Effect of Changes in Surface Visual Properties of Heat-treated Wood on the Psychological Preference

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Heat treatment of wood is an attractive, environmentally friendly modification, which can change surface visual properties of wood including color and grain, but it is unclear how heat-treated wood is perceived and evaluated compared with untreated wood. In this paper, Chinese fir was heat-treated at 160, 180, 200, or 220 °C for 2 or 4 h. The changes of wood surface color and grain contrast were measured. A subjective questionnaire and eye-tracking technology were used for psychological evaluation. The results showed that changes in the visual properties of heat-treated wood had a significant effect on psychological preference—heat-treated wood was generally more preferred than the untreated, particularly at 200 °C for 4 h. Grain contrast and hue played an important role in the preference for heat-treated wood. The preference gave people the positive psychological impression of warmth, weight, cost, prevalence, and comfort. Eye-tracking analysis showed that Chinese fir heat-treated at about 200 °C with high hue value and clear grain contrast was easier to gain more visual attention. The results would have a high technical reference value for the heat-treated wood in product visual design.

DOI: 10.15376/biores.19.3.4652-4669

Keywords: Heat-treated wood; Color; Grain contrast; Preference; Eye-tracking

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INTRODUCTION

As an aesthetically highly appreciated material, wood has been widely used in the field of construction, furniture, as well as interior and exterior decoration design (Manuel *et al*. 2015). The unique color, grain, and other appearance properties of wood cause the visual stimulation from human eyes, create a warm and gentle visual sense and a comfortable and relaxed state of mind, which has a positive impact on human psychology and physiology (Sakuragawa *et al.* 2005; Rice *et al*. 2006; Ikei *et al.* 2017; Jalilzadehazhari and Johansson 2019; Lipovac and Burnard 2021; Ojala *et al*. 2023). Nowadays, product design is increasingly focused on meeting consumer psychological preferences and emotional needs (McDonagh-Philp and Lebbon 2000; Hekkert 2006). The visual properties of materials have a significant influence on the product design process, and they play an important role in consumer acceptance and decision-making (Bumgardner *et al*. 2007; Artacho-Ramírez *et al*. 2008; Zhu *et al.* 2023). Therefore, exploring visual perception and evaluation of wood could meaningfully improve the use of wood in product design.

Modified wood has undergone treatment to improve its mechanical related properties (Sandberg *et al.* 2017). At the same time, modification processes change material properties directly available to human senses (Esteves and Pereira 2009). Heat treatment is a mature and environmentally friendly physical processing technology for modifying wood properties, which can improve dimensional stability, natural durability, and aesthetic qualities including color and grain effects (He *et al*. 2019). It can be utilized to create a variety of products, and particularly suited for exterior products, due to its high performance in outdoor applications and aesthetic characteristics (Gamache and Espinoza 2017). Thus, evaluating surface visual properties of heat-treated wood would be crucial and valuable for the wood product industry.

Researchers have carried out excellent studies evaluating the visual effect of wood. People's visual evaluations of wood surfaces are closely related to the physical properties of wood, such as color, grain, and knot count (Nakamura and Kondo 2008; Nyrud and Bringlimark 2010; Fujisaki *et al*. 2015; Manuel *et al*. 2015). For example, Broman (2001) concluded that the opinions of his respondents on knotty wood surfaces were influenced by a balance between the degree of harmony and activity of the surface with knots. Nyrud *et al*. (2008) found that consumers preferred wood surfaces with a homogeneous visual appearance and moderate color intensity. Høibø and Nyrud (2010) found that the harmony of wood surface was influenced by both wood properties and treatment. Wood qualities with few knots and an even knot structure should be preferred for visual products, and it is equally important to avoid production defects. From a preference study of Malagasy consumers, Ramananantoandro *et al*. (2013) concluded that consumers generally liked slightly dark wood color, tending towards yellow, with a visible oriented texture. Additionally, the discrepancy in national and cultural background might lead to different views towards wood. Peterson *et al*. (2019) discovered that Swedish people favored wood with a grain or knot because these visual elements conveyed a sense of harmony and activity, while the Japanese preferred a homogeneous appearance in line with their fondness of "purity."

There are a few studies concentrating on treated wood. Most of them explored people's attitudes towards preservative-treated wood. Fell *et al*. (2006) explored consumer perceptions regarding residential decking materials; they concluded that consumers had become more negative towards treated wood and more positive towards wood-plastic composites over two time periods, 2000 and 2003. For the heat-treated wood, Gamache and Espinoza (2017) compared naturally durable softwood, wood-plastic composite, pressure treated lumber, tropical hardwood, and heat-treated ash and aspen. They concluded that heat-treated wood was perceived as having better environmental performance, better aesthetics, and higher durability. Lipovac *et al.* (2019) researched the evaluation of modified wood by older adults from Slovenia and Norway. They found that wooden handrails were generally favored over the steel sample, whereas preference ratings and rankings of wood that had been thermally and chemically treated were similar to those of untreated wood. However, most of the previous studies were based on subjective evaluation or did not take the wood surface properties into account. Thus, the effects of changes in visual properties of heat-treated wood on human psychological preference has not been fully investigated.

To improve the accuracy of the evaluation results, eye tracking technology has been gradually applied to the visual psychology (Bendall *et al.* 2019), which focuses on the human eye through image processing technology, records the eye movement, and extracts physiological data indexes to evaluate psychological activities (Mele and Federici 2012;

Rahal and Fiedler 2019). By such means, it provides an in-depth understanding of psychological cognitive processing mechanism and enhances the reliability of the study. The combination of implicit eye movement data and explicit subjective evaluation results can improve the scientific character and objectivity of the evaluation (Yu *et al*. 2021; Huang *et al*. 2024). Relevant scholars have applied eye-tracking technology to research the visual stimulation of wood. Nakamura and Kondo (2008) recorded eye-tracking data from 20 subjects and composed the distribution maps of eye-fixation pauses, objectively quantified the visual inducement of knots. Kato and Nakamura (2016) measured eye movements of observers viewing videos of the gloss transition regarding fiddleback figures, elucidated that grain contrast played an important role in visual attractiveness. These findings provided a basis for studying the psychological preference of heat-treated wood.

The aims of this study were to analyze and quantify the visual properties and psychological preference concerning heat-treated wood, as well as to investigate the relationship between visual properties and psychological preference. The visual properties of heat-treated wood including color and grain contrast were measured, subjective evaluation scoring was performed by the semantic differential scale, the eye-tracking technology was used to capture objective physiological data from participants. The results of the study can assist the high-value and efficient utilization of heat-treated wood in living environment.

EXPERIMENTAL

Materials

Chinese fir (*Cunninghamia lanceolata* (Lamb.) Hook), a type of fast-growing wood species that is cultivated in China, was sourced from Yongzhou City, Hunan Province, China. Plain-sawn boards with a dimension of 100 mm × 100 mm × 20 mm (length × width × thickness) were prepared as test samples. All samples had no visible defects. Before starting the test, all samples were dried to a moisture content of 12% and randomly sorted into 9 groups, 5 samples in each group, of which one group served as untreated.

Heat treatment

During the heat treatment, wood samples were placed in a heat treatment device (DHG-9205A, HUMGINE, Shanghai, China) with steam as the protective medium. Heat treatment process was started at room temperature and then rose to the target temperature of 160, 180, 200, or 220 °C with a heating rate of 2 °C/min. The target temperature was maintained for 2 h or 4 h. The heat-treated wood was taken out and stabilized at room temperature, and the surfaces of the wood were sanded until flat for further testing.

Color measurement and accuracy validation

The color values were measured by a colorimeter (NR200, 3nh, Guangdong, China). The sensor head was 8 mm in diameter. Measurements were made using a D65 illuminant and 10° standard observer. Percentage of reflectance, collected at 10 nm intervals over the visible spectrum was converted into the CIELab color system, where L^* represents the lightness, a^* and b^* describe the chromatic coordinates on the red-green and yellow-blue axis, respectively (ISO/CIE 11664-4:2019). For each test sample, color measurements were taken at 5 points, each point was scanned 3 times, and an average was calculated. The CIELab color system is not the only way in which color differences can be arranged to be approximately uniform with regard to visual perception. The Munsell color system with three independent dimensions, hue (*H*), chroma (*C*), value (*V*) has been designed to reflect human perception and discrimination of colors from a design perspective (Roy Choudhury and Naskar 2019). Therefore, the Munsell color system is widely used in cognitive psychology experiments (Roberson *et al*. 2005). The following is the conversion formula from CIELab to Munsell color system:

$$H = -0.03636L^{*} + 0.02663r - 14.3\theta + 0.09131r\theta + 14.826 \quad (1)$$

$$V = 0.1002L^{*} - 1.16 \quad (2)$$

$$C = 0.1439r + 1.054\theta - 1.022\theta^{2} + 0.0497r\theta - 0.167 \quad (3)$$

$$\theta = \arctan\left(\frac{a^{*}}{b^{*}}\right) \quad (4)$$

$$r = \sqrt{{a^{*}}^{2} + {b^{*}}^{2}} \quad (5)$$

where, *H*, *V*, and *C* represent the hue label value (hue), the lightness value (value), and the purity/color degree (chroma), respectively. The parameters *r* and *θ* are intermediate variables used in the transformation. *H* is a quantified indicator value based on YR, which can be represented as *H*YR when its value is within the range of 0 to 10 (*e.g.*, 5.6YR); when the value exceeds the above range, it is represented in the following way: 0>*H*>-10: (*H*+10) R; 20>*H*>10: (*H*-10) Y; H>20: (*H*−20) GY.

Using a scanner (15152, Deli, Ningbo, China) with 1200 dpi resolution to obtain sample electronic pictures, pre-processing was conducted through Adobe Photoshop software. Pictures were standardized to a uniform size of 1440 pixels ×1440 pixels, with 300 dpi resolution. In order to verify the color accuracy and guarantee the fidelity of color representation, five randomly selected pictures from the scanned wood were compared to corresponding real samples. The picture color values extracted from RGB values were converted into $L^*a^*b^*$ values (Connolly and Fleiss 1997). The color differences ΔE^* between the color values of electronic pictures and real samples were calculated using the following formulas,

$$\triangle L^{*} = L^{*}_{picture} - L^{*}_{sample} \quad (6)$$

$$\triangle a^{*} = a^{*}_{picture} - a^{*}_{sample} \quad (7)$$

$$\triangle b^{*} = b^{*}_{picture} - b^{*}_{sample} \quad (8)$$

$$\triangle E^{*} = \sqrt{\triangle {L^{*}}^{2} + \triangle {a^{*}}^{2} + \triangle {b^{*}}^{2}} \quad (9)$$

where, ΔL^*, Δa^*, and Δb^* represent the color change values between electronic pictures and real samples. When the ΔE^* between the two colors is less than 6, the human eye is unable to distinguish the color difference between the two (Cui *et al*. 2004), thus verifying that the electronic picture can be used as a substitute for the real sample.

Grain contrast measurement

Wood is a material of biological origin with non-uniform color. The color value by itself is not sufficient to characterize grain pattern. In order to evaluate whether the grain contrast intensity on the wood surface was enhanced or diminished by heat treatment, color contrast evaluations were also carried out. There are different methods available to calculate the contrast in an image (Moulden *et al*. 1990; Bhuiyan and Khan 2018). When a higher level of accuracy is required, standard deviation of luminance method for contrast evaluation should be applied only for histograms with normal distribution. Meanwhile, greyscale images are preferred due to their minimal subjective impact on the human eye compared to chromatic contrast (Dagher *et al*. 2023). In this study, by applying Adobe Photoshop software to decolorize the wood electronic pictures, grayscale images were obtained and the standard deviations of luminance values were calculated. The standard deviation (STDEV) value in Photoshop represents how widely intensity values of luminance vary in the region of interest of the image.

Participants and procedure

Thirty-two healthy student volunteers (16 males and 16 females were with a mean age of 21.2, ranged from 19 to 23 years old) were recruited as participants. No color blindness, anomalous trichromatism, or night blindness was found in them. All participants signed written consent forms to participate before the experiment.

The eye-tracking experiment was conducted in a quiet and uniform light environment. The eye tracker was EyeLink 1000 plus (SR research, Ottawa, Canada), which is a highly accurate video eye tracker on the market, with a sampling rate of up to 2000 Hz for both eyes. As shown in Fig. 1, the pre-experiment was carried out before the formal experiment, the participants were asked to sit in an adjustable chair, ensuring that the distance between their eyes and the monitor was 85 centimeters, and the height of their eyes was level with the top quarter of the monitor. The instruction was first presented on the computer screen (21-inch with a resolution of 1920 pixels×1080 pixels), participants were not told the purpose of the experiment, just told that they were free to view the pictures as they pleased. Then the participant's right eye for 9-point calibration was captured. Subsequently, the screen started to play three wood pictures as stimulus. After participants fully understood the experimental requirements and procedures, formal eye-tracking experiment was conducted.

Stimuli of different heat-treated wood pictures were arranged in four quadrants on a white background view page, which was referred to as a group page. Up, down, left, and right positions were exchanged to form new stimulus images to eliminate the influence caused by the change of stimulus position. In other words, the wood under each heat treatment condition was repeatedly displayed 4 times, with a total of 9 group pages. Each group page was presented randomly with a viewing time of 6 s. The short observation time was defined to prevent the participants from becoming bored and to record sufficient eye-tracking data for analysis (Nakamura and Kondo 2008). Eye calibration was performed between each group page repeatedly. After the eye-tracking experiment, the participants conducted a subjective evaluation questionnaire experiment on the computer. Real samples were not used in order to avoid the interference of olfactory factors.

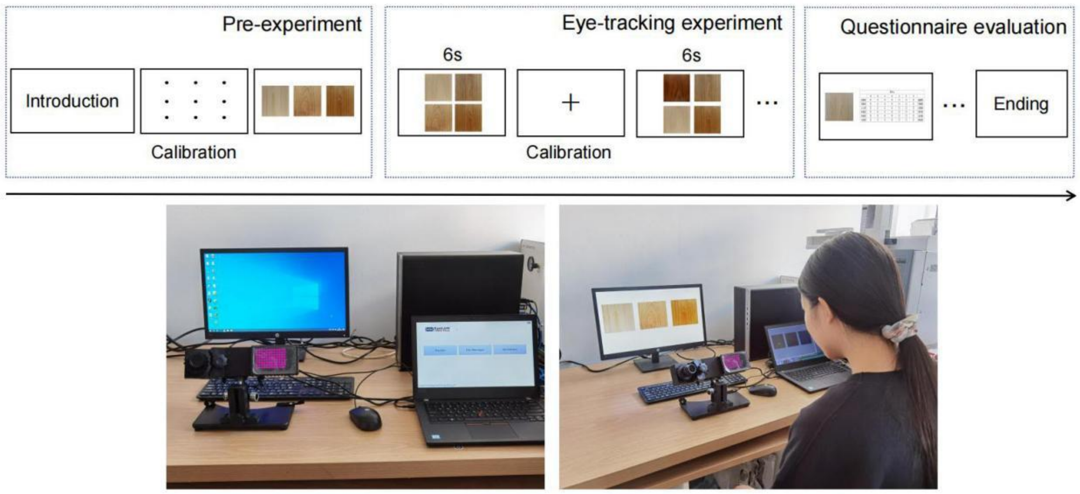

Fig. 1. Experimental procedure

Selection of evaluation dimensions and indexes

Two evaluation methods were used, namely, an eye-tracking study and a subjective evaluation scoring. The first fixation duration, first fixation time, fixation duration, and fixation count in the areas of interest (AOI) were the main analysis indexes for the eye-tracking experiment output. The experimental data showed the participants' visual attention. Previous studies have indicated that the first fixation time reflected the familiarity with a certain information, longer fixation duration, and higher fixations count represented more focused attention (Li *et al.* 2021; Su *et al.* 2021). When the fixation duration and fixation count were inconsistent, the most attractive part of the image can be described by the heat map, which can intuitively reflect the preferences and attention of the participants towards the corresponding areas (Nakamura and Kondo 2008).

Subjective evaluation scoring was performed with use of the semantic differential scale (SD), which is useful for quantifying individual impressions and measuring impressions of objects by using multiple pairs of Kansei adjectives with antithetical meanings (Llinares and Page 2007). Based on the previous work examining wood (Overvliet and Soto-Faraco 2011; Kanaya *et al.* 2016; Shitara *et al.* 2017; Lipovac *et al.* 2022), six pairs of bipolar adjectives were selected in this study, which included sensory properties (*i.e.*, cold−warm, soft−hard) and affective attributes (*i.e.*, artificial−natural, cheap−expensive, uncommon−common, uncomfortable−comfortable, dislike−like). A questionnaire was designed to measure psychological evaluations using a 7−point Likert scale (−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.

Statistical Analysis

In the present study, the raw data included color, grain contrast, eye-tracking data, and questionnaire evaluation data. These data were processed by the SPSS software. The statistical analysis methods were descriptive analysis, correlation analysis, significance analysis, and multiple regression analysis. The description analysis and significance analysis were used for exploring the preference variances between untreated wood and heat-treated wood, as well as the differences in eye-tracking data. Correlation analysis was performed to probe the effects of material properties on preference and eye-tracking on preference. Multiple regression analysis was applied to elucidate the relationship between visual properties and psychological preference of the heat-treated wood.

RESULTS AND DISCUSSION

Visual Properties of Heat-treated Chinese Fir

The appearances of the untreated and heat-treated Chinese fir samples are shown in Fig. 2. The wood color varied from light yellow to dark brown and wood grain highlighted as the temperature and time of heat treatment increased. Specifically, when the temperature was 160 °C, the color change was not obvious. At 180 to 200 °C, the wood color changed to brown, and the grain became clearer. The heat treatment at 220 ℃ changed the color of Chinese fir samples to dark brown.

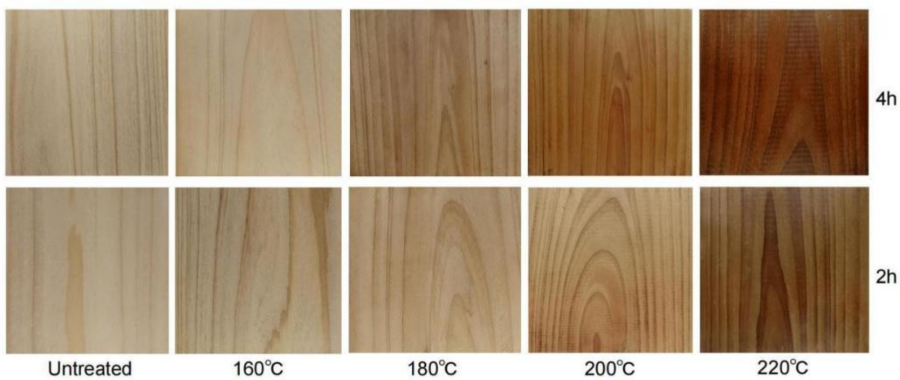

Fig. 2. The untreated and heat-treated Chinese fir samples

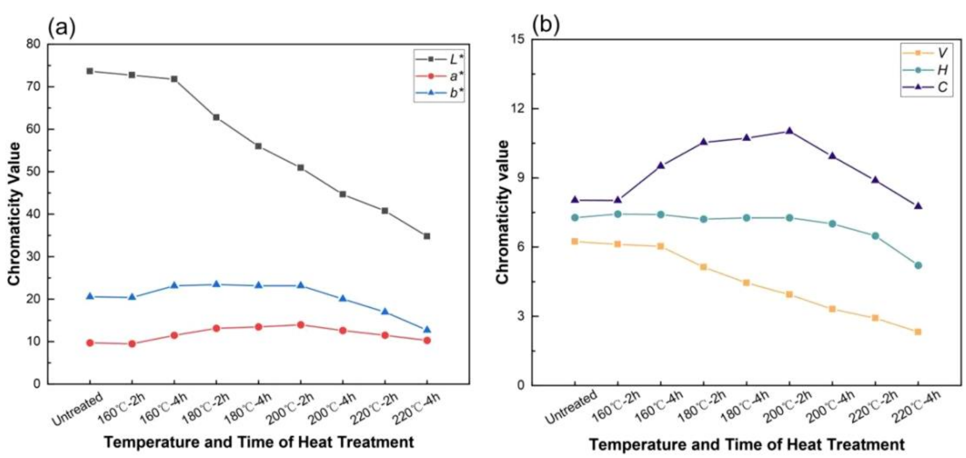

Fig. 3. Chromaticity values of Chinese fir under different heat treatment conditions. (a) CIELab color system; (b) Munsell color system

The chromaticity values are listed in Table 1, while their trends are visually displayed in Fig. 3. In the CIELab color system, with the increase of temperature and time, the $L*$ value showed a significant downtrend, which indicated a decrease in brightness of Chinese fir. This is due to the intense decomposition of the hemicellulose as the heat treatment temperature rises, the partial pyrolysis of cellulose and lignin catalyzed by the acidic substances produced during the process, and the volatilization of organic substances, which leads to a significant decrease in the brightness of the wood. Compared with the *L** value, the overall changes of *a** value and *b** value were relatively small, showing a trend of rising initially but then declining. The values of *a** and *b** reached the maximum near 200 °C. Researchers have found a similar phenomenon when investigating heat treatment on other fast-growing wood species (Tuong and Li 2010; Srinivas and Pandey 2012). In the Munsell color system, lightness value (*V*) was highly correlated with the *L** value, chroma value (*C*) rose to a peak at 200 °C for 2 h, then gradually fell. The overall change in hue value (*H*) was not significant at heat treatment temperatures below 220 °C, fluctuating between 7.0YR and 7.5 YR, with a slight decrease at 220 °C

Table 1. Results of Color and Grain Contrast of Chinese Fir Samples

	Temp.	Time	CIELab Color			Munsell Color			Grain Contrast
			*L**	*a**	*b**	V	H	C	S
Untreated group	/		73.65 (0.75)	9.71 (0.13)	20.55 (0.32)	6.24 (0.35)	7.28 (0.23)	8.03 (0.42)	11.28 (1.36)
Heat-treated group	160 °C	2h	72.70 (1.39)	9.48 (0.69)	20.39 (2.01)	6.12 (0.14)	7.43 (0.42)	8.02 (0.59)	11.29 (1.03)
		4h	71.77 (0.87)	11.47 (0.41)	23.14 (0.84)	6.03 (0.09)	7.41 (0.11)	9.51 (0.33)	11.37 (0.55)
	180 °C	2h	62.74 (1.35)	13.12 (0.68)	23.42 (0.89)	5.13 (0.14)	7.21 (0.13)	10.54 (0.49)	12.76 (0.37)
		4h	55.98 (1.70)	13.46 (0.95)	23.16 (1.26)	4.45 (0.17)	7.27 (0.18)	10.72 (0.69)	12.99 (1.24)
	200 °C	2h	50.90 (1.85)	13.96 (0.80)	23.16 (1.57)	3.94 (0.19)	7.27 (0.35)	11.02 (0.61)	13.74 (0.95)
		4h	44.65 (1.00)	12.61 (0.31)	20.53 (0.29)	3.31 (0.10)	7.01 (0.14)	9.93 (0.23)	15.66 (0.68)
	220 °C	2h	40.76 (1.12)	11.49 (0.30)	16.96 (0.54)	2.92 (0.11)	6.49 (0.23)	8.89 (0.20)	15.98 (1.62)
		4h	34.78 (1.97)	10.28 (0.77)	12.71 (1.99)	2.33 (0.20)	5.21 (0.69)	7.76 (0.65)	12.80 (0.54)

Note: Values in parentheses are standard deviations.

Table 2. Descriptive Analysis of Heat-treated Wood Preference

Type of Wood	Mean Score	Median Score
Untreated	-0.48^{d}	-1
160 °C-2h	-0.52^{d}	-1
160 °C-4h	-0.45^{d}	-1
180 °C-2h	-0.21^{cd}	0
180 °C-4h	0.48^{bc}	1
200 °C-2h	1.34^{a}	1
200 °C-4h	1.52^{a}	2
220 °C-2h	0.83^{ab}	1
220 °C-4h	-1.41^{e}	-1

Note: Values with different letters are significantly different($p<0.05$)

The grain contrast (*S*) was calculated as the values of the standard deviation of the luminance in the image histogram, which represents luminance values frequencies in the image (Dagher *et al*. 2023). The values of *S* are shown in Table 1. The grain contrast of the heat-treated Chinese fir changed between 11.29 and 15.98, which was higher than the value of the untreated group. An example of luminance histograms of grayscale images of untreated wood (left image) and heat-treated wood (right image) are compared in Fig. 4. This showed that the difference between the grain grayscale value and the background grayscale value became larger after heat treatment, which made the wood grain more obvious. Under the heat treatment condition of 220 °C-2 h, the grain contrast of the Chinese fir was most noticeable. This verifies that heat treatment can make the wood grain clearer.

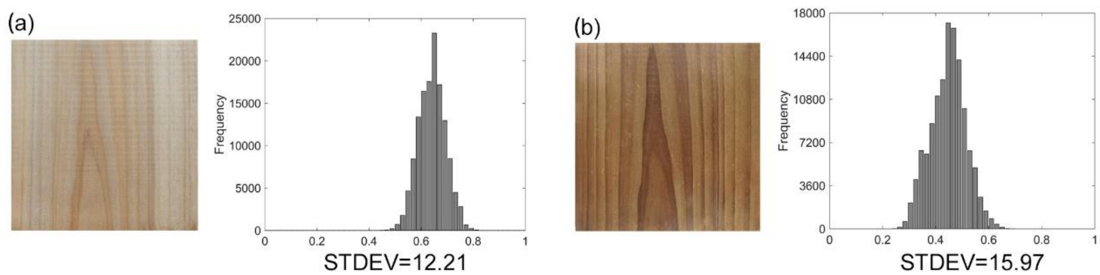

Fig. 4. Example of luminance histograms of grayscale images of a Chinese fir sample before and after heat treatment; (a) Before heat treatment; (b) After heat treatment

Psychological Evaluation of Heat-treated Chinese Fir: Overall Preference

Human psychological preference can be viewed as the integration of underlying affective attributes and physical surface perceptions (Okamoto *et al*. 2016). The preference score came from the semantic differential scale "dislike-like". Descriptive statistics of heat-treated wood visual preference are reported in Table 2 and Fig. 5. High scores were assigned to heat-treated wood at 200 °C, while untreated wood received low scores. Specifically, the mean and median scores for heat-treated wood at 180, 200, and 220 °C for 2 h were almost above zero, whereas those for untreated, heat-treated at 160 °C and 220 ℃-4 h were below zero. A significant variation in preference scores was observed among the evaluated samples at a 5% significance level, as indicated by the analysis of variance. The results of Fisher's least square difference (LSD) test revealed that wood heat-treated at 200 °C for 4 h received the highest level of preference. Untreated, 160 °C, and 180 °C for 2 h did not exhibit significant differences, and they were all relatively less appreciated by participants. Heat-treated wood at 220 °C for 4 h received significantly lower scores compared to the other samples. The results indicated that the darker colors of heat-treated wood at 200 °C were more preferred compared to the untreated wood. Hidayat *et al*. (2017) studied the color characteristics of Korean white pine and royal paulownia by heat treatment and obtained a similar conclusion on consumer preference.

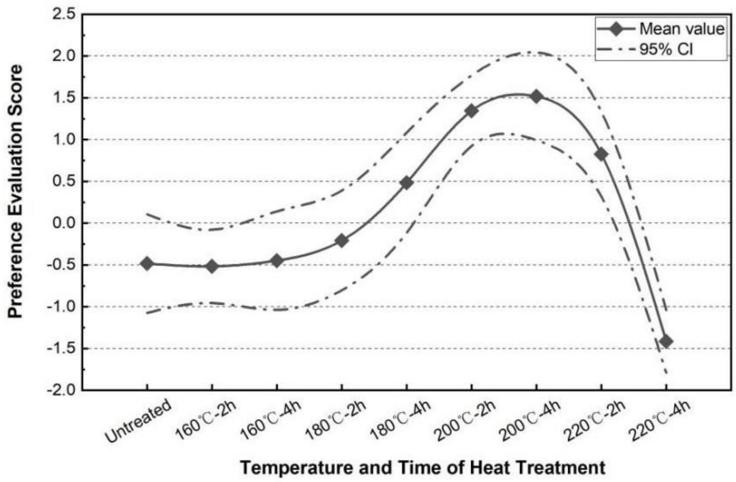

Fig. 5. Preference evaluation scores for heat-treated wood

Material Attributes Psychological Evaluations

Preference of materials is associated with certain perceived material attributes (Brandt and Shook 2005). The psychological evaluation results in Fig. 6, based on the material attributes, revealed that the different heat treatment temperatures and times of Chinese fir samples had varying effects on human psychological responses, showing significant differences in sensory and affective attributes. Regarding the sensory attributes, with the increase of the heat treatment temperature and time, the warm sense gradually intensified, reaching its peak at 200 °C for 4 h. At the same time, the sense of heaviness also continued to increase. For the affective attributes, as the wood color deepened and the wood grain became more prominent, the value of expensive was constantly improving. The natural sense of the heat-treated wood was generally positive. However, as a result of the heat treatment of 220 °C, there was a significant decrease in its natural attributes. The prevalence and comfort provided by heat-treated wood were generally favorable, while it exhibited a noticeable decrease when heat-treated at temperatures exceeding 200 ℃, indicating that the heat-treated wood generally caused positive psychological responses, which could be negatively affected by excessive dark color.

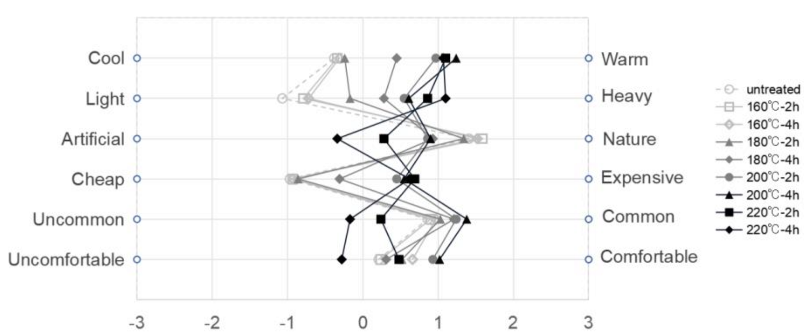

Fig. 6. SD profiles of heat-treated wood attributes psychological evaluations

Relationship between Material Attributes and Preference

Table 3 demonstrates the correlation between preference and the attributes of heat-treated wood. Overall, well-rated wood was perceived to possess higher levels of warmth, weight, cost, prevalence, and comfort. No statistically significant relationships were found between preference and the nature sense. The correlation coefficients were generally small to medium in magnitude, while preference and comfort were relatively large. The observed results were partially consistent with previous research (Rice *et al.* 2006; Lipovac *et al.* 2022), where materials that received higher scores in terms of preference were perceived to possess a greater degree of warmth. While Jonsson *et al*. (2008) indicated a negative correlation between preferences and heaviness, results in this research revealed that the favored samples were perceived as being heavier. This discrepancy could result from different categories of wood. Dark heat-treated wood has a color that is closer to precious tropical hardwood, giving the perception of greater weight. For the same reason, preference was significantly positively correlated with the sense of value. Therefore, heat-treated wood is considered a more expensive and luxurious material (Espinoza *et al*. 2015). For the prevalence, heat-treated wood is not as common as untreated wood, but its popularity score was similar in this research. This suggested that heat-treated wood exhibited specific visual properties that are perceived similarly to properties of more common wood materials. With respect to comfort, the results indicated that more comfortable material tended to be more favored, which was consistent with the results obtained in other studies (Jonsson *et al.* 2008; Demattè *et al.* 2018; Li *et al.* 2021).

Table 3. Correlation Analysis of Material Attributes and Preference

	Cold-warm	Light - heavy	Artificial - nature	Cheap-expensive	Uncommon-common	Uncomfortable-comfortable
Preference	0.282**	0.264**	0.033	0.286**	0.163**	0.508**

Note: ** = p <0.01.

Relationship Between Visual Properties and Preference

The correlation analysis results between visual properties and preference are shown in Table 4. Preference was significantly positively correlated with hue (*H*), chroma (*C*), and grain contrast (*S*), and negatively correlated with value (*V*). Meanwhile, *V* had a low correlation coefficient with preference, but it was strongly correlated with *H* and *S*. Considering multicollinearity, *V* was excluded. A regression analysis was performed with *H*, *C*, *S* as the predictor variable and preference as the dependent variable. As shown in Table 5, the model could explain 61.1% of preference in heat-treated wood, and the whole regression model was highly significant, F=134.696, $p<0.000$. *H* as a predictor of preference was statistically significant ($\beta=0.465$, $p<0.001$), and similarly *S* as a predictor was highly significant ($\beta=0.697$, $p<0.001$). However, *C* as a predictor was not significant ($\beta=0.092$, $p=0.092$). Therefore, the grain contrast and hue of heat-treated wood had a significant impact on visual preference. Specifically, a regression model was established: visual preference=-11.634+0.764*H*+0.433*S* ($R^2=0.611$). This provides important references for the design and selection of heat-treated wood.

Table 4. Correlation Analysis of Visual Properties and Preference

	V	H	C	S	Preference
V	1				
H	0.772**	1			
C	-0.082	0.452**	1		
S	-0.793**	-0.289**	0.386**	1	
Preference	-0.222**	0.289**	0.544**	0.562**	1

Note: ** = p <0.01.

Table 5. Regression Analysis Between Visual Properties and Preference

Model	Unstandardized Coefficients	Standardized Coefficients	t	p	Collinearity Statistics	
	B	β			tolerance	VIF
(constant)	-11.634		-17.556	0.000		
H	0.764	0.465	8.807	0.000	0.543	1.841
C	0.085	0.092	1.689	0.092	0.504	1.983
S	0.433	0.697	13.653	0.000	0.581	1.721
R^2	0.611					
F	F=134.696, p<0.000					
1. D-W	1.843					

Eye-tracking Analysis

The correlation analysis results in Table 6 indicate that four visual properties exhibited either non-significant differences or weak correlation coefficients with participants' first fixation duration and first fixation time, while demonstrating significant correlations with fixation duration and fixation count. Specifically, *C* and *S* were positively correlated with fixation duration and fixation count, whereas *V* showed negative correlations with these eye-tracking indexes. These findings highlighted the significant impact of color and grain on visual attention towards heat-treated wood. Notably, grain contrast exhibited a stronger correlation with fixation duration and fixation count compared to lightness and chroma. As a result, fixation duration and fixation count were identified as the primary eye-tracking indexes for investigating the visual psychology of heat-treated wood. This finding was consistent with the results discovered by Yu *et al.* (2021), and Li *et al.* (2021) in their exploration of effective eye-tracking indexes related to wood material perceptual cognition.

Table 6. Correlation Analysis of Eye-tracking Indexes and Visual Properties

	First Fixation Duration	First Fixation Time	Fixation Duration	Fixation Count
V	0.039	0.129**	-0.318**	-0.296**
H	0.062	0.047	-0.004	-0.094*
C	0.114*	-0.054	0.278**	0.153**
S	-0.005	-0.153**	0.446**	0.354**

Note: * = p <0.05; ** = p <0.01.

Figure 7 shows the fixation duration and fixation count data obtained from the eye-tracking experiment of the heat-treated wood under different conditions. The fixation duration and fixation count of the heat-treated wood were significantly higher than those of the untreated wood, indicating that the heat-treated wood had gained more attention. In terms of fixation duration, the highest attention time was observed by the heat treatment at 200 °C for 4 h, which was consistent with the subjective preference evaluation scores. Regarding fixation count, the wood with the highest fixation count was the one heat-treated at 220 °C for 2 h. In general, the untreated wood exhibited significant differences compared to the wood heat-treated at 180, 200, and 220 °C, but did not show significant differences compared to the wood heat-treated at 160 °C. The results showed that heat-treated wood at about 200 °C were easier to get more visual attention. This result exhibited certain similarities with the findings from questionnaire evaluations, indicating that the fixation data can quantify the visual appeal of the heat-treated wood to some extent. Through integration with an assessment of surface color and grain, heat-treated wood under these specific conditions displayed a resemblance to the color of valuable hardwood species and featured a clear and strong wood grain, thereby facilitating heightened visual appeal.

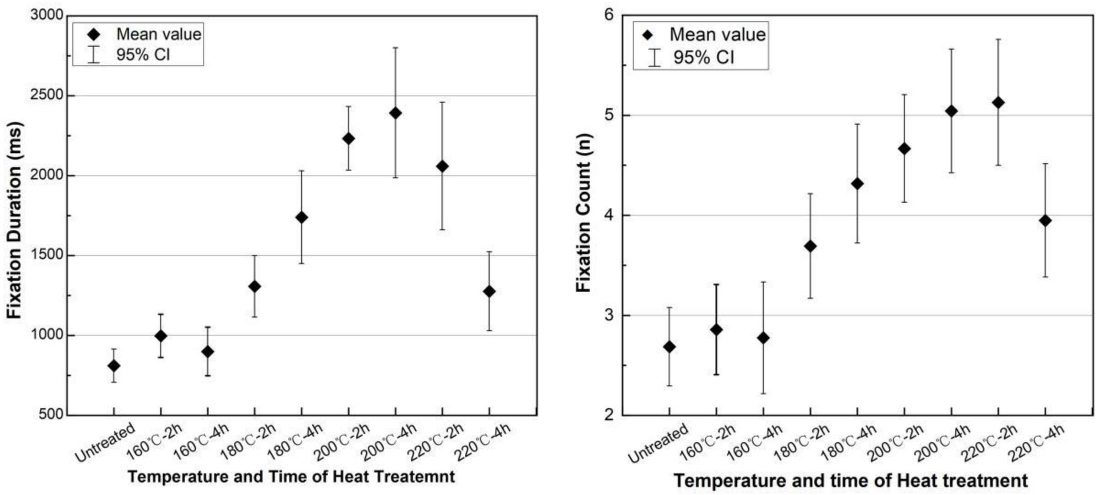

Fig. 7. Fixation duration and fixation count of heat-treated wood

Table 7. Significance Analysis of Eye-tracking Indexes on Untreated and Heat treated Wood

(I) Group	(J) Groups	Fixation Duration		Fixation Count	
		Mean Different (I-J)	Significance p	Mean Different (I-J)	Significance p
Untreated	160 °C-2h	-186.381	0.386	-0.090	0.846
	160 °C-4h	-88.014	0.670	-0.037	0.933
	180 °C-2h	-496.107	0.006**	-0.925	0.017*
	180 °C-4h	-928.943	0.000***	-1.533	0.000***
	200 °C-2h	-1421.074	0.000***	-1.741	0.000***
	200 °C-4h	-1581.635	0.000***	-2.275	0.000***
	220 °C-2h	-1248.592	0.000***	-2.296	0.000***
	220 °C-4h	-465.123	0.015*	-1.181	0.004**

Note: * = p <0.05; ** = p <0.01; ***=p<0.001

Relationship Between Fixation Data and Preference

To investigate the relationship between objective eye-tracking indexes and subjective preference, correlation analysis was used to analyze three datasets. Table 8 presents the results of the correlation analysis between fixation duration, fixation count, and preference. The data revealed a significant relationship across all three groups. Specifically, the correlation coefficient between fixation duration and preference was 0.243, while the correlation coefficient between fixation count and preference was 0.205, both indicating weak correlations. This indicated that the objective eye-tracking indexes may not fully and accurately reflect subjective evaluation. Notably, the correlation coefficient between fixation duration and fixation count was 0.766, signifying a strong correlation. Researchers reported that the visual cognition of laminated bamboo furniture and also found color change significantly affected fixation duration and fixation count, and also showed a significant positive correlation with the overall subjective evaluation (Wan *et al*. 2021). Accordingly, surface properties that capture consumers' visual attention for long duration and at high frequency should be adopted in the design of heat-treated wood to improve overall visual psychological evaluation.

Table 8. Correlation Analysis of Eye-tracking Indexes and Preference

	Fixation Duration	Fixation Count	Preference
Fixation duration	1		
Fixation count	0.766**	1	
Preference	0.243**	0.205**	1

Note: ** = p <0.01.

CONCLUSIONS

1. In the course of heat treatment, the visual properties of Chinese fir underwent significant changes. Lightness (*V*) decreased notably from 7.28 to 5.21 with rising temperature and time. Chroma (*C*) peaked at 200 °C for 2 h before gradually declining. Hue (*H*) fluctuated between 7.0YR and 7.5YR below 220 °C, with a slight decrease at 220 °C. Grain contrast (*S*) ranged from 11.28 to 15.89, reaching a maximum at 220 °C for 2 h.
2. Changes in the visual properties of heat-treated wood had a significant effect on psychological preference. The subjective evaluation results indicated that compared to the untreated Chinese fir, the heat-treated wood was more preferred, particularly at 200 °C for 4 h.
3. Grain contrast and hue of heat-treated wood had a significant impact on human visual preference. The higher the hue value, the stronger the grain contrast, and the higher the preference score was. Meanwhile, this preference exhibited a significant positive correlation with the psychological impressions of warmth, weight, cost, prevalence, and comfort.
4. Eye-tracking analysis showed that Chinese fir heat-treated at about 200 °C attracted more visual attention. While the eye movement results showed commonalities with subjective evaluation to a certain extent, the objective eye-tracking indexes may not completely reflect subjective preference. Combining eye-tracking technology with subjective evaluation was more effective in analyzing participants' psychological preference for heat-treated wood.

ACKNOWLEDGMENTS

This work was supported by the science project of Jiangsu Vocational College of Agriculture and Forestry (2023kj11)，Qing Lan Project of Jiangsu Province (2023), the Fundamental Research Funds for the Central Universities (BLX202235 and BFUKF202315).

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Article submitted: February 27, 2024; Peer review completed: March 30, 2024: Revisions received: April 8, 2024; Revisions accepted: April 20, 2024; Published: May 28, 2024.
DOI: 10.15376/biores.19.3.4652-4669