

Multimodal Evaluation of Warmth Perception in Wood: An Experimental Study Based on Visual, Tactile, and Visual-Tactile Interactions

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The inherent warmth of wood is widely valued in design applications, yet the mechanisms underlying its perception across different sensory modalities have not been fully explored. The aim of this work was to investigate the physical properties that influence warmth perception of wood across different species and surface treatments, and to clarify the respective contributions of visual and tactile warmth during multisensory integration. In this work, 10 material samples were technically characterized and their perceived warmth was evaluated by participants under three conditions: vision-only, touch-only, or combined visual-tactile interactions. Infrared thermography was used to quantify material temperature changes. Results showed that color dominated warmth perception under the visual assessment, while thermal properties and hand-material interface temperature differences significantly influenced tactile warmth perception. Wood species exhibited substantial effects on warmth perception, whereas surface treatments showed limited impact. Visual-tactile warmth perception was significantly positively correlated with both modalities, predominantly mediated by tactile inputs during direct contact, with visual characteristics providing critical complementary information. These findings advance the understanding of wood's multisensory warmth perception and provide valuable insights for user-centered wood space and product design.

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INTRODUCTION

In daily interactions with materials, human perception relies on the integration of multiple sensory modalities, including vision, touch, hearing, smell, and taste, each contributing to varying degrees (Schifferstein 2006; Krishna 2012; Martín *et al.* 2015). Among these, vision and touch serving as dominant modalities that dynamically refine perceptual outcomes through predictive coding mechanisms (Balaji *et al.* 2011; Kapoor *et al.* 2024). According to this theory, the brain generates predictions of sensory inputs based on prior experiences and optimizes perception through prediction errors (Spratling 2017). When predictions align with inputs, signals are more effectively integrated; significant mismatches trigger model updates to resolve conflicts (Talsma 2015). Critically, the visual-tactile integration produces two distinct effects depending on the perceptual task. When estimating the size or surface roughness of an object, visual-tactile integration results in an averaging effect, biasing the tactile perception toward the visual

estimation (Xiao *et al.* 2016). When estimating the weight or force of an object, visual-tactile integration results in a contrast effect, biasing the tactile perception away from the visual expectation (Brayanov and Smith 2010; Ho *et al.* 2014). These findings break through single sensory mode and highlight the need for empirical validation of multisensory interactions in natural materials to clarify their universality and boundary conditions.

Among natural materials, wood stands out as a compelling example of how visual-tactile interactions can shape human sensory experiences. Its abundance, environmental friendliness, and renewability have made it a preferred material for constructing living spaces and indoor furniture, where its distinctive appearance and texture provide both visual and tactile stimulation, evoking a sense of comfort and relaxation. This unique combination of sensory qualities positively influences human psychology and physiology (Sakuragawa *et al.* 2005; Ikei *et al.* 2017). Studies have predominantly focused on single sensory modalities, such as visual aspects (Fujisaki *et al.* 2015; Manuel *et al.* 2015) or tactile aspects (Lindberg *et al.* 2013; Bhatta *et al.* 2017; Ikei *et al.* 2017). In recent years, there has been a growing interest in multimodal research. For example, Overvliet and Soto-Faraco (2011) explored the role of vision and touch in perceiving naturalness of wood using four psychophysical methods. Their findings revealed consistent results across methods, with both senses strongly correlating with visual-tactile naturalness perception. Fujisaki *et al.* (2015) studied how people perceive wood properties by evaluating vision, touch, and audition separately. They found that emotional responses to wood were similar across all three senses, suggesting a supra-modal representation of these properties. Similarly, Kanaya *et al.* (2016) compared evaluations of wood blocks' brightness, sound sharpness, and smoothness. They found strong positive correlations between touch and sound for all properties, and between vision and touch for two properties. These findings indicated that multisensory correlations were learned through experience, but their strength depended on the specific sensory combinations involved.

The perception of warmth, as a critical material attribute, significantly affects material choices by designers and consumer purchase decisions. Physically, warmth involves tactile and visual perceptions. Tactile warmth is governed by thermal properties such as thermal conductivity and specific heat capacity, which determine heat transfer rates between materials and skin. Visual warmth stems from colors that convey thermal associations, as well as factors such as gloss and surface roughness (Wastiels *et al.* 2012). Physiologically, warmth perception is closely linked to the body's physiological responses. The skin, as the primary sensory organ, detects temperature changes through thermoreceptors located in the epidermis and dermis. These receptors activate when exposed to temperature variations and transmit warmth-related signals *via* sensory neurons to the brain, where they are processed and integrated to form the perception of warmth (Sakuragawa *et al.* 2005). Psychologically, warmth perception intertwines with memories and emotions, such as comfort and intimacy. Thus, warmth is a subjective experience from the integration of multisensory information (Bhatta 2020; Choi *et al.* 2016).

Wood is generally perceived as being warmer than many other building construction materials (Hoibo and Nyrud 2010). Visually, wood reflects long-wavelength light, primarily in yellow to red hues, with more intense reflection in these wavelengths contributing to its warm perception (Sakuragawa *et al.* 2005). Additionally, surface gloss might also influence warmth perception: low-gloss wood creates a warmer impression

through uniform light distribution, reduced glare, and enhanced natural color and texture. In contrast, high-gloss wood, reflecting more light, may evoke colder sensations (Jafarian *et al.* 2018). Furthermore, rough surfaces are generally perceived as warmer than smooth ones (Grüll *et al.* 2012), while the relationship between warmth perception and surface texture requires further exploration. In tactile terms, human skin contact with materials evokes thermal sensations (cold or warm), which depend on the material's temperature state (Bergmann Tiest and Kappers 2008). Tactile warmth is determined by the material's initial temperature, its surface contact thermal efficiency, and its thermal conductivity (Wastiels *et al.* 2012). Several studies have explored the phenomenon of wood tactile warmth more comprehensively from a physical perspective. For instance, Wang *et al.* (2000) found that the maximum temperature decrease of the fingertip was positively related to the natural logarithm of the material's specific gravity and thermal conductivity, while warmth perception exhibited a negative linear relationship with these properties. Similarly, Obata *et al.* (2005) identified a strong positive linear correlation between the tactile warmth of wood and the logarithm of the contact temperature, noting that materials with lower thermal effusivity were perceived as warmer at room temperature. In practical applications, particularly in furniture and interior spaces, wood surfaces rarely remain untreated, coatings such as oil and varnish are commonly used to improve visual quality and functionality (Hayoz *et al.* 2003). Therefore, in addition to the inherent thermal properties of wood, these surface treatments applied to wood may also influence warmth (Ikei *et al.* 2017; 2024).

The perception of warmth in wood represents a complex and multisensory phenomenon, significantly influenced by visual-tactile interaction that affect user experience. This research area holds dual significance. Wood is ubiquitous in architectural spaces and often undergoes modifications *via* coatings. Clarifying the visual-tactile integration can inform sensory-driven surface treatment standards. Academically, as visual-tactile interactions remain an emerging field in experience design, the independent and interactive contributions of these modalities to warmth perception of wood remain unclear. Therefore, investigating the warmth perception of wood through visual and tactile modalities is both timely and essential for advancing multisensory research and optimizing user-centered wood material design and applications.

EXPERIMENTAL

Participants

A total of 54 healthy volunteers participated in the study (24 men and 30 women), aged between 19 to 23 years (mean age=21.4, SD=1.68). All participants had normal or corrected-to-normal vision, normal tactile sensitivity, and no professional expertise in wood-related fields. Written informed consent was obtained from all participants prior to the study. The experiments were conducted in accordance with the principles stated in the 1964 Declaration of Helsinki and posterior amendments.

Materials

Three types of solid wood material were used as test samples: Chinese fir (*Cunninghamia lanceolata* (Lamb.) Hook), white oak (*Quercus alba* L.), and black walnut (*Juglans nigra* L.), representing both softwoods and hardwoods with distinct

properties and visual features, widely used in interiors and furniture. Plain-sawn boards with a dimension of 200 mm × 150 mm × 20 mm (length × width × thickness) were prepared as test samples, ensuring that all samples were free of visible defects. For each species, three surface treatment conditions were prepared: (1) untreated (sanded only with 240-grit sandpaper), (2) oiled (wood wax oil coating), and (3) varnished (polyurethane resin coating). Surface treatments were performed after initial sanding to ensure uniformity. Considering the individual differences of wood, three replicates were prepared for each condition. In addition, aluminum plate of the same dimension was prepared as reference material. The sample IDs are listed in Table 1, and their visual representations are provided in Fig. 1.

Table 1. Materials and Assigned ID Used in the Experiment

Sample No.	Material	Treatment	Sample ID
1	Chinese Fir	untreated	Fu
2	Chinese Fir	oiled	Fo
3	Chinese Fir	varnished	Fv
4	White Oak	untreated	Ou
5	White Oak	oiled	Oo
6	White Oak	varnished	Ov
7	Black Walnut	untreated	Wu
8	Black Walnut	oiled	Wo
9	Black Walnut	varnished	Wv
10	Aluminum	-	Al



Fig. 1. Material samples

Design and Procedure

Participants were asked to evaluate ten samples under three conditions: vision-only (VIS), touch-only (TAC), or a combination of vision and touch (GEN). To avoid potential bias from prior exposure to the samples, a between-subjects design was employed. Each condition was randomly assigned to 18 participants (8 men and 10 women).

All samples were prepared and stored in the workshop for two months to eliminate any material or treatment-related odors. The experiment was carried out in an air-conditioned laboratory environment during winter, utilizing a combination of natural and artificial diffuse lighting. The room temperature was maintained at 23.0 ± 0.5 °C, with an average relative humidity of $42.5 \pm 7.5\%$. Prior to testing, the wood samples were

conditioned in the laboratory environment for at least 24 hours to ensure stability.

After arriving to the laboratory, participants rested for a moment to relax and adjust to the indoor temperature of the room, the experiment commenced only after their hand temperature stabilized at 35.0 ± 0.3 °C. During the experiment, the participants sat in an adjustable chair and wore headphones to eliminate potential acoustic cues. The reference material (aluminum) was consistently tested first to establish a baseline, followed by randomized wood samples. Each sample was exposed for 15 seconds, with a 10-second inter-stimulus interval between trials to mitigate potential carryover effects. For the vision-only experiment, participants viewed the sample from a distance of approximately 50 cm at a 45° angle. For the touch-only experiment, a custom-designed white box with a 13 cm × 9 cm rectangular opening was used. Participants inserted their left hand to touch samples without visual access, while the experimenter placed each sample through an opening at the back (Fig. 2). During the vision-touch experiment, participants could freely observe and touch the samples while simultaneous infrared thermography testing was conducted. In each of the three conditions, participants were asked to complete a subjective questionnaire evaluation on the computer.

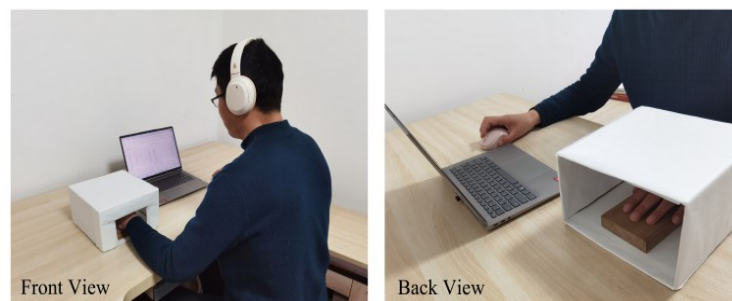


Fig. 2. Touch-only experiment

Experiments

Measurements of physical material properties

Several technical parameters potentially influencing material warmth perception were measured, including thermal properties, surface characteristics, and color metrics. The thermal conductivity λ was measured using a thermal conductivity analyzer (TPS 2500S, Hot Disk, Sweden) in accordance with the standard GB/T 32064-2015. The heat flux was measured using a heat flux meter (TNL3500, TINEL, China) attached to the palm during contact with the material. Upon contact, the heat flux increased sharply, peaked at a maximum value $q_{\max}$, and then gradually decreased. The material thermal property coefficients λ and $q_{\max}$ are excellent indicators for predicting warmth during contact (Wang *et al.* 2000, 2001).

The surface profile was measured using a portable surface roughness tester (NR200, TIMES, China). For each sample, the arithmetical mean roughness R_a and root-mean-square roughness R_q were calculated by averaging measurements from five locations. R_a represents the average height of surface irregularities, while R_q reflects the root-mean-square average of height deviations. Both parameters are effective for identifying variations in surface profile height (Wastiels *et al.* 2012; Sousa *et al.* 2022). Gloss describes the amount of light reflected by a surface and is represented on a scale from 0 to 100 gloss units. Following the standard GB/T 4893.6-85, the gloss of the wood surface was measured at five points using a gloss meter (MN268, Qili, China) with a 60° specular reflection geometry. The gloss values were recorded as longitudinal gloss G_{ZL}

and tangential gloss *GZT*. The color values were measured using a colorimeter (NR200, 3nh, China) based on the CIELAB color system, where L^* denotes lightness, a^* represents the red-green axis, and b^* indicates the yellow-blue axis. For each sample, color measurements were taken at five points to account for surface color variations.

Infrared thermography test

To evaluate the temperature changes of wood samples before and after touching, infrared thermography was used. This has been shown to be a validated method for surface temperature assessment in furniture studies (Sales *et al.* 2017). This non-contact, non-invasive technique has proven reliable for skin surface temperature measurement (Roy *et al.* 2006). Measurements were conducted using a FLIR E4 thermal camera (USA) with 80×60 pixel resolution, ± 2 °C accuracy, and <0.15 °C thermal sensitivity. The emissivity of human skin was set to 0.98, as recommended in the manufacturer manual. The camera was positioned 0.5m above and perpendicular to the table surface to ensure measurement accuracy.

Prior to the participants being seated, the initial surface temperature of the wood samples was recorded using the thermal camera. Subsequently, participants maintained consistent hand contact with the samples for 10 seconds. Using a short contact duration has the potential to prevent sensory adaptation, as prolonged touch causes the skin to act as a continuous heat source, reducing thermal discrimination and increasing the likelihood of adaptation (Bhatta *et al.* 2020; Wang *et al.* 2001). Immediately after the participants removed their hands from the samples, the surface temperature was measured again. The average surface temperature of the samples recorded before contact served as the pre-stage temperature, while the post-stage temperature was calculated as the average of five points taken from the fingers and palm imprints left on the sample surface after contact (Fig. 3). All thermographic images were analyzed using FLIR Thermal Studio software.

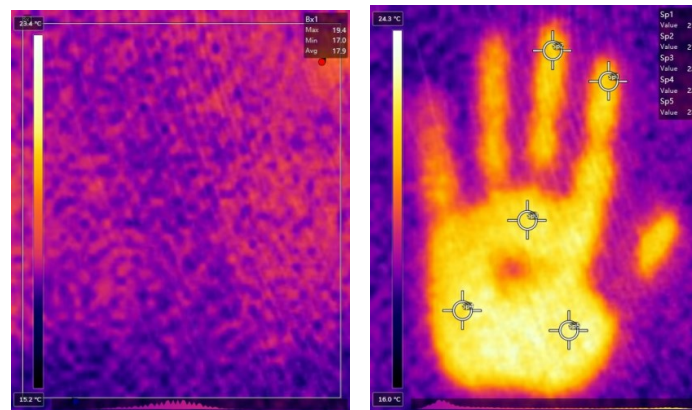


Fig. 3. Thermal images at the pre-stage (left) and post-stage (right)

Questionnaire evaluation

Questionnaire evaluation scoring was conducted using the Semantic Differential (SD) scale, a method effective for quantifying subjective impressions and assessing perceptions of objects through multiple pairs of Kansei adjectives with opposing meanings (Llinares and Page 2007). For each sample, participants were asked to evaluate the perceived warmth by the questions: “I think building or furniture covered with this material is [cold—warm]”. To conceal the purpose of the test, the adjective pairs were

presented together with six other word pairs, such as soft–hard and cheap–expensive, which were not analyzed further. The questionnaire employed a 7-point Likert scale ranging from –3 to +3, grade 1. For example, “cold–warm”, extremely cold: –3, moderately cold: –2, slightly cold: –1, neither: 0, slightly warm: 1, moderately warm: 2, extremely warm: 3.

Data Analysis

The experimental data were analyzed using Pearson correlation and ANOVA to assess warmth perception across visual (VIS), tactile (TAC), and visual-tactile (GEN) conditions. The physical properties of the materials were measured and correlated with subjective warmth ratings. Two-way ANOVA examined wood type and surface treatment effects, while regression analysis modeled visual-tactile warmth perception. Data analysis was conducted using SPSS 26, and all graphs were plotted using OriginPro 2024.

RESULTS AND DISCUSSION

Physical Properties of Materials

Thermal properties are summarized in Table 2 and Fig. 4a. Aluminum exhibited significantly higher thermal conductivity and heat flux than wood samples, highlighting inherent metal-wood differences. Meanwhile, the three wood types showed similar thermal conductivity, around 0.2 W/mK. However, their heat flux varied considerably: fir ranged from 112 to 120, whereas oak and walnut showed values between 140 and 157. These variations primarily stemmed from species characteristics such as density, moisture content, and chemical composition (Strobel *et al.* 2017), with surface treatments showing minimal impact. Similar findings were reported for Japanese cypress and oak, where species differences outweighed coating effects (Tsunetsugu and Sugiyama 2021).

Surface characteristics analysis (Fig. 4b-c) revealed an inverse correlation between surface roughness and gloss. Aluminum had the lowest roughness and most glossy surface. Among the wood samples, untreated wood surfaces were the roughest and least glossy, while varnished surfaces were the smoothest and glossiest. Oiled surfaces fell in between. The results showed that surface treatment, especially varnishing, greatly affected roughness and glossiness. Generally, differences in wood species had little impact on these properties. However, in the case of oil-treated wood, fir demonstrated notably higher roughness and lower glossiness compared to oak and walnut. This may be due to the fact that the larger vessel structures of hardwood facilitate better oil penetration and smoother surfaces (Chen 2021).

Chromaticity measurements (Fig. 4d) showed significant interspecies variations. For untreated wood, fir was lightest, followed by oak, with walnut darkest. In terms of a^* and b^* values, fir and oak showed no significant differences, whereas walnut exhibited slightly lower a^* and b^* values, indicating a shift toward blue-green tones. After surface treatment, the lightness L^* of all three wood species decreased significantly. The L^* value reduction ranged from 7.5% to 15.76% for oiled wood and from 10.13% to 16.36% for varnished wood, with varnish treatment showing a greater reduction than oil treatment. Additionally, the a^* and b^* values of treated wood increased, suggesting a shift toward red and yellow tones, resulting in a warmer overall hue. Aluminum's chromaticity resembled untreated fir but with more yellow tone.

Table 2. Material Properties of 10 Samples

			Fu	Fo	Fv	Ou	Oo	Ov	Wu	Wo	Wv	Al
Thermal measures	Thermal Conductivity λ	[W/mK]	0.147	0.146	0.142	0.271	0.256	0.254	0.204	0.214	0.208	178
	Maximum heat flux $q_{\max}$	[W/m ²]	114.3	112.9	119.5	156.3	150.1	154.2	140.8	153.2	152.7	269.7
Surface measures	Average roughness R_a	[μm]	3.633	3.191	0.907	3.416	2.767	1.223	3.589	2.054	0.641	0.238
	Mean square roughness R_q	[μm]	4.540	4.057	1.082	4.437	3.586	1.543	4.440	2.740	0.800	0.349
	Longitudinal Gloss G_{ZL}	[%]	5.1	8.7	17.8	3.1	14.2	15.2	3.3	15.6	17.0	4.2
	Tangential Gloss G_{ZT}	[%]	3.3	5.5	18.4	2.6	7.9	15.3	2.5	9.7	14.2	4.2
Color measures	Lightness L^*	[-]	70.47	64.67	63.33	61.90	57.26	53.64	53.56	45.12	44.80	69.85
	Red-Green value a^*	[-]	11.16	13.71	13.92	10.94	12.87	14.68	8.88	10.18	10.13	4.37
	Yellow-Blue value b^*	[-]	21.69	28.95	26.65	20.23	23.71	24.40	15.12	14.28	15.08	33.45

Table 3. Temperatures of Pre-stage and Post-stage

	Pre-stage			Post-Stage			Temperature different (°C)	p
	Mean		95% CI	Mean		95% CI		
Fu	23.32	0.62	(23.03, 23.61)	31.81	0.73	(31.47, 32.15)	8.49	0.000
Fo	23.22	0.66	(22.90, 23.53)	32.02	0.74	(31.68, 32.36)	8.80	0.000
Fv	23.50	0.74	(23.15, 23.84)	32.83	0.87	(32.42, 33.23)	9.33	0.000
Ou	23.40	0.61	(23.07, 23.64)	30.96	1.02	(30.51, 31.41)	7.60	0.000
Oo	23.25	0.53	(23.00, 23.50)	30.86	0.98	(30.42, 31.30)	7.61	0.000
Ov	23.56	0.68	(23.24, 23.87)	30.35	0.95	(29.90, 30.79)	6.79	0.000
Wu	23.42	0.62	(23.13, 23.71)	31.42	0.93	(30.98, 31.85)	8.00	0.000
Wo	23.38	0.47	(23.16, 23.60)	31.30	0.88	(30.89, 31.71)	7.92	0.000
Wv	23.31	0.69	(22.98, 23.65)	31.33	0.91	(30.90, 31.75)	8.02	0.000
Al	23.13	0.03	(22.81, 23.44)	23.21	0.47	(23.17, 23.43)	0.08	0.602

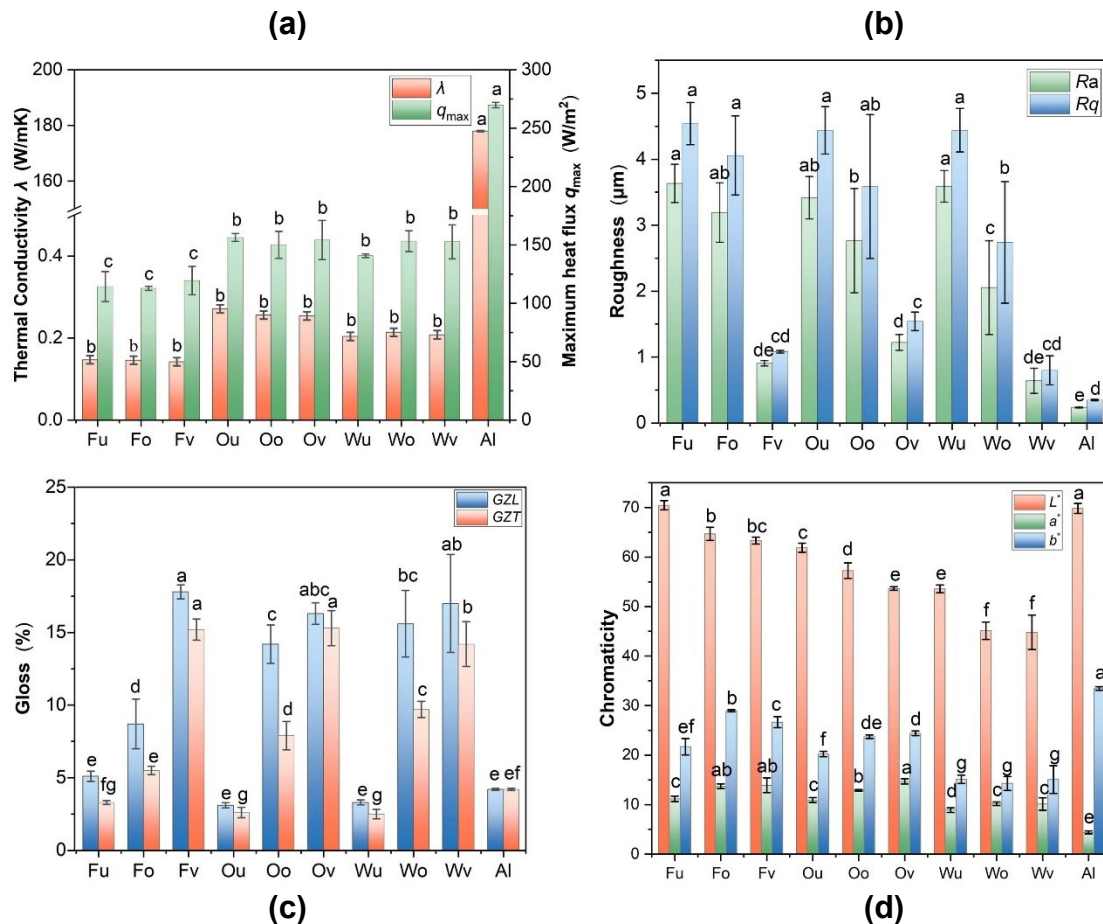


Fig. 4. Material properties and significance plots. (a) Thermal properties; (b) roughness; (c) gloss; (d) chromaticity

Infrared Thermography Measurement

The temperatures during the pre-stage and post-stage are presented in Table 3. In the pre-stage, no statistically significant differences were observed in the surface temperatures of the samples, with mean temperature ranging between 23 and 24 °C. This result was anticipated, as the samples had been stored at room temperature for over 24 h prior to the measurements, allowing their surface temperature to stabilize with the ambient temperature.

In the post-stage, the surface temperatures of all wood samples exceeded that of the reference material aluminum. The temperature distribution of wood is visually displayed in Fig. 5. Among the three types of wood, oak generally exhibited lower temperatures compared to the others, with varnished oak having the lowest temperature (mean = 30.35 °C, 95% CI = 29.90 °C to 30.79 °C). In contrast, fir showed higher temperatures than the other two types, with varnished fir recording the highest temperature (mean = 32.83 °C, 95% CI = 32.42 °C to 33.23 °C). This may be due to differences in wood species. Softwood fir has lower thermal conductivity, so it warms up more easily when touched, while oak has higher thermal conductivity, allowing heat to transfer or dissipate faster.

The hand-material interface temperature difference (Δt) for each sample was calculated by subtracting the mean temperature of the pre-stage from that of the post-stage, and the results are presented in Table 3. All wood types exhibited significant

differences, whereas aluminum showed no significant change between the two stages. The overall temperature differences for the wood samples ranged between 7.6 and 9.4 °C. Fir demonstrated the largest surface temperature change, oak showed the smallest, and walnut fell between the two. When comparing the surface treatment to the untreated, minor variations in temperature differences were observed, but no significant overall change was detected. The experimental findings corroborated existing literature on material thermal characterization. Notably, Loredan *et al.* (2022) employed infrared thermography to analyze temperature changes in different desktops during contact, demonstrating consistency with the present study. The temperature differentials, which corresponding to fundamental thermal properties of the materials, confirmed infrared thermography as a reliable technique for quantitative heat transfer analysis in hand-wood interface.

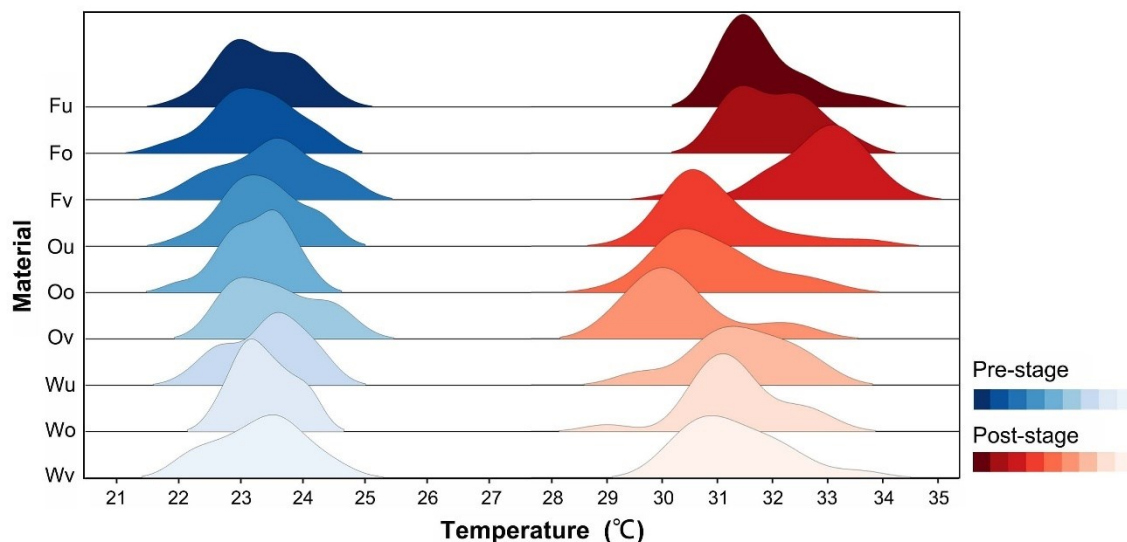


Fig. 5. Temperature distribution of wood during pre-stage and post-stage

Subjective Assessments

A comparative analysis of warmth perception across ten materials was conducted under varying sensory conditions to examine multisensory influences. A two-way ANOVA with Material (Fu, Fo, Fv, Ou, Oo, Ov, Wu, Wo, Wv, Al) and Condition (GEN, VIS, TAC) as factors revealed significant main effects of Material [$F(9,510)=151.4$, $p < 0.001$] and Condition [$F(2,510)=115.787$, $p < 0.001$], along with a significant Material $\times$ Condition interaction [$F(18,510)=8.058$, $p < 0.001$]. These results suggested that both the type of material and the test condition significantly influence warm perception, and the effect of material varies depending on the condition.

The mean warm ratings of all samples under different conditions are depicted in Fig. 6. In the visual-only condition, except for oiled and varnished walnut, the warm ratings of all other materials were positive. Among them, Chinese fir had the highest the warm rating (1.22 to 1.39), followed by oak (0.61 to 0.83), untreated walnut (0.44), and aluminum (0.28), while surface-treated walnut had the lowest ratings (-0.39 to -0.67). In the tactile-only condition, aluminum (-1.91) was the coldest of the materials. Among the wood samples, only Chinese fir had a positive value, the others had negative values, with varnished oak (-1.56) being the lowest. In the visual-tactile interaction condition, the

warmth ratings of all materials, except for oiled and varnished walnut, significantly increased compared to the tactile-only condition, indicating that the addition of visual perception positively influenced people's perception of warmth. This multimodal perceptual interaction indicates that visual information plays a significant role in the perception of warmth. The warmth conveyed by the color and texture of wood was often intertwined with emotional associations, evoking memories of safety, comfort, and a sense of belonging (Strobel *et al.* 2017; Sousa *et al.* 2022). For oil-treated and varnished walnut, there was no significant difference in warmth perception across the three conditions. This could be attributed to the surface treatment darkening the color of walnut, as excessive darkness may negatively impact perceived warmth (Wastiels *et al.* 2012; Zhang *et al.* 2024).

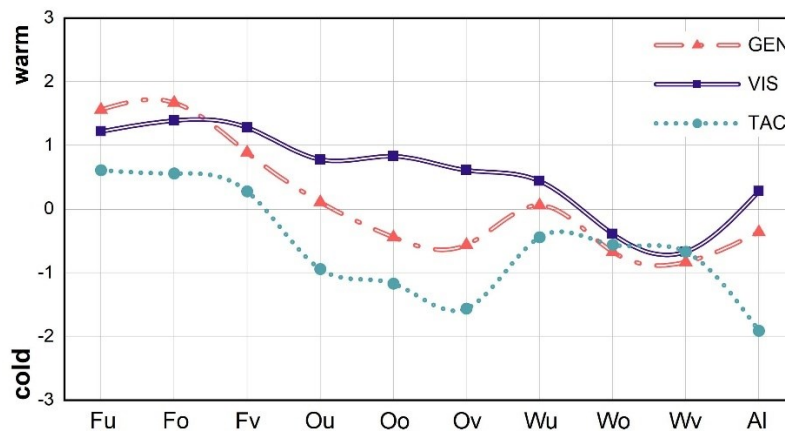


Fig. 6. Plots of the mean ratings to the variable 'warm-cold' for the materials according to the different test conditions (GEN, VIS, TAC)

Wood Type and Surface Treatment

The ANOVA results demonstrated significant variations in warmth perception across the three experimental conditions (VIS, TAC, GEN) concerning different surface treatment methods (untreated, oiled, varnished) applied to three wood species (Chinese fir, white oak, black walnut). As presented in Table 4, wood type exerted a highly significant effect on warmth perception across all experimental conditions ($p < 0.001$). Surface treatment also showed significant effects, though the significance levels varied among conditions: $p < 0.01$ for VIS, $p < 0.05$ for TAC, and $p < 0.001$ for GEN. Notably, a significant interaction between wood type and surface treatment was observed exclusively in the visual condition ($p < 0.01$), while no significant interactions were detected in either tactile or visual-tactile conditions. Thus, in these two conditions, the effect of surface treatment on warmth perception was independent of the type of wood, and vice versa.

Table 4. Significant Differences for the Wood Type and Surface Treatment in the Warmth Perception

Conditions	Warm-Cold		
	VIS	TAC	GEN
Wood Type	F=68.256	F=64.028	F=87.401
	p<0.001	p<0.001	p<0.001
Surface Treatment	F=4.925	F=3.406	F=11.535
	p<0.01	p<0.05	p<0.001
Wood Type×Surface Treatment	4.559	0.323	1.623
	p<0.01	n.s.	n.s.

Note: n.s. denotes no significant differences.

As illustrated in Fig. 7, significant differences in warmth perception were observed among the three wood species. Under visual conditions, fir had the highest warmth perception, while walnut had the lowest. In the tactile condition, fir also showed the highest warmth perception, with oak being the lowest. Under visual-tactile interaction, fir significantly surpassed oak and walnut, which had lower warmth perception and no significant difference between them. These results aligned with previous studies, indicating that despite minor differences in material properties, there were notable variations in warmth perception among different wood species (Tsunetsugu and Sugiyama 2021).

Regarding surface treatment, untreated wood consistently exhibited the highest warmth perception, followed by oiled wood, with varnished wood ranking lowest. Bhatta *et al.* (2020) conducted a tactile paired-comparison experiments on untreated and modified pine, yielding similar results. The observed trends aligned with the established notion that rough surfaces generally elicit warmer perceptions than smooth surfaces. This phenomenon can be attributed to the microstructure of rough surfaces, which reduces the effective contact area with the skin, thereby lowering the heat transfer rate (Grüll *et al.* 2012). In both visual and visual-tactile conditions, significant differences were observed between untreated and varnished wood ($p < 0.001$), with oiled wood also differing from the others ($p < 0.05$). In the tactile condition, untreated and oiled wood differed from varnished wood ($p < 0.05$), but no significant differences were found between untreated and oiled wood. This similarity can be attributed to their physical properties, such as surface roughness and heat flux, with oiled wood retaining a texture closer to that of untreated, natural wood (Ikei *et al.* 2017).

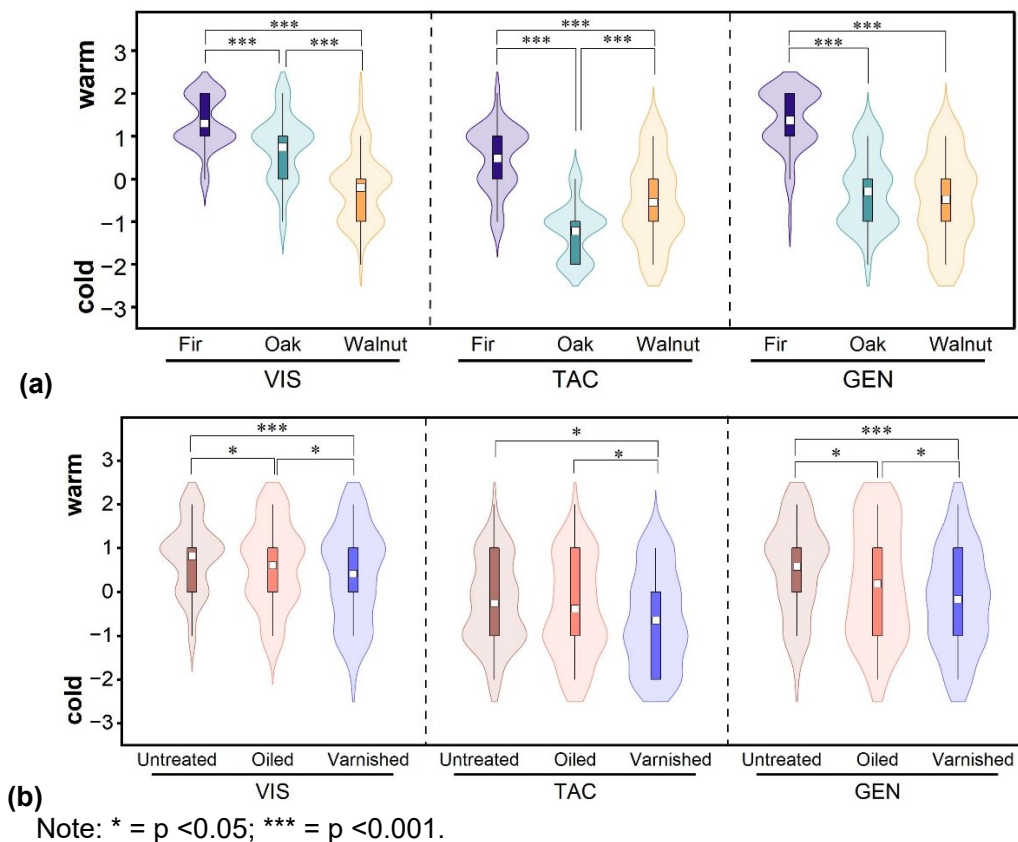


Fig. 7. Significant differences in warmth perception among wood type and surface treatment in test conditions (VIS, TAC, GEN). (a) wood type; (b) surface treatment

Relationship between Physical Properties and Warmth Perception

The Pearson correlation analysis results between physical properties and warmth perception under different conditions (VIS, TAC, and GEN) are shown in Fig. 8. Among thermal properties, the highest correlation was observed for maximum heat flux $q_{\max}$ across all three conditions. Despite the fact that heat flux varied, $q_{\max}$ was an important indicator for assessing the warmth perception of materials during contact (Shitara *et al.* 2017). Interestingly, visual warmth perception showed a significant negative correlation with $q_{\max}$, which was likely because materials with high heat flux, such as metals, tend to evoke a cooler visual impression. Under conditions involving tactile interaction, thermal conductivity λ exhibited a significant negative correlation with warmth perception. Materials with higher thermal conductivity were associated with greater heat flux, which, according to a logarithmic relationship, resulted in a perception of colder temperatures (Obata *et al.* 2002; Wongsriruksa *et al.* 2012). Conversely, the temperature difference Δt at the hand-material interface showed a significant positive correlation. This finding contrasts with Wang *et al.* 2000, who reported that a larger temperature difference resulted in a perception of the material being colder. This discrepancy may stem from differences in the measurement objects at the hand-material interface. When the hand contacts the material, heat transfers from the warmer hand to the cooler material. A smaller temperature difference in the material suggests better thermal conductivity, enabling rapid heat absorption or release and causing more noticeable temperature changes in the hand. Thus, tactile warmth perception could be evaluated by both the basic

thermal properties of the material and the temperature difference at the hand-material interface.

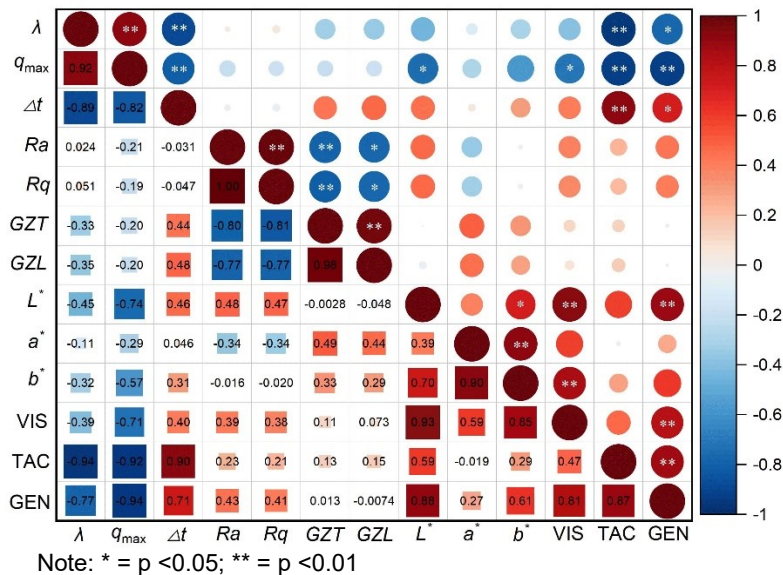


Fig. 8. Pearson correlation heatmap between physical properties and warmth perception

For surface properties, the correlation heatmap indicated positive correlations between roughness, glossiness, and warmth perception. Although these correlations did not reach statistical significance, they may still contribute to an enhanced psychological perception of warmth. Prior studies have demonstrated that locally rough surfaces were perceived as warmer than smooth surfaces, while glossy surfaces tended to create a cooler impression compared to textured materials (Briand Decré and Cloonan 2019; Jin and Li 2023).

For the color properties, under visual condition, a strong positive correlation was found between warmth perception and both lightness L^* and yellow-blue value b^* . In the visual-tactile interaction condition, L^* showed a significant positive correlation with warmth perception. These findings align with previous research indicating that light wood was considered warm and comfortable, whereas dark wood was considered depressing and closed (Kanaya *et al.* 2016; Poirier *et al.* 2019). Furthermore, when participants were given a choice of spatial color, they consistently preferred brighter colors, irrespective of hue (Hidayetoglu *et al.* 2012). Meanwhile, in the presence of visual engagement, changes in color exerted a greater impact on warmth perception compared to other visual elements (Zhu *et al.* 2023). Therefore, the warmth of wood was composed of both the tactile warmth formed by its thermal properties and the visual warmth driven by its brightness.

Visual and Tactile Contributions to Warmth Perception

As shown in Fig. 8, visual-tactile warmth (GEN) was significantly positively correlated with both visual warmth (VIS) and tactile warmth (TAC). A regression analysis was performed with VIS and TAC as the predictor variables and GEN as the dependent variable. As shown in Table 5, the model explained 96.5% of the variance in GEN ($R^2=0.965$) and was highly significant ($F=83.714$, $p<0.001$). Both VIS and TAC were

significant predictors of GEN ($p < 0.001$), with the regression model formulated as: $GEN = 0.692VIS + 0.776TAC$. The results indicated that tactile warmth perception had a stronger influence on visual-tactile warmth perception compared to visual warmth perception. This aligns with the modality appropriateness hypothesis, which suggests that the brain prioritizes sensory information from the modality that is most appropriate for the task at hand. In cases of multiple sensory stimuli, the sense with higher precision tends to dominate perception (Ward 1994). In the context of warmth perception, tactile information is inherently more direct and reliable for assessing thermal properties, while visual cues provide additional context. Thus, the greater influence of TAC on GEN supports the hypothesis that tactile information is more appropriate and influential in warmth perception.

Table 5. Regression Analysis Between VIS, TAC and GEN

Model	Unstandardized Coefficients	Standardized Coefficients	t	p	Collinearity Statistics	
	B	β			tolerance	VIF
(constant)	0.112		0.930	0.388		
VIS	0.692	0.522	6.084	0.001	0.782	1.278
TAC	0.776	0.624	7.263	0.000	0.782	1.278
R^2	0.965					
F	$F = 83.714, p < 0.001$					
D-W	1.905					

In multimodal perception, the involvement of each modality is different. Several studies have compared the involvement of vision and touch in multimodal sensory perceptions using different stimuli. Wastiels *et al.* (2011) compared warmth perceptions of indoor wall materials under different modality conditions, including vision alone, touch alone, and vision and touch in combination. They found that overall warmth perceptions (*i.e.*, for the vision and touch condition) corresponded to visual perceptions, whereas touch tended to be disregarded. However, with the broader literature on multisensory integration, where tactile inputs often played an important role in certain perceptual evaluations. Fenko *et al.* (2010) compared the experience of warmth for two products (scarves and breakfast trays) of different colors and materials, and found that both tactual properties and visual properties contributed equally to the judgment of warmth for both products. Shitara *et al.* (2017) investigated the visual and tactile impressions of wood, revealing that emotional evaluations, such as comfort and preference, were strongly influenced by visual perception. In contrast, evaluations related to sensory evaluation with touch, including warmth-coldness and roughness-smoothness, were largely reflective of tactile influences in the visual-tactile ratings. These findings collectively demonstrated that the warmth perception of wood emerges from multisensory integration, predominantly mediated by tactile inputs through its characteristic low thermal conductivity and surface treatment during direct contact, while visual aspect, particularly warm tone, provide critical complementary information. This sensory hierarchy, characterized by tactile primacy and visual modulation, not only corroborates the modality appropriateness principle in multisensory processing but also offers valuable insights for wood material design and thermal comfort optimization.

CONCLUSIONS

1. Under visual conditions, color parameters demonstrated a significant positive correlation with warmth perception, with lighter wood colors being perceived as warmer. Color emerged as the dominant factor in visual warmth perception, outweighing other visual attributes such as glossiness and roughness. Under tactile conditions, thermal conductivity (λ) and maximum heat flux ($q_{\max}$) showed a significant negative correlation with warmth perception, indicating that materials with higher thermal conductivity were perceived as colder. Additionally, the temperature change (Δt) of wood upon contact with human skin exhibited a positive correlation with warmth perception, suggesting that greater temperature changes enhanced warmth perception. The thermal properties of materials and the human-material thermal interaction provided robust evidence for tactile warmth perception.
2. Significant variations in warmth perception were observed across different wood species. Softwoods (e.g., Chinese fir) were consistently perceived as warmer than hardwoods (e.g., white oak and black walnut) under both visual condition and tactile condition. In the visual-tactile interactions, Chinese fir exhibited the highest warmth perception, while black walnut scored the lowest. Surface treatments also significantly influenced warmth perception. Untreated wood was perceived as the warmest, followed by oil-treated wood, with varnished wood ranking the lowest. Overall, wood species had a greater impact on warmth perception than surface treatments.
3. Visual-tactile warmth perception (GEN) was significantly positively correlated with both visual warmth (VIS) and tactile warmth (TAC). The overall warmth of wood was a combination of tactile warmth, determined by its thermal properties, and visual warmth, driven by its brightness. Tactile warmth perception exerted a stronger influence on visual-tactile warmth perception. The inclusion of visual input enhanced the perception of material warmth, serving as a crucial complementary factor in warmth perception.
4. The findings provide practical guidance for furniture and interior design. Visually, selecting lighter colored woods helps create warmer spaces. Tactually, for frequently touched furniture parts such as chair armrests and tabletops, using low-thermal-conductivity wood can enhance warmth. Untreated or oil-treated wood is preferable in designs aiming for warm atmospheres. Designers should weigh visual and tactile factors, focusing more on tactile warmth, to craft pleasing warm environments.

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