9 |
| (e) | Norway spruce | 0.44 | 11.4 |
| (f) | Northern red oak | 0.65 | 11.3 |
| (g) | American ash | 0.72 | 11.7 |
| (h) | Black walnut | 0.63 | 10.8 |
| (i) | Veneered plywood | 0.62 | 8.6 |
| (j) | Decorative particleboard | 0.69 | 8.3 |

2.3. Presentation of Stimuli

For the visual condition, each specimen was placed in a cardboard box of matching dimensions with a top observation window (390 mm × 80 mm) to limit exposure to non-target surfaces. A photographic light tent fixed the viewing position, 50 cm from the table edge, and ensured uniform illumination. An LED light source (400 W, 5000 K) mounted at the top provided stable lighting. Participants wore headphones with white noise to eliminate incidental auditory cues. The setup is shown in Figure 2a.

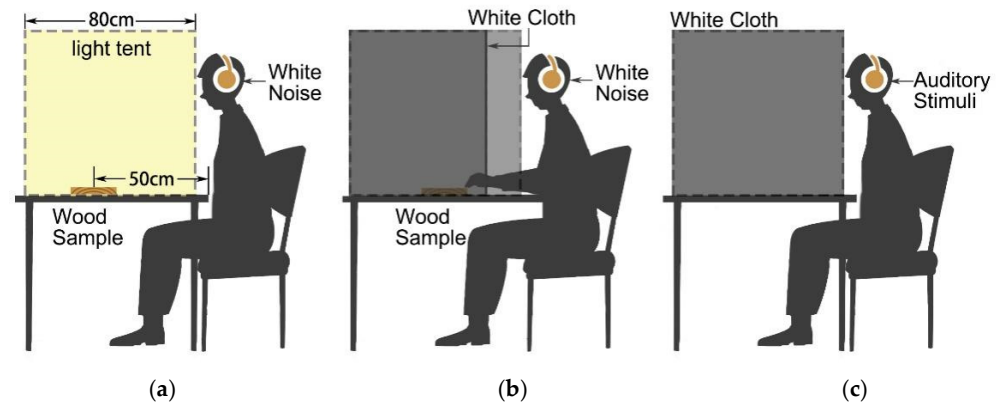


Figure 2. Schematic diagram of stimulation presentation under: (a) Visual conditions; (b) Tactile conditions; (c) Auditory conditions.

For the tactile condition, the same tent was used without lighting, and the specimen was concealed behind a white cloth to block visual information. Participants explored the surface with their fingers and rested the hand for at least 3 s to ensure adequate tactile contact. After each trial, the surface was wiped to remove sweat or oil and avoid cross-participant contamination. White noise was again delivered through headphones to mask sounds from touch. The tactile setup is shown in Figure 2b.

Auditory stimuli were generated by inducing free vibration in each specimen using an impact hammer. Specimens were suspended under free–free boundary conditions with rubber bands positioned at the nodal points ($\approx 0.224 L$ from each end). A single perpendicular tap at midspan excited the vibration, and the resulting sound was recorded with a microphone (T8-2, Shenzhen Mivsn Electronic Technology Co., Ltd., Shenzhen, China). Vibration responses were simultaneously captured, amplified, filtered, and processed via FFT to extract resonance frequencies for computing dynamic parameters. Ten recordings were made per specimen. After preprocessing in Adobe Audition 2024, the most representative signal was selected. A 1-s segment (100 ms pre-onset to 900 ms post-onset) was extracted and repeated five times to form a 5-s stimulus with normalized amplitude. Participants listened via headphones and could replay the sound. The auditory setup is shown in Figure 2c.

2.4. Questionnaires

The Semantic Differential (SD) method was applied to evaluate subjective responses using 22 bipolar adjective pairs rated on a 7-point scale (−3 to +3). The adjective pairs were selected with reference to previous studies [3,21], as listed in Table 2. Questionnaires are provided in Appendix A.

Table 2. Bipolar adjective pairs used in the scale for different perception layers.

| Category | Bipolar Adjective Pairs | | |
|----------|-------------------------|-------------|-------------|
| Visual | Low-high contrast | Matte-gloss | Dark-bright |
| Auditory | Dampened-ringing | Dull-sharp | Mixed-pure |

Table 2. Cont.

| Category | Bipolar Adjective Pairs | | |
|------------------------------|-------------------------|----------------|-------------------|
| Tactile and other properties | Rough-smooth | Hard-soft | Cold-warm |
| | Dense-sparse | Dry-wet | Heavy-light |
| Affective properties | Old-new | Ugly-beautiful | Artificial-nature |
| | Plain-sophisticated | Dislike-like | Cheap-expensive |
| | Unpleasant-pleasant | Dirty-clean | Tense-relaxed |
| | Common-rare | | |

2.5. Study Protocol

The experiment was conducted in an artificial climate chamber maintained at 22 ± 3 °C and $50 \pm 5\%$ relative humidity, with low ambient noise and constant lighting. A within-subject design was used: In stage 1, all participants evaluated each specimen under single-sensory conditions, with a 20-min interval between successive sessions to minimize carryover effects. In Stage 2, the same participants evaluated the specimens under triple-sensory conditions, with a two-week interval separated the two stages to reduce fatigue and memory effects. Order effects were counterbalanced using a Latin square, with presentation sequences listed in Table 3.

Table 3. The experiment order for different test groups.

| Group | Single-Sensory Conditions | | | Multisensory Conditions |
|------------------|---------------------------|----------|----------|-------------------------|
| Group A (n = 20) | Visual | Auditory | Tactile | Visual-tactile-auditory |
| Group B (n = 20) | Tactile | Visual | Auditory | Visual-tactile-auditory |
| Group C (n = 20) | Auditory | Tactile | Visual | Visual-tactile-auditory |

After a briefing, participants provided informed consent, completed a demographic questionnaire, and completed a practice session that always began with the visual condition and used specimens identical in size to the test samples but excluded from formal testing. The formal session then began, in which the ten specimens were presented in random order and participants completed the semantic differential ratings on a tablet. The procedure, shown in Figure 3, complied with Chinese sensory analysis regulations [22].

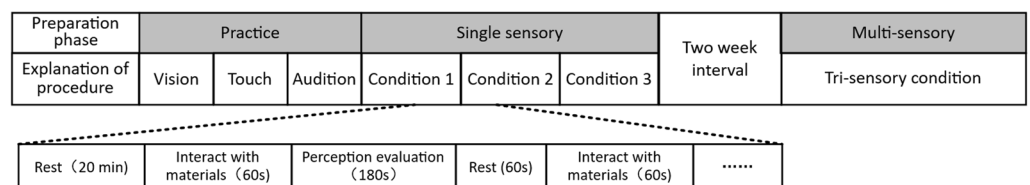


Figure 3. Schematic diagram of experimental procedure.

2.6. Determine of the Physical Properties of Wooden Materials

2.6.1. Visual Related Physical Properties

Visual properties included gloss, texture descriptors, surface color, and color differences. Surface color was measured using a chroma meter (CR-5, Konica Minolta, Tokyo, Japan) in the CIE Lab^* space to obtain L^* (lightness), a^* (red–green), and b^* (yellow–blue). Ten equidistant points were sampled on each specimen, and mean values were calculated. Color differences were quantified using the CIEDE2000 (ΔE_{00}) formula, which provides improved perceptual uniformity via weighting of lightness, chroma, and hue,

with hue-rotation corrections [23]. RGB images were converted to Lab^* using OpenCV (version: 4.10.0). Global color heterogeneity was computed as the mean pairwise ΔE_{00} across 5000 randomly sampled pixels, while difference between early and latewood was obtained by segmenting the two regions using Otsu thresholding and calculating ΔE_{00} between their mean Lab^* values.

$$\Delta E_{00} = \left[\left(\frac{\Delta L'}{k_L S_L} \right)^2 + \left(\frac{\Delta C'}{k_C S_C} \right)^2 + \left(\frac{\Delta H'}{k_H S_H} \right)^2 + R_T \left(\frac{\Delta C'}{k_C S_C} \right) \left(\frac{\Delta H'}{k_H S_H} \right) \right]^{1/2} \quad (1)$$

where $\Delta L'$, $\Delta C'$, and $\Delta H'$ are the differences in lightness, chroma, and hue, respectively; S_L , S_C , and S_H are weighting functions for lightness, chroma, and hue; k_L , k_C , and k_H are parametric factors; and R_T is the rotation function that accounts for the interaction between chroma and hue differences in the blue region.

Texture features were derived from Gray-Level Co-occurrence Matrices (GLCM). High-resolution color photographs were converted to grayscale using OpenCV, and GLCMs were computed with 256 gray levels, a pixel-pair distance of 3, and four orientations: 0° , 45° , 90° , 135° . Each matrix was normalized, and four standard descriptors: contrast, homogeneity, energy, and correlation were calculated. To reduce anisotropy, values from the four orientations were averaged to obtain final texture features.

Gloss was measured with a calibrated multi-angle gloss meter (LS197, Shenzhen Linshang technology CO., Ltd., Shenzhen, China) following Chinese standard GB/T 9754-2007 [24]. Five points were measured per specimen (four at the edges and one at the center), and measurements were taken at both 60° and 85° incident angles to account for angle-dependent reflectance. All values were averaged to represent the specimen's gloss.

2.6.2. Tactile Related Physical Properties

Tactile properties comprised thermal conductivity, 2-D surface roughness parameters, Ra , and 3-D areal roughness parameters, Sa .

Thermal conductivity was measured with a quasi-steady-state heat conductometer (FWDR-II, Harbin Hongrun Teaching Test Equipment Factory, Harbin, China). The instrument was calibrated against two standard references under controlled laboratory conditions in accordance with the JJF 98-2024 [25]. Specimens measuring 130 mm in length, 130 mm in width, and 10 mm in thickness, produced from the same batch as those used in the main experiment, were tested to determine thermal conductivity. The temperatures of the hot and cold specimen surfaces were continuously monitored, and once a stable difference was achieved, the thermal conductivity was calculated according to Equation (2).

$$\lambda = \frac{q_c \delta}{2\Delta t} \quad (2)$$

where λ is the thermal conductivity, in $W/(m \cdot ^\circ C)$; q_c is the constant heat flux density applied perpendicular to the specimen's end face in the X-direction, in W/m^2 ; δ is the specimen thickness, in mm; Δt is temperature difference between the hot and cold surfaces when the specimen reaches quasi-steady-state conditions, in $^\circ C$.

Ra was measured with a contact profilometer (TR200, Guangdong Junda Instrument Co., Ltd., Shenzhen China) following the Chinese national standard. Measurements were taken using a sampling length $l_r = 2.5$ mm, an evaluation length $l_n = 5l_r$, a Gaussian filter, and a cut-off wavelength $\lambda_c = 2.5$ mm. For each specimen, five parallel traces were recorded in both the longitudinal and transverse grain directions. The instrument was calibrated against a certified roughness standard before each session. Sa was obtained using an optical profilometer (InfiniteFocus G5, Alicona, Raaba, Austria). Three

2.5 mm × 2.5 mm regions were scanned on each specimen, located approximately 10, 20, and 30 cm from one end while avoiding large vessel cavities. Final R_a and S_a values for each orientation were computed as the mean of their respective measurements.

2.6.3. Auditory Related Physical Properties

Auditory properties—characteristic frequency, specific dynamic modulus of elasticity, radiation damping, and acoustic impedance—were extracted from recorded impact sounds.

To determine the vibration–acoustic properties, which provide a quantitative description of vibrational behavior, specimens were excited under free–free boundary conditions, and the resonance frequencies were extracted from the vibration signals using fast Fourier transform (FFT). The dynamic modulus of elasticity (MOE) was then calculated according to Equation (3), and the specific dynamic MOE (E/ρ) was derived therefrom.

$$E = \frac{48\pi^2\rho L^4 f^2}{m^4 T^2} \quad (3)$$

where E is the dynamic modulus of elasticity; ρ is the specimen density, in kg/m^3 ; L is the specimen length, in mm; f is the resonance frequency of the n -th bending mode, in Hz; T is the specimen thickness, in m, m is the dimensionless modal constant for a free–free beam.

A higher acoustic radiation quality constant and a lower acoustic impedance indicate superior vibration efficiency and performance. These two parameters, which collectively reflect vibrational efficiency, were calculated using Equations (4) and (5), respectively.

$$R = \sqrt{E/\rho^3} \quad (4)$$

where R is the acoustic radiation quality constant, in $\text{m}^3 \cdot \text{Pa}^{-1} \cdot \text{s}^{-3}$.

$$\omega = \sqrt{\rho E} \quad (5)$$

where ω is the acoustic impedance, in $\text{Pa} \cdot \text{s} \cdot \text{m}^{-1}$.

2.7. Statistical Analysis

Although the perceptual ratings in this study were collected using Likert-type ordinal scales, the use of seven or more response categories allows them to approximate interval-level measurement. With a sample of 60 participants, such data are commonly treated as interval-scaled, thereby justifying the application of parametric methods such as Pearson correlation and stepwise regression [26,27]. Normality was assessed using the Shapiro–Wilk test. Although some variables did not fully meet the criterion, skewness values were all below $|1|$ and kurtosis values below $|2|$, suggesting no substantial deviation from normality. Consistent with established practice, data with adequate sample size and acceptable skewness and kurtosis were treated as approximately normal [28].

Inter-participant correlations (IPC) were then computed for each evaluation item under all sensory conditions to assess judgment consistency and quantify agreement across participants.

Exploratory factor analysis (EFA) was performed to identify the latent structure of sensory evaluations. Exploratory structural equation modeling (ESEM) was then conducted in Mplus 8.3 to estimate direct and indirect pathways from lower-level perceptual attributes to higher-order aesthetic and emotional judgments. Configural, metric, and scalar invariance were tested across the four sensory conditions to allow cross-condition comparison of path coefficients.

To quantify the relative contributions of vision, touch, and audition to multisensory evaluations, a Bayesian weighted integration model was applied. Because multisensory trials involved simultaneous perception through all modalities, all sensory inputs were assumed to

originate from a common source. For each observation i , the multisensory rating was modeled as a weighted combination of the corresponding unimodal ratings, as shown in Equation (6).

$$M_i = \mu + w_V V_i + w_T T_i + w_A A_i + \epsilon_i, \quad \epsilon_i \sim N(0, \sigma^2) \quad (6)$$

where M_i is the multisensory rating for observation i ; V_i , T_i , and A_i represent the corresponding visual, tactile, and auditory ratings; w_V , w_T , and w_A are the weight coefficients. μ is the intercept term, and ϵ_i is the residual error with mean 0 and variance σ^2 .

To ensure the interpretability of weights, the vector $w = (w_V, w_T, w_A)$ is subject to a Simplex constraint, which enforces non-negativity and unit sum of weights, as shown in Equation (7):

$$w \in \Delta^2 = \{(w_V, w_T, w_A) : w_j \geq 0, \sum_j w_j = 1\} \quad (7)$$

According to Bayes' theorem, the posterior distribution of parameters can be derived as Equation (8):

$$p(w, \mu, \sigma \mid data) \propto p(data \mid w, \mu, \sigma) p(w, \mu, \sigma) \quad (8)$$

Observations are assumed to be independent and identically distributed, so the likelihood function is:

$$p(M \mid w, \mu, \sigma, V, T, A) = \prod_{i=1}^N \frac{1}{\sqrt{2\pi\sigma}} \exp\left(-\frac{(M_i - \mu - w_V V_i - w_T T_i - w_A A_i)^2}{2\sigma^2}\right) \quad (9)$$

To avoid subjective bias, weakly informative priors were used in this study. The contributions of the three sensory modalities were assumed to be equal, and the weight w follows a uniform Dirichlet prior:

$$p(w) = \text{Dirichlet}(1, 1, 1) \quad (10)$$

The intercept μ adopts a weakly informative Gaussian prior:

$$p(\mu) = N(0, 10^2) \quad (11)$$

The noise parameter σ uses a half-Cauchy prior to ensure scale stability:

$$p(\sigma) = \text{Half-Cauchy}(\sigma \mid 0, 2.5) \quad (12)$$

Substituting Equations (10)–(12) into Equation (9) gives the complete posterior expression. As the joint distribution of the Dirichlet prior and Gaussian likelihood lacks an analytical form, the HMC (NUTS) algorithm was used for sampling to approximate the posterior, with the sampling process implemented in Stan via the *brms* package (version: 2.23.0) in R (version 4.5.1) [29].

Besides, to relate objective physical parameters to subjective ratings, Pearson correlations were first computed between mean evaluation scores and physical measures, and significantly associated pairs with $p < 0.05$ were used for subsequent linear mixed-effects models (LMMs). Physical parameters were treated as fixed effects, and random intercepts were specified for participants and wood samples to account for subjective-level variability. All models were estimated in R using *lme4* (version: 1.1.37) with maximum likelihood [30]. Marginal R^2 and conditional R^2 was computed to quantify variance explained by fixed predictors, and by the both fixed and random components respectively. Between-group R^2 and corresponding 95% confidence intervals were derived from 1000 parametric bootstraps to evaluate each predictor's ability to explain mean differences across samples.

3. Results

3.1. Results of Inter-Participant Correlations Analysis

IPC analysis was conducted by computing Pearson correlation coefficients for ratings of all wood samples between every pair of participants, followed by calculating the mean and standard error. This procedure quantifies consensus for each evaluation item, where higher IPC values indicate greater consistency in the perceived relative ordering of specimens [3].

As shown in Figure 4a, IPC results under the visual condition revealed high consistency for surface brightness and moderate consistency for glossiness. The strong agreement on brightness reflects its status as a low-level visual attribute with high cross-participant stability [31]. In contrast, glossiness showed lower agreement, likely because it is influenced by uneven reflections produced by hardwood features such as vessels and ray patterns. These structural elements can create directional or patchy highlights, introducing greater variance in perceived glossiness compared with brightness.

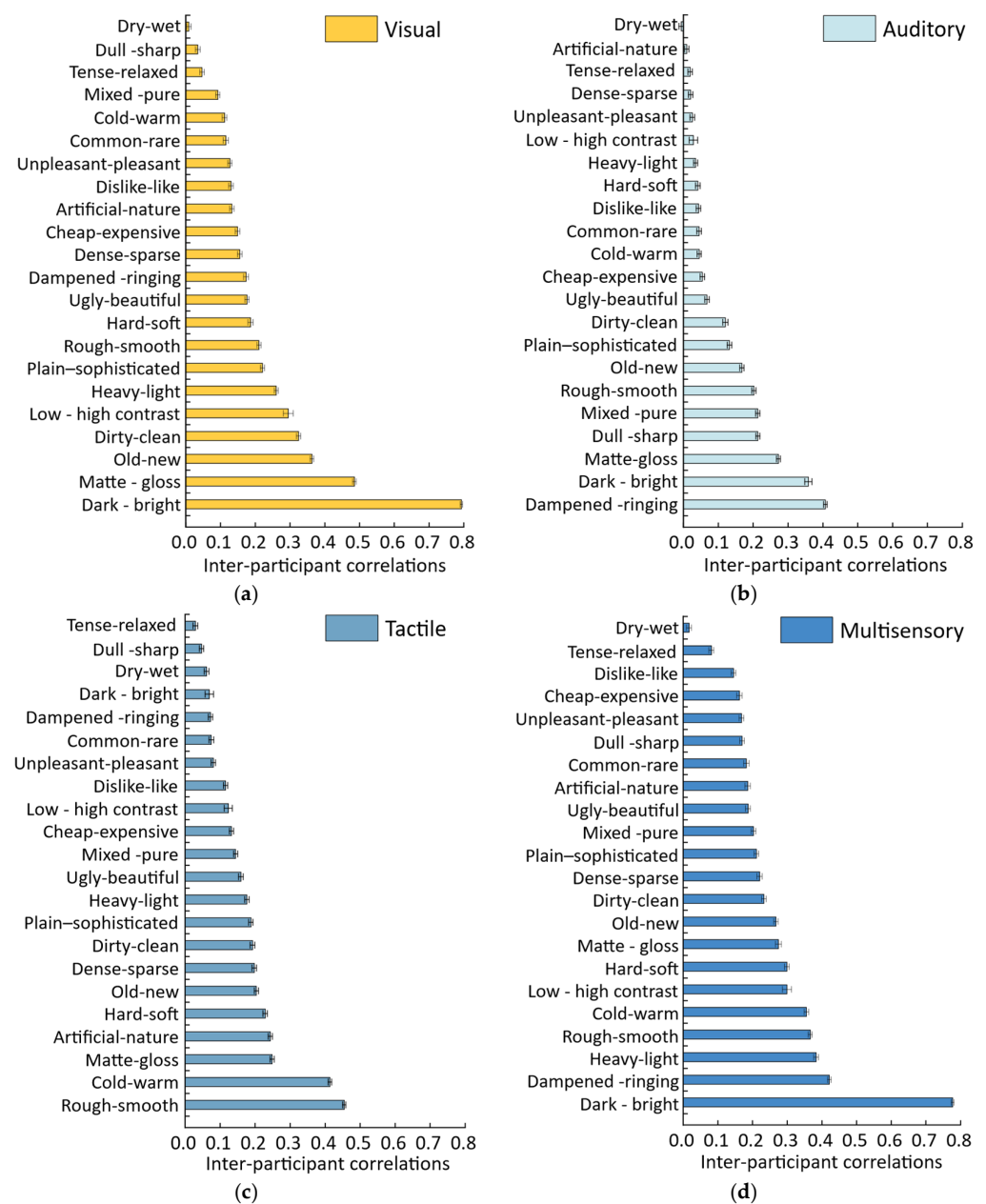


Figure 4. The average Pearson correlation coefficient between participants under: (a) visual condition; (b) auditory condition; (c) tactile condition; (d) multisensory condition.

Nevertheless, similarly high IPC values for glossiness and brightness were also observed under auditory and tactile conditions, indicating that these perceptions are not purely visual but supported by multisensory cues. Previous research has shown that surface gloss can be inferred from non-visual properties such as smoothness or sound characteristics [32], underscoring its inherently cross-modal nature.

Under the auditory condition, IPC values were generally lower than in the visual condition, indicating weaker cross-participant agreement when judgments relied on sound alone. Loudness and timbre showed relatively strong consistency, reflecting shared recognition of fundamental acoustic features. Roughness also produced a high IPC value, likely because listeners map frequency and vibration characteristics onto tactile roughness, revealing a stable audio–tactile correspondence.

In the tactile condition, attributes tied directly to surface contact, such as roughness and warmth, exhibited the highest consistency. Naturalness also reached its highest IPC value under touch, suggesting that haptic information becomes the primary basis for evaluating naturalness when vision is unavailable. This pattern aligns with evidence that tactile cues, being more uniform and less semantically driven than visual cues, promote stronger agreement across individuals [21].

Affective evaluation items showed low IPC values across all unimodal conditions but increased markedly under the multisensory condition. This indicates that emotional and aesthetic judgments depend on the integration of multiple sensory inputs; unimodal cues provide insufficient information for reliable higher-order evaluation. These findings support the view that emotional responses to materials rely on cross-modal processing and highlight the importance of multisensory experience in environmental appraisal.

3.2. Results of Exploratory Factor Analysis

Prior to exploratory factor analysis (EFA), Kaiser–Meyer–Olkin (KMO) statistics and Bartlett’s tests of sphericity were computed. Across all sensory conditions, KMO values exceeded 0.80 and Bartlett’s tests were significant ($p < 0.001$), confirming the adequacy of the data for factor extraction. EFA was then conducted using maximum-likelihood estimation with Geomin rotation. A three-factor solution was specified based on eigenvalue inspection and theoretical interpretability, and this model explained approximately 50% of the total variance across conditions, as shown in Table 4.

In the visual condition, Factor 1 comprised affective appraisal items such as pleasantness and liking, and was labeled Emotional Judgment. Visually inferred roughness also loaded on this factor, indicating that surface roughness strongly shapes emotional evaluation when assessed through vision alone. Factor 2 grouped surface-related attributes including brightness and glossiness together with timbre and loudness, suggesting cross-modal visual–auditory correspondences. Factor 3 captured Internal Properties, including hardness, density, weight and warmth, indicating that participants could infer internal material characteristics independently of surface impressions even without physical contact.

The tactile condition yielded a similar three-factor configuration. However, roughness shifted from Emotional Judgment to Surface Properties, where it aligned with naturalness and newness, demonstrating its role as a direct psychophysical cue during haptic exploration. Naturalness showed the highest loading in this modality, reinforcing touch as the primary channel for assessing this attribute. Internal properties separated from surface texture under tactile, which is consistent with evidence that roughness perception relies predominantly on somatosensory processing (S1), whereas hardness involves more cognitive inference associated with medial prefrontal engagement [33,34].

Table 4. Factor loading of exploratory factor analysis by sensory condition.

| Code | | Vision | | | Touch | | | Audition | | | Multisensory | | |
|------|---------------------|----------|----------|----------|----------|----------|----------|----------|----------|----------|--------------|----------|----------|
| | | Factor 1 | Factor 2 | Factor 3 | Factor 1 | Factor 2 | Factor 3 | Factor 1 | Factor 2 | Factor 3 | Factor 1 | Factor 2 | Factor 3 |
| 1 | Matte-gloss | 0.006 | 0.813 | −0.022 | 0.064 | 0.654 | 0.047 | −0.039 | 0.806 | 0.103 | 0.115 | 0.436 | −0.211 |
| 2 | Low-high contrast | −0.155 | 0.141 | −0.040 | 0.034 | −0.017 | 0.185 | −0.066 | 0.161 | −0.024 | −0.152 | 0.100 | −0.154 |
| 3 | Dark-bright | 0.057 | 0.655 | −0.402 | 0.035 | 0.342 | −0.236 | −0.006 | 0.624 | 0.104 | 0.093 | 0.701 | −0.276 |
| 4 | Dampened-ringing | −0.063 | 0.723 | 0.013 | 0.021 | 0.745 | −0.244 | 0.005 | 0.906 | 0.095 | −0.075 | 0.914 | 0.083 |
| 5 | Dull-sharp | −0.231 | 0.584 | 0.209 | −0.174 | 0.637 | −0.128 | 0.228 | 0.641 | −0.035 | −0.171 | 0.494 | 0.060 |
| 6 | Mixed-pure | 0.417 | 0.262 | 0.024 | 0.293 | 0.345 | 0.049 | −0.403 | 0.459 | 0.014 | 0.199 | 0.544 | 0.063 |
| 7 | Rough-smooth | 0.412 | 0.339 | 0.105 | 0.291 | 0.567 | 0.021 | −0.114 | 0.567 | −0.168 | 0.506 | −0.306 | −0.258 |
| 8 | Hard-soft | 0.055 | 0.082 | −0.747 | 0.096 | −0.057 | −0.719 | −0.173 | −0.101 | 0.671 | 0.093 | 0.236 | −0.651 |
| 9 | Cold-warm | 0.164 | −0.084 | −0.604 | 0.149 | −0.392 | −0.396 | −0.295 | −0.354 | 0.242 | −0.020 | 0.368 | −0.300 |
| 10 | Heavy-light | −0.055 | 0.260 | −0.709 | −0.007 | 0.198 | −0.833 | −0.003 | 0.525 | 0.622 | 0.022 | 0.266 | −0.704 |
| 11 | Dense-sparse | −0.230 | 0.011 | −0.704 | −0.193 | −0.053 | −0.642 | 0.111 | 0.114 | 0.743 | −0.175 | 0.123 | −0.643 |
| 12 | Dry-wet | 0.100 | 0.055 | 0.063 | 0.156 | 0.091 | 0.125 | −0.065 | −0.133 | −0.185 | 0.067 | −0.047 | 0.104 |
| 13 | Old-new | 0.567 | 0.403 | −0.080 | 0.273 | 0.498 | 0.031 | −0.268 | 0.421 | −0.192 | 0.658 | 0.075 | −0.178 |
| 14 | Plain-sophisticated | 0.809 | −0.013 | 0.189 | 0.616 | 0.270 | 0.092 | −0.483 | 0.219 | −0.357 | 0.853 | −0.109 | 0.021 |
| 15 | Ugly-beautiful | 0.852 | −0.038 | 0.001 | 0.765 | 0.129 | −0.013 | −0.668 | 0.163 | −0.167 | 0.895 | 0.063 | 0.094 |
| 16 | Artificial-nature | 0.107 | 0.014 | −0.320 | 0.149 | −0.528 | −0.186 | −0.423 | −0.212 | 0.142 | −0.040 | 0.459 | −0.018 |
| 17 | Dislike-like | 0.906 | −0.119 | −0.039 | 0.853 | 0.015 | −0.055 | −0.821 | −0.020 | −0.068 | 0.853 | 0.015 | 0.039 |
| 18 | Tense-relaxed | 0.645 | −0.065 | −0.105 | 0.714 | −0.125 | −0.126 | −0.711 | −0.072 | 0.131 | 0.556 | 0.236 | 0.114 |
| 19 | Unpleasant-pleasant | 0.833 | −0.142 | −0.034 | 0.834 | −0.019 | −0.093 | −0.836 | −0.034 | 0.073 | 0.781 | 0.096 | 0.132 |
| 20 | Cheap-expensive | 0.560 | −0.245 | 0.372 | 0.598 | 0.042 | 0.222 | −0.493 | −0.014 | −0.373 | 0.553 | −0.096 | 0.363 |
| 21 | Common-rare | 0.270 | −0.209 | 0.364 | 0.386 | 0.019 | 0.204 | −0.357 | −0.025 | −0.300 | 0.354 | −0.085 | 0.445 |
| 22 | Dirty-clean | 0.605 | 0.371 | −0.033 | 0.396 | 0.356 | 0.048 | −0.422 | 0.289 | −0.131 | 0.703 | 0.138 | −0.097 |
| | % of variance | 22.36% | 12.20% | 11.70% | 17.98% | 13.25% | 9.68% | 16.92% | 16.62% | 9.22% | 22.51% | 12.61% | 9.42% |

Under the auditory condition, attributes including brightness, glossiness, roughness, and warmth were integrated into Factor 2 together with timbre, suggesting that impact sounds evoke vivid visual and tactile imagery through cross-modal mapping. High-frequency components were associated with smoother and colder impressions, in agreement with established audio–visual and audio–tactile correspondences [35,36]. Internal properties again remained independent.

In the multisensory condition, the three-factor configuration was largely preserved. Roughness exhibited cross-loadings on both Emotional Judgment and Surface Properties, indicating that when multiple senses are available, roughness extends beyond sensory registration and acquires affective value.

Overall, three perceptual dimensions emerged across all sensory conditions: Emotional Judgment, Surface Properties, and Internal Properties. Emotional Judgment consistently constituted the dominant dimension; Surface Properties were modality-dependent and incorporated cross-modal cues such as brightness, glossiness, and loudness; Internal Properties remained structurally stable and independent. Roughness acted as a pivotal attribute, shifting between affective and sensory roles depending on modality. Naturalness consistently aligned with Surface Properties under touch and audition, suggesting grounding in direct sensory features rather than higher-order aesthetic appraisal. Finally, texture contrast and moistness showed weak loadings (<0.20), indicating limited contribution to the core perceptual structure of wood.

Figure 5 presents the distribution of wood samples factor scores with 95% confidence ellipses for each sensory condition, accompanied by variable loadings. These biplots visualize how participants differ in their evaluations along two dominant perceptual dimensions.

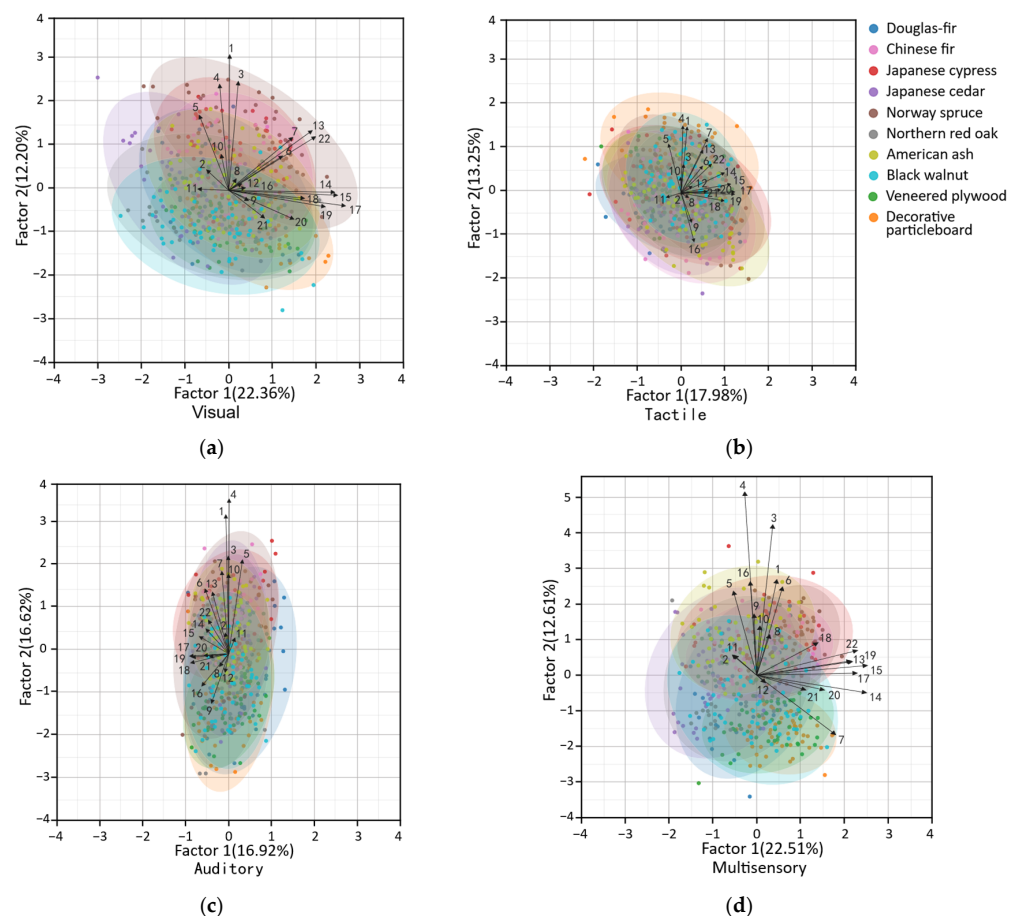


Figure 5. Factor loading plot under (a) Visual condition; (b) Tactile conditions; (c) Auditory condition; (d) Multisensory conditions. Numeric labels on the vectors denote adjective pairs corresponding to those presented in Table 4.

Across the visual, tactile, and multisensory conditions, sample dispersion was markedly greater along Emotional Judgment (Factor 1) than on the surface-Related Properties (Factor 2), indicating wide variation in emotional judgments but relatively consistent evaluations of surface properties. By contrast, the auditory condition showed the reverse trend, with a greater spread on Factor 2 and a tighter clustering on Factor 1, meaning that sound elicited larger individual differences in inferred material properties while emotional responses were relatively similar. Touch produced the most compact distribution across all modalities, indicating the strongest agreement among participants. This pattern aligns with the direct and verifiable nature of haptic cues, which depend less on semantic inference than visually or aurally inferred information.

Variable loadings indicate how perceptual attributes align with the two latent dimensions, brightness, glossiness, and loudness loaded strongly on Factor 2 in the visual, auditory, and multisensory conditions, whereas tactile loadings were more evenly distributed, suggesting that haptic evaluations emerge from the integrated contribution of multiple cues rather than being driven by a small set of dominant attributes. Notably, naturalness showed a strong loading in the tactile condition, highlighting the particular relevance of touch in how naturalness is perceived.

3.3. Results of the Exploratory Structural Equation Model

EFA revealed that roughness, warmth, newness, and naturalness did not remain fixed in any single factor across sensory conditions. Their shifting affiliations indicate that they are neither purely evaluative nor solely tied to direct perception of material properties, but instead function as intermediate attributes that mediate between low-level sensory cues and higher-level aesthetic judgment. This structure aligns with the three-tier semantic framework proposed by Katahira et al., comprising physical perception, intermediate impressions, and value-based evaluation [37]. In line with this framework, the Factor 1 produced by EFA could be divided into value-based evaluation and intermediate impression items such as naturalness, perceived value, and newness, which shifted depending on the sensory modality.

Factors 2 and 3, describing surface and internal properties, corresponded to material-level perception; however, the affiliation shifts in roughness and warmth across conditions indicated they did not consistently remain in this physical domain. Their meanings were strongly modulated by visual and multisensory cues such as brightness, color, and hardness [38], indicating that they operate as mid-level perceptual attributes rather than strictly physical ones.

Finally, although most low-level sensory items such as glossiness and brightness displayed stable factor memberships, several informative cross-loadings persisted. Constraining such cross-loadings to zero in confirmatory models can inflate factor loadings and latent correlations, resulting in biased structures. To preserve these meaningful secondary loadings while maintaining model interpretability, exploratory structural equation modeling (ESEM) was adopted. ESEM allows cross-loadings to be estimated rather than forced to zero, thereby yielding a more accurate and theoretically coherent representation of the latent perceptual structure [39]. The resulting model is shown in Figure 6.

Multi-group exploratory structural equation modelling (MG-ESEM) was conducted using the robust maximum likelihood estimator (MLR). The low-level physical layer was estimated exploratorily with Geomin oblique rotation to permit correlated latent factors, whereas the impression and emotional judgment layers were specified using a confirmatory measurement model. Items with standardized loadings below 0.40 or with salient cross-loadings were removed to ensure a clean factor structure and discriminant validity.

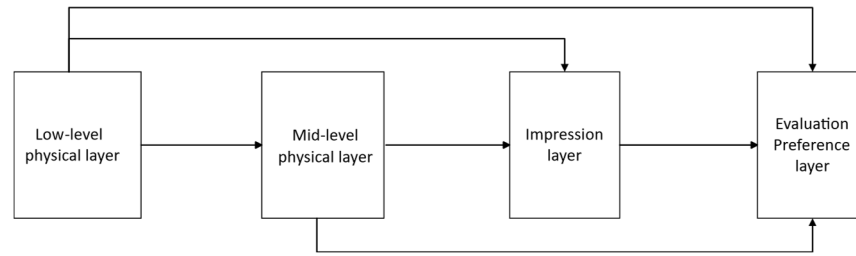


Figure 6. Hypothesized factor-path model diagram. Arrows indicate hypothesized relationships among variables.

Measurement invariance across the four sensory conditions was assessed in a sequential framework, testing configural, weak, and strong invariance. Fit index changes are reported in Table 5. Although the ΔCFI of -0.014 at the weak-invariance step slightly exceeded the conventional -0.01 criterion [40], it remained within the -0.02 tolerance recommended when meaningful group differences are expected [41]. Measurement invariance was thus considered acceptable, allowing valid comparison of structural paths and mediated effects across sensory conditions.

Table 5. Multigroup Measurement Invariance Test Results in ESEM.

| | RMSEA | CFI | Δ RMSEA | Δ CFI |
|-----------------------|-------|-------|----------------|--------------|
| Configural invariance | 0.063 | 0.942 | — | — |
| Weak invariance | 0.069 | 0.928 | 0.006 | -0.014 |
| Strong invariance | 0.071 | 0.918 | 0.003 | -0.010 |

Figures 7–10 illustrate the ESEM results for each sensory condition, elucidating the multi-level path structures underlying participants’ perceptions and judgments of wood materials, as well as the variations across sensory conditions. The measurement models demonstrated reliability across conditions, with all standardized factor loadings exceeding 0.50. The average variance extracted (AVE) for the two confirmatory factors, cleanliness and emotional judgment, reached or approached 0.50 in most conditions, reflecting adequate convergent validity and explanatory power. Although cross-loadings existed between the two exploratory latent variables, all were below 0.30, indicating acceptable discriminant validity.

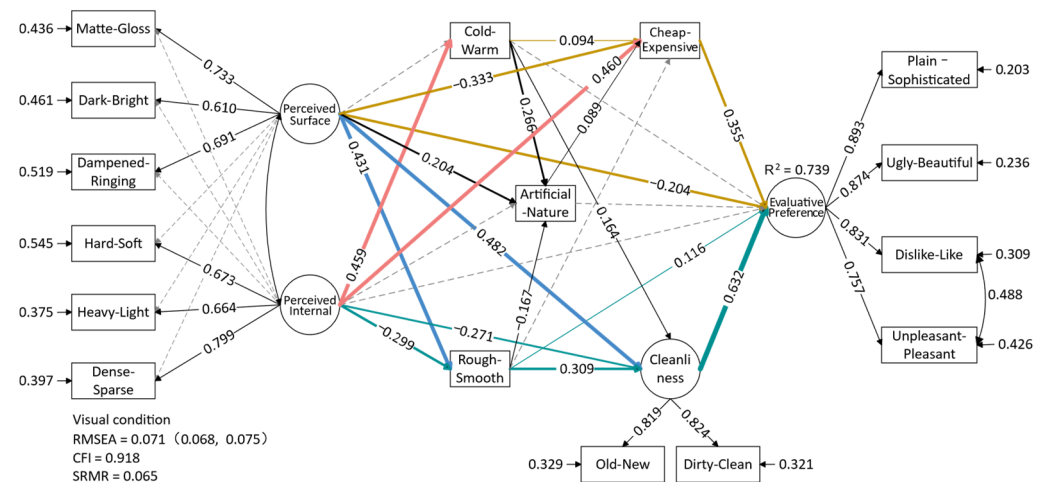


Figure 7. Exploratory structural equation modeling model under the visual condition. Ellipses represent latent variables and rectangles represent observed variables. Solid arrows indicate significant paths, while dashed arrows denote non-significant paths.

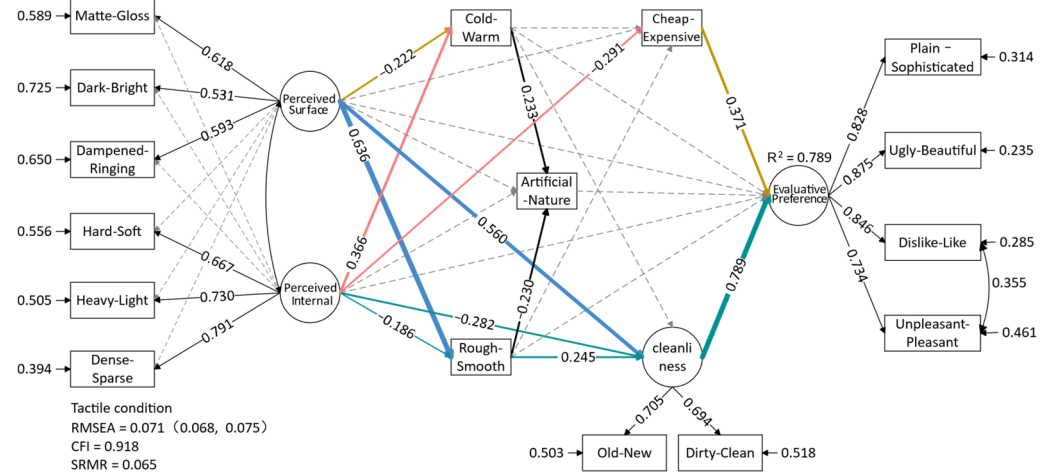


Figure 8. Exploratory structural equation modeling model under the tactile condition. Ellipses represent latent variables and rectangles represent observed variables. Solid arrows indicate significant paths, while dashed arrows denote non-significant paths.

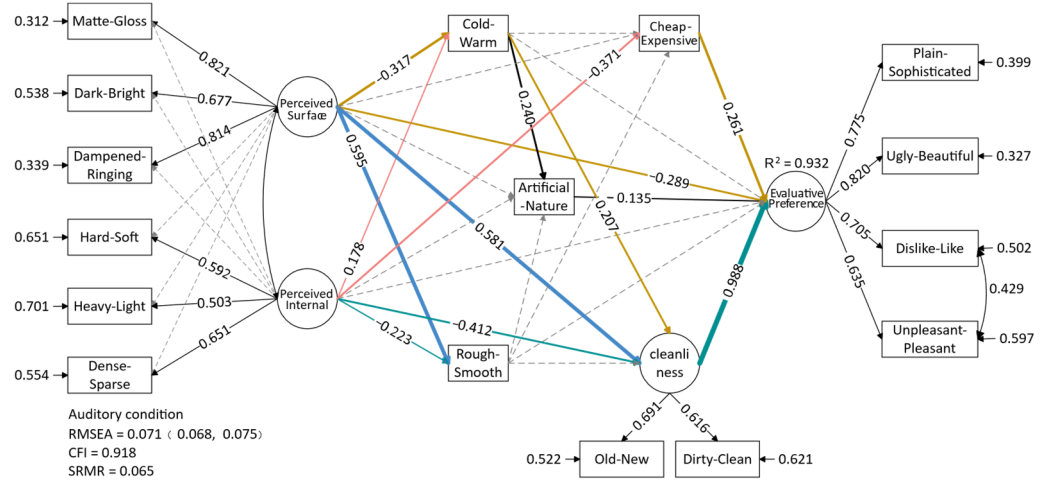


Figure 9. Exploratory structural equation modeling model under the auditory condition. Ellipses represent latent variables and rectangles represent observed variables. Solid arrows indicate significant paths, while dashed arrows denote non-significant paths.

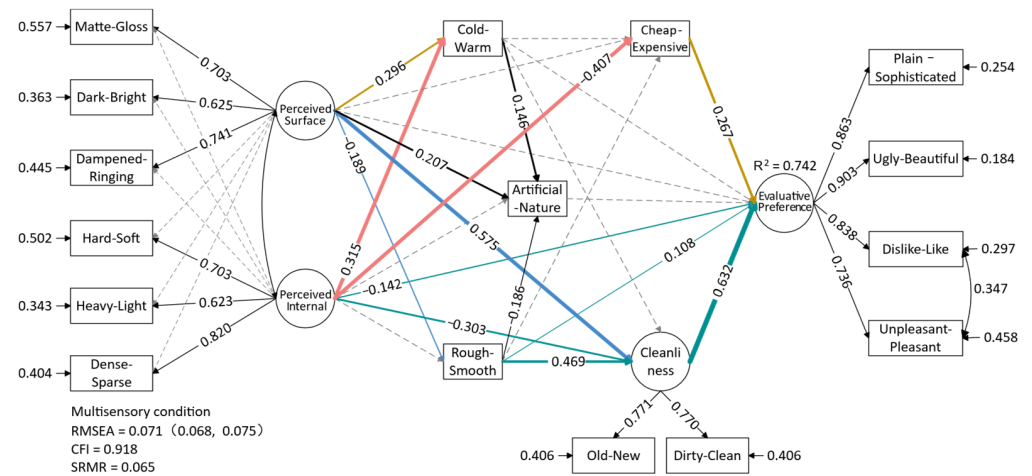


Figure 10. Exploratory structural equation modeling model under the multisensory condition. Ellipses represent latent variables and rectangles represent observed variables. Solid arrows indicate significant paths, while dashed arrows denote non-significant paths.

Figure 7 shows that in the visual condition both surface and internal qualities influenced emotional judgment mainly through perceived value and cleanliness. Surface qualities also exerted a direct negative effect, indicating that visually darker, harder, and thicker wood was evaluated more valuable and favorably. Roughness had only a weak direct effect on emotional judgment but contributed indirectly through cleanliness, as smoother visual impressions elicited tidier associations that improved aesthetic evaluation. Warmth increased perceived naturalness and cleanliness but had no direct effect. Cleanliness was the dominant mediator with the highest path coefficient, whereas naturalness did not significantly affect emotional judgment.

Figure 8 indicates that in the tactile condition physical attributes affected emotional judgment almost entirely through indirect pathways. Cleanliness showed a strong positive effect and served as the primary mediator. Warm and rough tactile sensations increased perceived naturalness, yet naturalness itself did not influence emotional judgment directly. These patterns reflect the strongly verifiable nature of haptic cues, with value judgments arising mainly through intermediary impressions rather than physical features alone.

Figure 9 shows that the AVE for cleanliness was 0.429, which is below the 0.50 benchmark and lower than other condition. This finding indicates that auditory cues provide a weaker basis for cleanliness impressions. Despite this limitation, cleanliness remained the strongest mediator of emotional judgment. Naturalness exerted a positive effect on emotional judgment, whereas surface qualities produced a negative effect. Together, these results suggest that sounds shape evaluation mainly through associative, semantic inferences about cleanliness and naturalness rather than through direct perceptual evidence.

Figure 10 demonstrates that multisensory information enhanced convergent validity and greater explained variance, as all item loadings exceeded 0.50 and that confirmatory factors achieved AVE values above 0.50. The structural model combined features from the unimodal analyses: internal qualities, roughness, cleanliness, and perceived value each contributed significantly to emotional judgment, while the direct effect of surface qualities lost significance. This pattern indicates that when information is supplied by multisensory, emotional judgments depend more on mediated impressions and inferred value than on raw physical attributes.

Indirect effects were estimated by Monte Carlo simulation with twenty thousand resamples. Paths with absolute standardized indirect effects greater than 0.05 and their 95 percent bias-corrected confidence intervals are reported in Figure 11.

In the visual condition, both perceived surface and internal qualities influenced emotional judgment indirectly via perceived cleanliness and value. The cleanliness-mediated effects were 0.304 [0.216 to 0.402] for surface qualities, and -0.171 [-0.260 to -0.088] for internal qualities. Mediation via perceived value produced effects of -0.118 [-0.180 to -0.065] for surface qualities and -0.163 [-0.228 to -0.107] for internal qualities. A serial pathway running from low-level attributes through roughness to cleanliness was also significant but smaller in magnitude.

Under tactile testing, mediation through cleanliness and value remained strong. The serial path from perceived surface qualities via roughness to cleanliness increased from 0.084 [0.050, 0.125] in the visual model to 0.123 [0.022, 0.262] in the tactile model, indicating that haptically smoother, harder, and heavier specimens were more likely to be judged as cleaner and more valuable and thus received higher evaluation preference.

Across auditory and multisensory conditions, cleanliness and perceived value consistently served as the strongest mediators of emotional judgment. In the auditory condition, these two impression-layer variables remained the dominant routes, supplemented by a weaker but significant indirect effect via sound-evoked warmth.

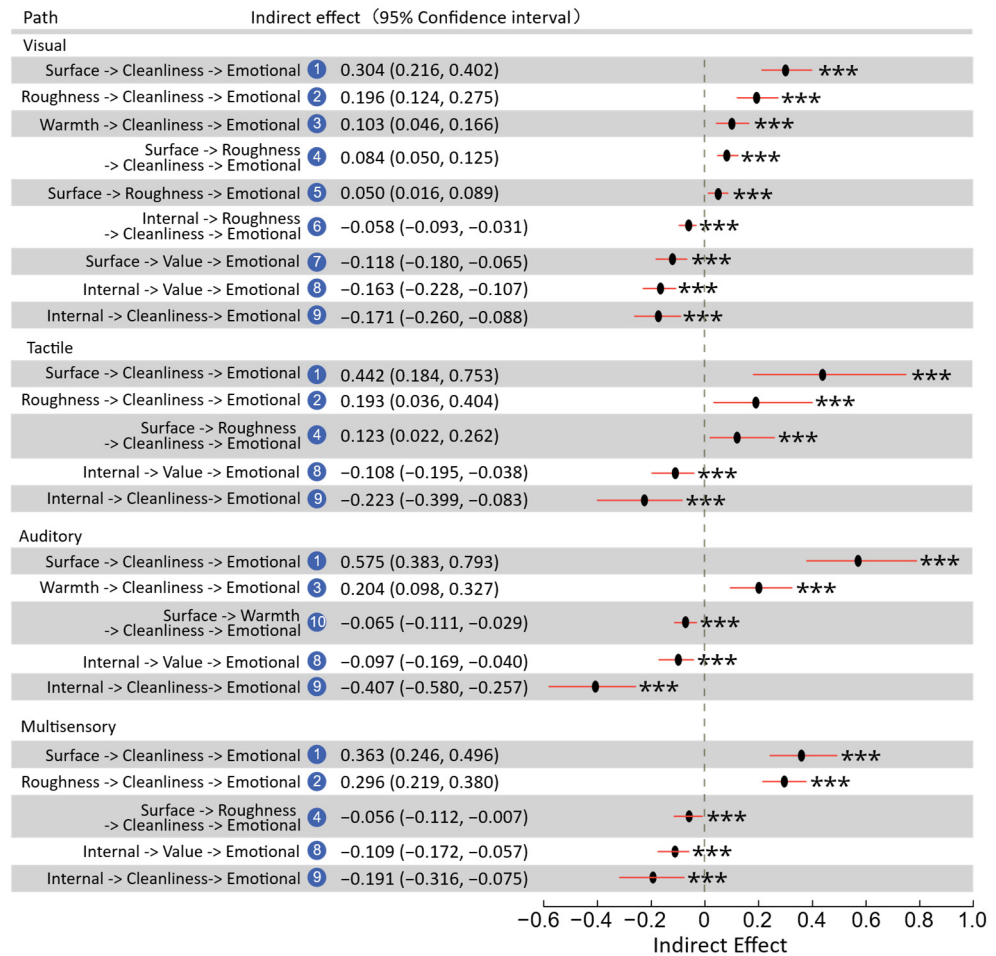


Figure 11. Indirect effects and their 95% confidence intervals under different sensory conditions. *** $p < 0.001$.

In the multisensory condition, the strongest mediated paths precisely mirrored those observed under touch and were fully subsumed within the broader visual path structure, revealing robust visuo-haptic integration. This pattern further indicates that, when multiple senses are engaged simultaneously, emotional judgment relies primarily on higher-order impressions rather than on direct physical sensory cues.

3.4. Results of the Analysis of Sensory Weight

Figure 12 presents the relative sensory weights in multisensory integration. All parameters had the maximum potential scale reduction factor (\hat{R}) < 1.01 and minimum effective sample size (n_{eff}) > 400 , indicating successful convergence of the Markov chains and reliable posterior inference.

For surface qualities, vision was the dominant cue, with a weight of 0.679 [0.631, 0.725]. Audition provided moderate modulation (0.290 [0.247, 0.334]), whereas touch contributed minimally. This indicates that judgments of gloss, brightness, and other surface attributes are primarily visually driven, with auditory cues offering supportive refinement—a pattern consistent with cross-modal enhancement mechanisms [42,43]. For internal qualities, both vision and touch served as key channels, with comparable weights of 0.461 [0.405, 0.519] and 0.404 [0.345, 0.461], respectively, both clearly exceeding audition. These results suggest that internal qualities depend on the integration of visual and tactile cues, while auditory information plays only a minor role. For roughness and warmth, touch showed the highest weights of 0.555 [0.504, 0.607] and 0.544 [0.482, 0.607], respectively. Vision also made

non-negligible contributions, indicating that visual cues such as color, and gloss interact with tactile sensations to shape multisensory judgments.

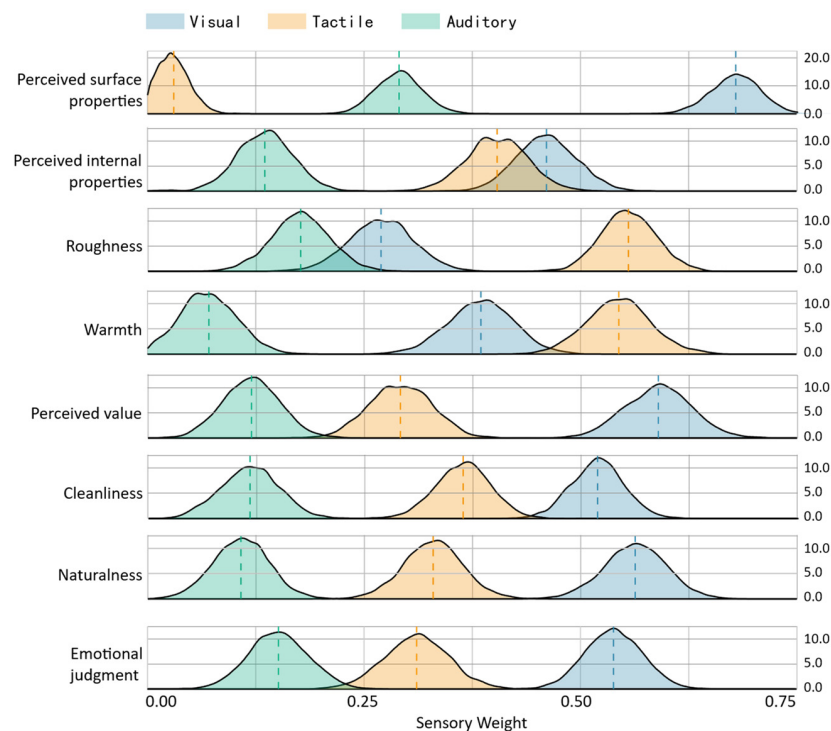


Figure 12. Posterior distributions of relative modality weights for each perceptual dimension. Vertical dashed lines indicate the mean estimated sensory weight for each modality.

For value, cleanliness, and naturalness, the weighting patterns were consistent across dimensions: vision was the dominant channel, with weights above 0.5; touch played a secondary yet notable role with weights around 0.3; and audition contributed only weak modulation. These findings indicate that higher-level affective evaluations rely primarily on visual information, supported by tactile input, while auditory cues exert comparatively minor influence.

3.5. Correlation Between Physical Properties and Subjective Evaluation

The measurement results of various physical properties of wooden materials as shown in Table 6.

Pearson correlation coefficients were computed between measured physical parameters and mean sensory ratings for each modality. Figure 13 presents the resulting correlation matrices for the visual, tactile, and auditory conditions and reveals modality-specific mappings between physical properties and subjective impressions.

Under vision, almost all sensory ratings correlated significantly with visual physical features, indicating that gloss, color and grain are primary determinants of visual impressions. Gloss units measured at 60 degrees incidence, L^* and b^* were positively associated with ratings of perceived surface and internal properties, warmth and naturalness. By contrast, a^* , overall color difference and color difference between early and late wood were negatively associated with perceived roughness, cleanliness and overall aesthetic judgment. These results suggesting that higher lightness and yellowness tended to evoke impressions of brightness, softness, warmth and naturalness, whereas increased redness and greater color heterogeneity tended to signal roughness and soiling and to lower visual aesthetic ratings. Among descriptors of wood grain, perceived roughness and cleanliness correlated negatively with contrast, while correlated positively with homogeneity and energy, implying that regular, uniform grain patterns are linked to impressions of smoothness and tidiness.

Table 6. Measurement results of various physical properties of wooden materials.

| Physical Properties | Douglas-Fir | Chinese Fir | Japanese Cypress | Japanese Cedar | Norway Spruce | Northern Red Oak | American Ash | Black Walnut | Veneered Plywood | Decorative Particleboard |
|--|-------------|-------------|------------------|----------------|---------------|------------------|--------------|--------------|------------------|--------------------------|
| Gloss (60°) [GU] | 4.53 | 6.37 | 4.45 | 5.08 | 6.05 | 3.82 | 4.42 | 3.65 | 2.08 | 3.65 |
| Gloss (85°) [GU] | 11.60 | 7.60 | 4.06 | 7.22 | 7.66 | 13.78 | 13.24 | 16.90 | 19.04 | 2.62 |
| Lightness (L^*) | 64.12 | 73.17 | 80.05 | 67.55 | 82.67 | 63.89 | 69.58 | 47.56 | 52.58 | 51.89 |
| Red-green chromaticity (a^*) | 12.78 | 6.97 | 5.42 | 10.84 | 3.21 | 9.82 | 6.70 | 7.56 | 7.07 | 3.98 |
| Yellow-blue chromaticity (b^*) | 24.32 | 21.55 | 20.84 | 21.94 | 20.69 | 22.15 | 21.51 | 12.67 | 14.08 | 9.13 |
| Color difference (ΔE) | 6.63 | 6.35 | 4.57 | 11.06 | 2.71 | 10.81 | 7.25 | 10.96 | 7.52 | 8.19 |
| Color difference between early and late wood (segment ΔE) | 10.41 | 8.89 | 8.37 | 15.18 | 4.09 | 16.01 | 10.44 | 21.92 | 10.85 | 11.31 |
| Texture contrast | 180.14 | 160.63 | 108.52 | 342.94 | 92.66 | 627.01 | 212.33 | 376.91 | 172.28 | 326.31 |
| Texture homogeneity | 0.12 | 0.12 | 0.17 | 0.10 | 0.18 | 0.08 | 0.11 | 0.11 | 0.13 | 0.10 |
| Texture energy | 0.02 | 0.02 | 0.04 | 0.02 | 0.04 | 0.02 | 0.02 | 0.03 | 0.03 | 0.03 |
| Texture correlation | 0.61 | 0.73 | 0.68 | 0.78 | 0.35 | 0.30 | 0.62 | 0.24 | 0.38 | 0.18 |
| Frequency | 573.13 | 643.13 | 627.50 | 521.25 | 670.00 | 511.25 | 539.38 | 498.75 | 363.75 | 288.13 |
| Specific dynamic elastic modulus | 25.78 | 27.25 | 28.64 | 20.44 | 29.58 | 19.95 | 22.20 | 19.06 | 6.18 | 12.22 |
| Acoustic radiation quality constant (R) [$\text{Rm}^4/(\text{kg}\cdot\text{s})$] | 8.32 | 14.50 | 12.16 | 12.56 | 12.36 | 6.87 | 6.54 | 6.93 | 3.60 | 5.64 |
| Acoustic impedance (ω) [$\text{Pa}\cdot\text{s}\cdot\text{m}^{-1}$] | 4.8 | 1.77 | 2.77 | 1.32 | 2.86 | 4.21 | 5.75 | 3.78 | 1.47 | 2.35 |
| Dynamic elastic modulus [GPa] | 15.73 | 9.81 | 12.60 | 7.36 | 13.01 | 12.97 | 15.99 | 12.01 | 4.27 | 7.58 |
| Thermal conductivity [$\text{W}/(\text{m}\cdot\text{K})$] | 0.18 | 0.24 | 0.16 | 0.17 | 0.18 | 0.22 | 0.22 | 0.25 | 0.19 | 0.11 |
| Parallel to grain Ra [μm] | 2.47 | 3.23 | 4.15 | 2.92 | 3.86 | 3.86 | 4.37 | 4.73 | 1.31 | 4.56 |
| Parallel to grain Sa [μm] | 7.33 | 8.13 | 7.95 | 9.44 | 24.01 | 7.14 | 18.65 | 14.66 | 5.65 | 9.23 |
| Perpendicular to grain Ra [μm] | 4.55 | 9.57 | 6.14 | 6.57 | 6.27 | 4.96 | 7.29 | 10.91 | 5.48 | 9.25 |
| Perpendicular to grain Sa [μm] | 6.47 | 9.02 | 10.51 | 5.48 | 31.09 | 11.20 | 19.43 | 10.79 | 6.28 | 10.70 |

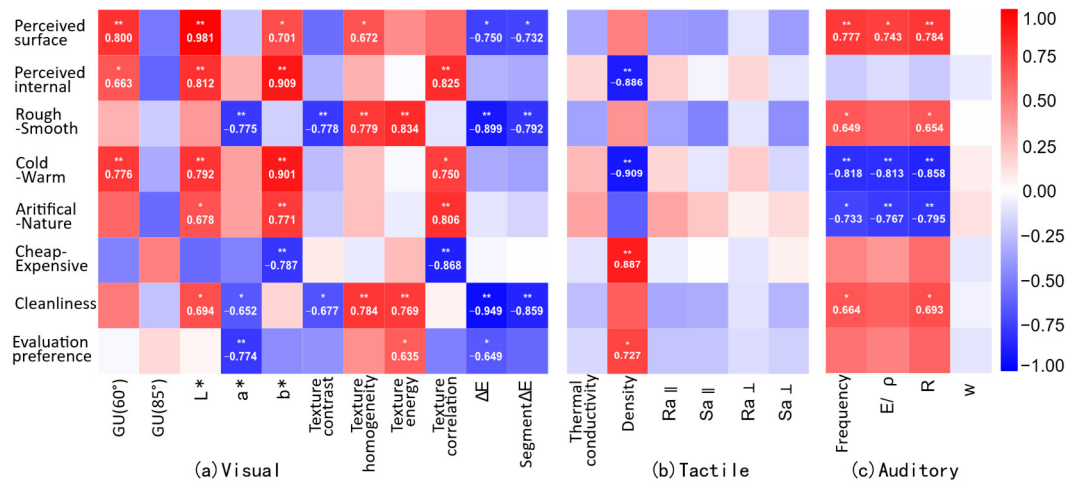


Figure 13. Correlation matrix between subjective evaluation and physical properties under visual, tactile, and auditory conditions. * $p < 0.05$, ** $p < 0.01$.

Under touch, wood density showed a strong negative relationship with perceived internal properties and warmth ($p < 0.01$), and a moderate positive relationship with emotional judgment ($p < 0.05$), indicating a haptic preference for denser samples. Thermal conductivity was not significantly related to all subjective evaluation, suggesting that, within the tested range of wood samples, hand-perceived thermal sensation is driven more by semantic associations with perceived internal properties than by measurable heat transfer. Measured roughness failed to predict perceived roughness. This discrepancy can be attributed to the fact that subjective roughness perception is jointly determined by asperity contacts governed by microscopic surface topography and by biomechanical skin interactions, including deformation and adhesion, that scale with the material's elastic modulus. Consequently, a single roughness metric cannot capture the percept accurately.

In the auditory condition, higher sound frequency, greater specific dynamic elastic modulus, and increased acoustic radiation damping were linked to higher ratings of surface properties, roughness and cleanliness and to lower ratings of warmth and naturalness, indicating that higher-frequency sounds evoke cross-modal impressions of brighter, smoother and colder materials.

Figure 14 summarizes results under the multisensory condition. The multisensory context largely preserved the mappings observed in the visual and tactile modalities and in several cases strengthened them. Notably, gloss measured at an 85 degree incidence angle and the roughness metric Sa , which had not reached significance in single sensory conditions, showed significant associations with multiple perceptual ratings under multisensory conditions. Meanwhile, several correlation directions shifted markedly in the multisensory condition. A weak positive relationship between density and surface properties observed in the tactile-only condition became a significant negative relationship when visual cues were added. Likewise, the negative associations between acoustic parameters such as frequency and specific dynamic modulus and the impressions of warmth and naturalness observed under audition alone reversed to significant positive correlations once visual and tactile information was present. These reversals are parsimoniously accounted for by reliability-weighted multisensory integration. When cues from multiple channels are combined, information from the most reliable modality receives greater weight. For surface texture perception, vision proved the more reliable cue and therefore dominated the fused estimate. Because denser hardwoods tend to appear darker, greater visual weighting introduced a negative density–texture association that supplanted the tactile-only pattern. By contrast,

perceptions of warmth and naturalness relied principally on visual and haptic evidence, so auditory cues carried lower weight and exerted less influence in the combined estimate.

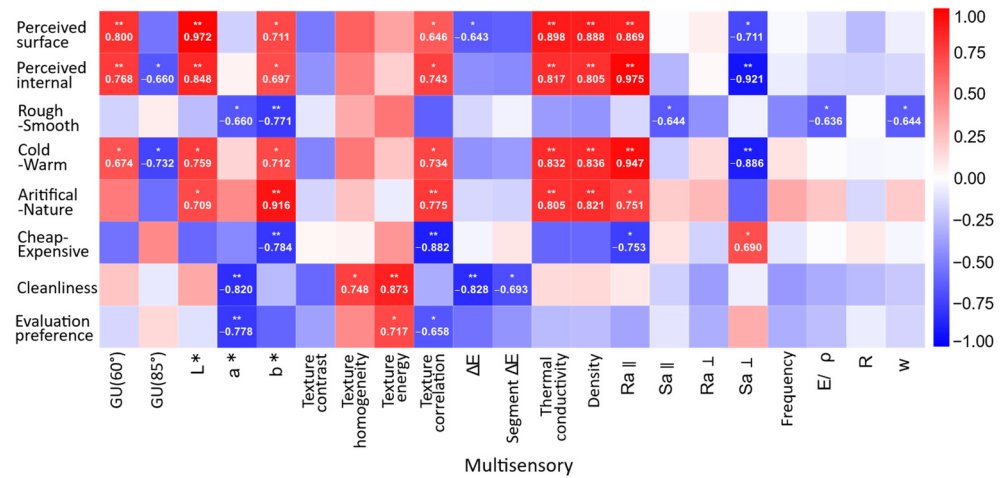


Figure 14. Correlation matrix between subjective evaluation and physical properties under multisensory conditions. * $p < 0.05$, ** $p < 0.01$.

3.6. Results of Linear Mixed-Effects Models Analysis

Linear mixed-effects models were used to quantify how measured physical properties account for variance in subjective ratings. Severe multicollinearity among auditory predictors was detected by variance inflation factors (VIF) exceeding twenty, so frequency alone was retained as the auditory predictor. Physical parameters were entered as fixed effects, while participants and wood specimens were modeled as random effects to partition within- and between-group variance. Marginal R^2 was used to quantify variance explained by fixed effects, conditional R^2 to assess total model fit including random effects, and between-group R^2 to capture how well the fixed effects explained average differences among samples.

Results for the visual condition are summarized in Figure 15. Between-group R^2 exceeded 0.60 for several key pairs, including surface qualities predicted by L^* , internal qualities and warmth–coldness predicted by b^* , cleanliness and roughness predicted by color difference, naturalness predicted by texture correlation, and emotional judgment predicted by a^* . These high between-group R^2 indicate that these physical features account well for sample-level differences in visual impressions. However, marginal and conditional R^2 values indicated that higher-order impressions predicted by physical attributes had weak explanatory power. Marginal R^2 values were generally below 0.30, and although conditional R^2 increased after accounting for random effects, it remained far below the between-group R^2 . This persistent gap reflects substantial unexplained variance at the individual level. Variance decomposition confirmed this pattern: predictors such as color difference for roughness, texture correlation for naturalness and perceived value, and a^* for emotional judgment showed large random components, with participant variance consistently exceeding sample variance.

Only surface impressions predicted by L^* showed both marginal and conditional R^2 above 0.60, with minimal random variance, indicating a stable population-level predictor. By contrast, color difference yielded a moderate marginal R^2 above 0.30 for perceived cleanliness, yet participant variance substantially outweighed sample variance, suggesting that the perceptual mapping between color heterogeneity and cleanliness differs across individuals.

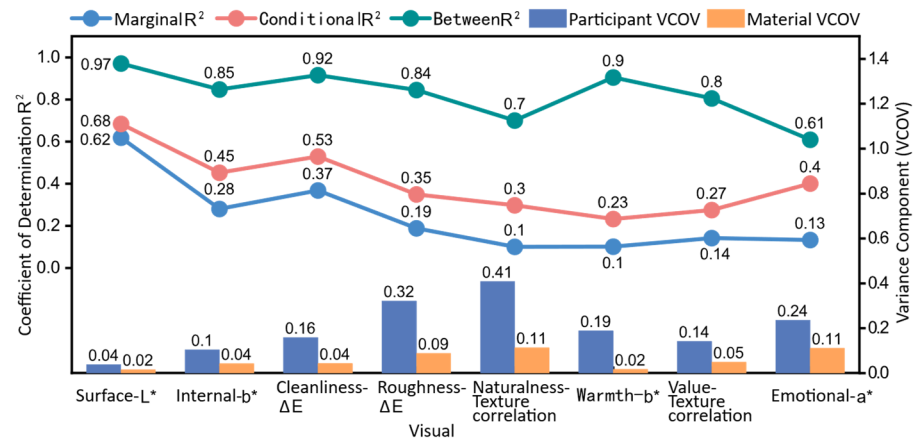


Figure 15. Coefficient of determination and variance components of random effect for linear mixed models under visual condition.

Figure 16 summarizes the LMM results for the tactile and auditory conditions. In the tactile condition, density was the dominant predictor of internal qualities and warmth. Both outcomes showed strong between-group $R^2 > 0.60$ and moderate fixed-effect strength as marginal $R^2 > 0.30$. For internal qualities, participant and sample variances were comparable, indicating that density explained both material differences and general perceptual trends. For warmth, participant variance was far greater, showing that density reliably ranked materials but could not account for individual thermal impressions.

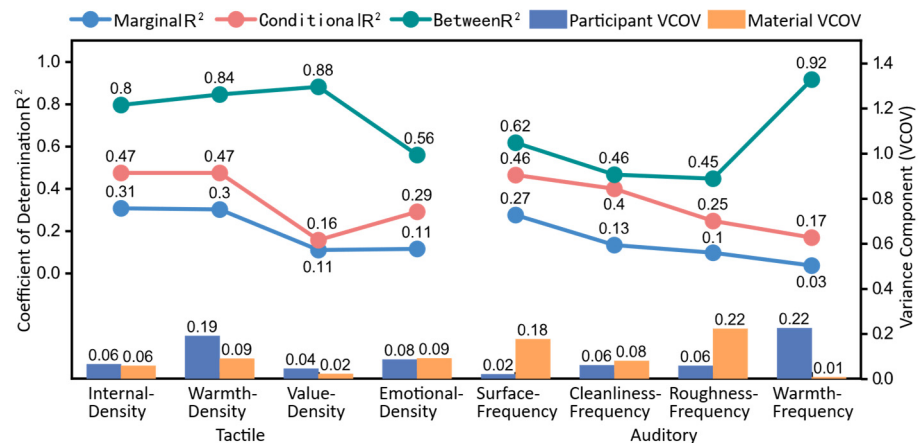


Figure 16. Coefficient of determination and variance components of random effect for linear mixed models under tactile and auditory conditions.

In the auditory condition, frequency served as the key acoustic predictor. For surface qualities, between-group R^2 exceeded 0.60 and marginal R^2 approached 0.30, with sample variance outweighing participant variance, indicating a stable group-level link between acoustic cues and perceived surface attributes. In contrast, warmth exhibited extremely high between-group $R^2 (>0.90)$ but very low marginal $R^2 (<0.10)$, and participant variance dominated, demonstrating that although frequency sorted materials consistently at the group level, semantic mapping to thermal impressions varied widely across individuals.

Figure 17 presents the results for the multisensory condition. The multisensory mappings largely preserved the relationships observed under vision and touch. L^* remained the primary determinant of surface qualities and showed the strongest overall performance as between-group R^2 , marginal R^2 , and conditional R^2 all exceeded 0.60, indicating that lightness consistently explained sample-level differences in surface appraisal. Density

retained moderate predictive value for internal qualities, with a marginal R^2 of 0.51 and minimal random variance, confirming its stable influence across participants.

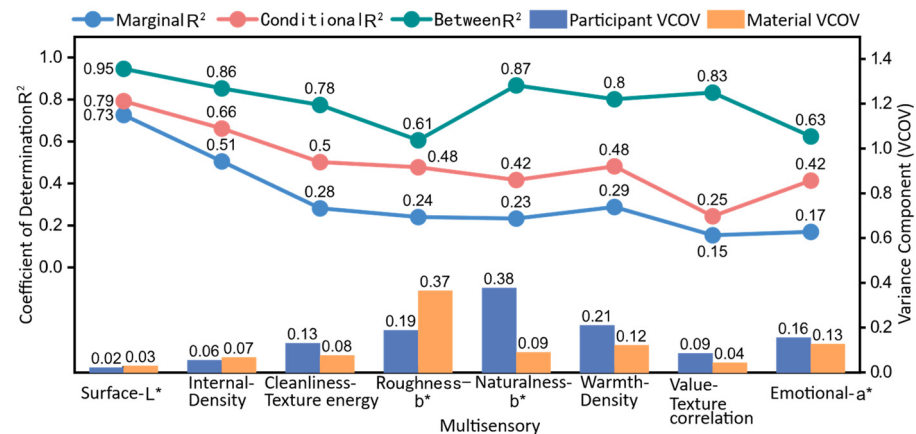


Figure 17. Coefficient of determination and variance components of random effect for linear mixed models under multisensory condition.

Although b^* continued to predict perceived naturalness and a^* remained the leading predictor of emotional judgment—with between-group R^2 values generally above 0.60—their marginal R^2 values were consistently below 0.30. Thus, while these parameters captured reliable group-level ordering, they explained little of the variance in impression judgments. Participant-level variability dominated these outcomes, indicating that single physical metrics alone are insufficient to account for individual multisensory response.

4. Discussion

4.1. Sensory Difference Between Wooden Materials Perception

The ESEM structural models revealed clear modality differences. The visual condition produced the highest number of significant paths and the greatest dispersion along the emotional judgment axis, whereas the tactile condition yielded fewer paths and tighter clustering, consistent with stronger inter-participant agreement. These patterns may reflect differences in underlying neural processing.

Visual information follows the ventral stream. Retinal signals are transduced and relayed to primary visual cortex V1 where basic features are extracted. Successive processing in extrastriate cortex areas V2, V3 and V4 for low-level features like color and texture, which are then consolidated in inferior temporal (IT) cortex for view-invariant material recognition. IT representations are transmitted through the parahippocampal gyrus (PHG), and perirhinal cortices (PRC) into the hippocampal for episodic memory integration, and into multimodal anterior temporal regions that function as a semantic hub [12].

Because visual processing supports both rapid bottom-up feature extraction and extensive top-down integration with memory and semantic networks, low-level material cues may influence emotional judgment directly or indirectly through memory- and meaning-based impressions. This dual pathway may help explain the richer path structure and greater individual variability in the visual condition, reflecting participant-specific histories, cultural associations and learned preferences.

In contrast, tactile processing of wood is initiated by mechanoreceptors in glabrous skin, including Meissner corpuscles, Merkel discs, Pacinian corpuscles and Ruffini endings, which transduce mechanical stimuli into neural impulses conducted by A β fibers. Signals ascend primarily via the dorsal column medial lemniscus pathway (DCML), relaying through the gracile and cuneate nuclei to the ventral posterolateral thalamus and then to primary somatosensory cortex (S1) where roughness and vibration attributes are extracted.

Parallel projections reach secondary somatosensory cortex (S2) and posterior insula for integrated texture and shape perception, and affective tagging is achieved through further routing to anterior insula, the amygdala and orbitofrontal cortex (OFC). Crude touch and thermal or nociceptive inputs follow the spinothalamic tract (STT) to adjacent thalamic nuclei before reaching cortical targets [11,44,45]. Compared with vision, this stream is considered relatively feedforward and somatically grounded, and may engage high-level semantic and episodic systems to a lesser extent. This may lead tactile judgments to rely more heavily on immediate psychophysical properties, which could contribute to tighter inter-participant agreement, fewer significant structural paths in the ESEM, and effects that are mediated mainly by haptic impressions such as perceived cleanliness and naturalness.

The auditory condition exhibited a distinctive profile. Factor scores along the surface-property varied widely among participants, yet brightness, glossiness, and roughness showed relatively high IPC, larger than 0.4. This indicates that impact sounds provide objective cues about material surfaces, enabling consistent relative rankings even when absolute ratings differ. By contrast, scores on the emotional judgment axis were tightly clustered with low IPC, reflecting uniformly neutral and weakly differentiated preferences.

This pattern is consistent with how material sounds are processed. Wood impacts are encoded in the cochlea, transmitted through brainstem auditory nuclei to the medial geniculate thalamus, and then decomposed in primary auditory cortex (A1) into frequency and decay characteristics. These signals subsequently engage posterior superior temporal regions that integrate information across modalities and can modulate early visual processing. Impact sounds also recruit insular areas linked to tactile perception, supporting cross-modal inference of surface features [46]. This may allow listeners to infer roughness and gloss from sound alone, even without direct touch or vision, although individual variation in rating scale usage. Emotional responses, however, are generally thought to involve stronger engagement of limbic valuation circuits. Although auditory information can reach orbitofrontal and amygdala regions, impact sounds from wood are relatively unfamiliar in everyday life and may lack strong affective associations [47]. This could be related to the relatively neutral and less variable emotional judgments observed.

In summary, the emotional experience of wood in architectural and furniture contexts can be optimized by integrating modality-specific regulatory mechanisms within a multisensory framework. For vision, substantial differences driven by culture and prior experience necessitate user segmentation, with wood color and grain pattern tailored to the preferences of distinct groups. For the young Chinese adult group examined in this study, brighter tones and more uniform grain patterns were associated with higher collective preference, although the relevance of these tendencies for other user groups remains to be investigated. For audition, impact sounds can be used to establish the association with perception and emotion judgement, thereby strengthening evaluations of material quality and affective valence. For touch, the relatively uniform encoding by mechanoreceptors and direct somatosensory projections to limbic regions can be exploited by carefully adjusting surface friction, vibration cues, and pressure feedback to enhance both tactile comfort and positive affective responses. Collectively, the coordinated use of these sensory channels enables a more comprehensive and effective optimization of wood-evoked emotion in built environments.

4.2. Pathways Influencing Emotional Judgments of Wooden Materials

Path analyses using ESEM consistently identified perceived cleanliness and value within the impression layer as the primary mediators linking physical attributes to emotional judgments. Across all sensory conditions the largest indirect effect was mediated by cleanliness, indicating that materials perceived as newer and cleaner were reliably

associated with higher evaluation preference. Naturalness produced significant mediation in some models but its indirect effects were substantially smaller than those of cleanliness.

These findings suggest that high perceived naturalness did not consistently enhance evaluation preference, but was instead modulated by both cultural and individual dispositions. Prior research shows that the same landscape feature can elicit contrasting appraisals across cultures, with natural debris along riverbanks perceived as authentic in many European samples but viewed as signs of neglect and evaluated less favorably by Chinese observers [18]. Individual differences in the need for order, as measured by the Personal Need for Structure (PNS) scale, similarly influence preference. A stronger need for structure predicts favoring clean, well-maintained environments, whereas lower need for structure aligns with greater tolerance for unmanicured scenes [48,49]. Given that cultural tendencies in China such as higher uncertainty avoidance, collectivism, and long-term orientation are associated with stronger preferences for order, Chinese participants generally exhibited higher structure-seeking tendencies than Western participants. Consequently, both cultural and individual factors made cleanliness and perceived value more salient mediators of aesthetic judgment, thereby explaining why tidy, intact surface cues exerted stronger effects than cues of unmaintained naturalness.

Within the mid-level physical layer, roughness functioned as a central cross-modal regulator. It showed a positive indirect effect on emotional judgment by enhancing perceived naturalness, yet simultaneously produced a negative indirect effect when interpreted as a cue of dust accumulation or poor maintenance, reducing perceived cleanliness. Thus, its influence depended on the relative weight assigned to naturalness versus cleanliness within a specific cultural or contextual framework.

Although low thermal conductivity of wood is widely assumed to promote preference by producing a warm tactile sensation, warmth perception exerted no significant direct effect on emotional judgment in any sensory condition. Its influence was limited to a modest indirect pathway via increased naturalness. This likely reflects the restricted variability in thermal conductivity among the tested samples and suggests that warmth perception relates more to physiological comfort and restorative experience than to core aesthetic evaluation, thereby contributing indirectly rather than as a direct determinant of attractiveness.

At the low-level physical layer, perceived surface and internal properties produced significant direct effects on emotional judgment across conditions, yet their indirect effects,—mediated by impression-level attributes, were consistently greater in magnitude. This indicates that low-level physical features influence aesthetic judgment primarily through cognitively and culturally shaped impression mapping rather than through immediate sensory preference, consistent with the classic physical to impression, and then to emotional mediation pathway observed across sensory modalities.

4.3. Sensory Weights in Multisensory Integration

Sensory weight analysis revealed a clear division of labor across modalities in wood perception. Visual input dominated evaluations of surface attributes, higher-order impressions, and emotional judgments, reflecting its superior role in resolving macroscopic material cues. Tactile input carried comparable or greater weight for internal properties and directly felt attributes such as warmth, and roughness. Notably, touch retained substantial influence on higher-level impressions and affective evaluations, underscoring its central role in material experience and occupant comfort. Auditory cues contributed minimally and primarily reinforced perception of surface properties through cross-modal correspondences. In the absence of learned associations, impact sounds did not reliably convey internal properties or support affective appraisal. Although sound has been proposed as a

proxy for thickness or density in virtual environments [35,50,51], its weighting remained low here, highlighting the importance of acquired audio–tactile mappings for effective auditory contribution [43,52].

The observed weighting pattern is consistent with reliability-weighted integration, in which sensory channels that provide more certain information for a given judgment receive greater influence. These findings support a human-centered, multisensory design strategy for wood in buildings. Visual attributes should be tailored to the needs of specific user groups, potentially by adjusting features such as brightness, color contrast, and texture uniformity according to group-related perceptual tendencies. For the young Chinese adults examined here, lighter tones and lower visual contrast were associated with higher preference. Tactile properties should be optimized to support broad comfort, and auditory cues should be incorporated when meaningful associations between sound, emotion, or physical attributes have been established. Through such coordinated multisensory refinement, emotional restoration and wellbeing in wooden environments can be more effectively supported [4,53].

4.4. Mapping Relationships Between Subjective Ratings and Physical Parameters

Correlation and linear mixed-effects analyses consistently showed that vision was driven primarily by surface color and texture, touch by density, audition by impact frequency, and multisensory perception by combined visual–haptic cues. These predictors explained substantial sample-level variance, with between-group R^2 typically exceeding 0.60. However, only L^* for perceived surface qualities and density for perceived internal qualities combined strong group-level explanatory power with meaningful individual-level predictability. For impression and emotional judgments, most physical parameters yielded marginal R^2 below 0.30, and random effects dominated, indicating limited capacity to predict individual ratings due to large variability in baseline perception and semantic interpretation.

Thus, objective physical metrics serve as reliable indicators of low-level attributes and the relative ranking of materials, yet they are insufficient to account for individual aesthetic or affective responses. Accurate, personalized prediction of higher-order impressions requires integrating non-physical determinants such as prior sensory experience, cognitive biases, and cultural semantics.

4.5. Limitations

This study has several limitations. First, the participants were limited to young university students. Therefore, the extent to which the findings can be generalized to other age groups, such as children or older adults—whose sensory functions and cultural backgrounds may differ—remains to be examined.

Second, the wood materials investigated in this study represent a focused subset of commonly used species. Future research could extend the present findings by including a wider range of wood materials, broader age groups, and participants from diverse cultural backgrounds, in order to further strengthen evidence-based strategies for restorative wood design.

Third, the results were obtained under controlled experimental conditions, which may differ from real-life architectural environments. As a result, the generalization of the findings to everyday settings should be made with caution.

In addition, the cultural context discussed in this study was primarily interpreted through comparisons with previous studies conducted in Western populations. This approach does not fully capture the complexity of intercultural design implications. Future

studies involving participants from multiple cultural backgrounds would help to further deepen understanding in this area.

Finally, olfactory stimulation was not included in the present study. Given the importance and complexity of olfactory perception, future research using experimental designs specifically tailored to smell is warranted to provide a more comprehensive understanding of multisensory experience.

5. Conclusions

This study examined how the physical attributes of wood are transformed into perceptual impressions and emotional judgments under controlled unimodal and multisensory conditions. The main findings are as follows:

- (1) Multisensory integration followed a reliability-weighting scheme. Vision dominated most perceptual dimensions, while touch contributed consistently and often exceeded vision in judging internal qualities, roughness, and thermal sensations. Audition exerted minimal influence on perceived internal properties but significantly modulated surface-related impressions such as roughness and gloss. This suggests that sensory cues should be optimized according to their relative reliability in biophilic environmental design, with greater emphasis placed on modalities that more reliably shape perceptual impressions.
- (2) Modalities differed in processing depth and individual variability. Visual processing was the most complex and most influenced by memory, experience and cultural semantics, producing the largest inter-individual differences. Tactile processing was more direct and consistent across participants. Auditory processing produced stable rankings of perceived physical attributes but neutral and highly variable affective responses due to limited emotional associations in daily life. These differences reflect distinct sensory processing characteristics and suggest that visual design primarily shapes symbolic impressions, while tactile qualities play an important role in achieving consistent comfort across user groups.
- (3) Perceived cleanliness was the dominant mediator linking low-level physical perceptions to emotional judgments. Among young Chinese adults, low color difference and uniform texture yielded high cleanliness and strongly enhanced evaluation preference, whereas perceived naturalness had negligible influence. This pattern contrasts with Western findings, where naturalness is often primary, and highlights culturally shaped preferences for order and structural harmony in Chinese aesthetics.
- (4) Physical parameters reliably predicted low-level perceptual dimensions, such as surface and internal qualities, but explained less variance in higher-order impressions and emotional evaluations. Conventional roughness indices also showed limited correspondence with perceived texture. These findings indicate that traditional physical descriptors alone are insufficient for predicting user experience, and that perceptually grounded material descriptors should be incorporated when evaluating and selecting wood for human-centered design.

Together, these findings provide empirical support for the three proposed hypotheses regarding perceptual structure, mediated pathways, and unequal multisensory contributions. For biophilic and human-oriented spaces used by young adults, the results suggest several material selection considerations. Visually, wood material selection may benefit from being tailored to specific user groups; for the young adult sample examined here, brighter tones, lower color contrast, and more uniform texture patterns were associated with stronger perceptions of cleanliness and higher preference. Tactilely, smoother surfaces and a greater sense of solidity may contribute to more consistent comfort-related impressions across users. In contrast, auditory impressions appear to depend more strongly on

contextual meaning, indicating that the perceptual role of material-related sounds may be limited unless supported by clear situational associations. Future research should include older and cross-cultural cohorts and examine dynamic multisensory interactions in real built environments to advance restorative wood-design principles.

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Institutional Review Board Statement: The survey in this paper was non-interventional, anonymous and focused on exploring impulses, attitudes, etc. The research was not conducted on patients, nor did it involve human material or human tissues. All respondents had the right not to participate in the survey and by filling out the questionnaire, they expressed their consent to participate in the research. Ethical clearance from our home institutions is not required for this type of research.

Informed Consent Statement: Informed consent was obtained from all subjects involved in the study.

Data Availability Statement: Some or all of the data, models, or code that support the findings of this study are available from the corresponding author upon reasonable request.

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Appendix A. Sensory and Affective Evaluation Questionnaire

General Instructions

For each material sample, you will be asked to rate your perception using a series of bipolar adjective scales. Please select the position on each scale that best matches your immediate impression. There are no right or wrong answers. All items were rated on a 7-point bipolar scale: -3 = strongly reflecting the adjective on the left; 3 = strongly reflecting the adjective on the right.

A. Visual condition: Based on what you just saw, please rate the material using the following scales.

B. Tactile condition: Based on what you just touched, please rate the material using the following scales.

C. Auditory condition: Based on the sound you just heard, please rate the material using the following scales.

D. Multisensory condition: Based on your overall impression from what you just saw, touched, and heard, please rate the material using the following scales.

| | -3 | -2 | -1 | 0 | 1 | 2 | 3 | |
|-----------------|------|------|------|-----|-----|-----|-----|---------------|
| 1. Low contrast | | | | | | | | High contrast |
| 2. Matte | | | | | | | | Gloss |
| 3. Dark | | | | | | | | Bright |

| | | |
|-----|------------|---------------|
| 4. | Dampened | Ringing |
| 5. | Dull | Sharp |
| 6. | Mixed | Pure |
| 7. | Rough | Smooth |
| 8. | Hard | Soft |
| 9. | Cold | Warm |
| 10. | Dense | Sparse |
| 11. | Dry | Wet |
| 12. | Heavy | Light |
| 13. | Old | New |
| 14. | Ugly | Beautiful |
| 15. | Artificial | Nature |
| 16. | Plain | Sophisticated |
| 17. | Dislike | Like |
| 18. | Cheap | Expensive |
| 19. | Unpleasant | Pleasant |
| 20. | Dirty | Clean |
| 21. | Tense | Relaxed |
| 22. | Common | Rare |

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