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Effects of visual stimulation using wooden-wall images with different amounts of knots on psychological and physiological responses

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Abstract

Wood is an important material used in decorating human living environment. Knots are prominent features found on wood surface. Moreover, they are commonly considered as undesirable surface defects, which reduce not only the mechanical properties but also the aesthetic qualities of lumber. The effects of visual stimulation using knotty wood on psychological responses among humans have been relatively well investigated. However, only few studies have assessed physiological responses. Hence, the present study aimed to assess whether knotty wood surface can reduce not only psychological but also physiological benefits for humans. Two full-sized knotty wooden-wall images and a clear wooden-wall image were used as visual stimuli using computer graphics techniques. Twenty-eight adult Japanese female university students viewed each image for 90 s in random order. During exposure to the visual stimuli, the oxyhemoglobin concentrations in the left and right prefrontal cortex and heart rate variability were consecutively measured and utilized as indicators of central and autonomic nervous system activities, respectively. In addition, the psychological effects of knotty images were examined using the modified semantic differential method and the Profile of Mood State 2nd Edition. There was no significant difference in the effects of the three images on physiological responses. All visual stimuli more or less promoted psychological comfort and relaxation. However, compared with the clear wooden-wall image, the wooden-wall image with several knots was associated with reduced psychological benefits, and the psychological responses in viewing the wooden-wall image with few knots did not remarkably differ.

Masashi Nakamura and Harumi Ikei have contributed equally to this work and share first authorship.

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Introduction

Wood is one of the oldest materials used in decorating human living environment. To date, it has been used as not only a structural material in various architectural buildings but also as an interior material that is directly viewed and touched by building occupants. In particular, the outward features of wood, such as warm color, different grain patterns, and mellow gloss, provide unique visual stimuli to human occupants. Recently, not only the psychological but also physiological impacts of such outward features of wood on human occupants staying in built environment involving wood and wooden products have been investigated (e.g., Fell 2010; Kotradyova et al. 2019; Lipovac et al. 2020; Shen et al. 2020). Burnard and Kutnar (2015) reviewed and summarized relevant studies on restorative environmental design. Additionally, Lipovac and Burnard (2021) systematically reviewed nine relevant studies and noted that visual exposure to wood may produce beneficial psychological and physiological states in humans, but the evidence is limited.

Knots are also one of such surface features of wood. Knots are the remains of branches in the tree trunk. The seasonal addition of new wood results in progressive layering over previously produced wood. As new growth increases the diameter of the main stem, branch bases become more deeply embedded in the trunk (Shmulsky and Jones 2019). Although the presence of a knot is important evidence that the wood came from a living tree, it has been considered as undesirable surface defects and can significantly reduce not only the mechanical but also the aesthetic qualities of lumber.

The effects of visual stimulation using knotty wooden images or knotty wooden products on psychological responses among humans have been well investigated. Masuda and Nakamura (1987) reported that knotty wall panels can easily evoke natural (or wild) impressions. However, agreeable impressions declined with the increase in the number of knots (Masuda and Nakamura 1987; Nakamura and Masuda 1993). Broman (1995, 1996) showed that consumers prefer the surfaces of Scots pine wood and emphasized that many people in Northern Europe want clear surfaces over knotty surfaces. Moreover, Broman (2001) showed that the balance between visual harmony and activity is an important factor in choosing knotty surfaces. Nyrud et al. (2008) assessed the preference of 88 consumers in terms of knotty wood deck products. Results showed that homogeneous appearance and medium color strength were important factors. Høibiø and Nyrud (2010) focused on the experimental fact that the surface homogeneity of wood was associated with preferred products. In addition, the surface homogeneity of wood deck products was remarkably influenced by knots. In terms of successful marketing of wood products, Manuel et al. (2015) classified floorboards, including knotty floors, into 15 visual classes and analyzed the similarity among classes. Results showed that seven different consumer groups had distinct preference profiles regarding their preferred floor images. Matsumoto et al. (2016a, b) emphasized that the quantity of knots in wooden-wall panels (i.e., an area fraction of knots to a wall panel) was an extremely important factor in the preference evaluations of various types of rooms, such as a residential living room, restaurant, and hotel reception.

The abovementioned studies have shown that knots are a psychologically undesirable visual characteristic of wood. Therefore, the existence of knots has unsatisfactory effects on the preference and commercial values of wood products. Only few studies have experimentally examined the physiological effect of knots on wood surfaces as a visual stimulus among humans. In the study of Sakuragawa et al. (2005), two full-sized wall panels, a knotty hinoki (Japanese cypress) wall panel and a white steel wall panel, were used. Then, the physiological and/or psychological responses evoked by the visual stimulation of both panels were compared. Results showed that visual stimulation using the knotty hinoki wall panel significantly decreased blood pressure among participants who liked the knotty wall panel. Further, there was no significant increase in blood pressure among participants who disliked it. However, the influence of the amount of knots on physiological responses among humans is still unknown. Nakamura and Kondo (2007, 2008) investigated the effect of knots using an eye-tracking technique and found a high linear relationship between the probability of fixations on knots and their subjective noticeability. However, their assessments were limited to eye movements and sensory evaluations among participants who viewed full-sized knotty wall images. To evaluate the effect of the basic design attributes of wooden-wall panels among humans, Yoshida et al. (2016) assessed eye fixation-related potentials, eye movements, and sensory evaluation among participants who viewed full-sized wooden-wall images, including a knotty wall. Although there were variations in cognitive responses caused by the visible characteristics of wooden walls, the visual effect of knots on cognitive response has not been fully elucidated.

Recently, the physiological effect of knotty images was evaluated when used as a visual stimulus (Ikei et al. 2020). Well-prepared full-scale knotty and clear wooden-wall images were used. Then, the oxyhemoglobin (oxy-Hb) concentration in the left and right prefrontal cortex, which is an indicator of brain activity, and the heart rate variability (HRV), which is an indicator of autonomic nervous activity, were assessed among participants viewing wooden-wall images. Results showed that the knotty wooden-wall image decreased the right prefrontal cortex activity compared with the gray image, which was used as control. Moreover, the clear wooden-wall images reduced the left prefrontal cortex activity compared with the gray image. However, in this experiment, there was no significant difference between the effects of knotty and clear wooden-wall images on the two physiological indices. Although knots have negative psychological effects as mentioned above, whether they have similar negative physiological effects has not yet been confirmed.

A research group including the authors reported that the tactile or visual stimulations by natural objects provide (1) improvement in the parasympathetic nervous activity, (2) reduction in the prefrontal cortex activity, and (3) surge of comfortable and relaxed feelings simultaneously (Ikei et al. 2017; Ochiai et al. 2017; Ikei et al. 2018a, b). In a previous experiment (Ikei et al. 2020), HRV was adopted as an indicator of autonomic nervous activity and oxy-Hb concentration in the left and right prefrontal cortex as an indicator of brain activity, which just had been employed in a series of studies.

HRV was calculated by extracting the fluctuation in the heartbeat rhythm from the electrocardiogram signal by the frequency analysis and deriving the power spectral density (PSD) of the low-frequency component (LF) and the high-frequency component (HF) to evaluate the autonomic nervous activities. The interpretation of using HF as an index for the parasympathetic nervous activity is not disputed by researchers, and the interpretation of using LF has not been necessarily fixed. LF or LF/HF has often been considered the index of the sympathetic nervous activity (Kobayashi et al. 1999; Hayano and Yuda 2021). Therefore, in previous studies, two parameters, HF and LF/HF, were employed as the indices of the autonomic nervous activity (Ikei et al. 2017, 2020; Ochiai et al. 2017; Ikei et al. 2018a, b).

With respect to the oxy-Hb concentration in the left and right prefrontal cortex, negative correlations were repeatedly found between the oxy-Hb concentration and the parasympathetic nervous activity and the oxy-Hb concentration and the comfortable and/or relaxed feelings (Ikei et al. 2017; Ochiai et al. 2017; Ikei et al. 2018a, b). Furthermore, Hoshi et al. (2009) reported that the oxy-Hb concentration in the prefrontal cortex of the participants decreased when they were in emotionally pleasant condition. A recent review article (Lipovac and Burnard 2021) has cast doubt on whether there is a negative correlation between the prefrontal activity and the physiological relaxation, and the need for further verification of this correlation was recognized. However, the oxy-Hb concentration in the prefrontal cortex was employed as the measure of brain activity in a previous experiment in consideration of results in a series of former studies (Ikei et al. 2020).

On the other hand, in an indoor green space experiment, fatigue assessed using a questionnaire positively correlates with right prefrontal cortex activity–left prefrontal cortex activity (Imamura et al. 2022). Furthermore, the right prefrontal cortex activity is higher than the left prefrontal cortex activity during the stressful state of mental arithmetic (Tanida et al. 2004). The relationship between left–right differences in prefrontal cortex activity and pleasant or stressful conditions should be elucidated in future studies.

The previous experiment (Ikei et al. 2020) assessed the physiological responses induced by knots, which are summarized as follows: First, both the knotty and clear wooden-wall images significantly reduced the prefrontal cortex activities compared with the gray image. Second, the knotty wooden-wall image significantly increased parasympathetic nerve activity. Third, clear wooden-wall image significantly reduced sympathetic nerve activity.

The authors hypothesized that there is a difference in the physiological responses between participants who observed wooden-wall images without knots and those who observed wooden-wall images with knots. However, this hypothesis could not clearly be confirmed in the previous experiment because only one wooden-wall image with knots was found (Ikei et al. 2020). Thus, in this study, it is intended to expand the previous experiment using two wooden-wall images with different numbers of knots and verify this hypothesis. Three wooden-wall images (a wooden-wall image with several knots, a wooden-wall image with few knots, and a wooden-wall image without knots [clear]) were prepared. Then, the physiological effects of visual stimulation using these images were assessed. The participants of the current study were instructed to view three full-sized wooden-wall images in random order. During the observation of each image, the oxy-Hb concentrations in the left and right prefrontal cortex and HRV were consecutively measured, and they were considered as the indicators of central and autonomic nervous system activities, respectively. In addition, the psychological effect of knotty wooden images was examined.

Materials and methods

Participants

A total of 28 female Japanese university students were recruited and participated in this study to bring the attributes of the participants closer to the previous experiment (Ikei et al. 2020). The mean age (± standard deviation) of the participants was 21.7 ± 1.3 years; mean height, 157.1 ± 4.5 cm; mean weight, 47.5 ± 3.7 kg; and mean right and left eyesight scores, 0.8 ± 0.3 and 0.9 ± 0.2, respectively (including corrected values; Landolt ring vision, 1.0 equals 20/20). Individuals who had their menstrual period during the study, those treated for any diseases, and those who smoke were excluded from the study. A written consent was obtained from all participants after they had been informed about the aim and procedure of the study. The study was conducted in accordance with the guidelines of the Declaration of Helsinki, and the protocol was approved by the Ethics Committee of the Center for Environment, Health and Field Sciences, Chiba University, Japan (project identification code number: 40). Then, it was registered in the University Hospital Medical Information Network of Japan (UMIN; unique ID: UMIN000038730).

Visual stimulation

Preparation of wooden-wall images

Genuine wood has large uneven or irregular features, such as different colors and grain patterns. These inhomogeneous features are hard to control artificially because wood is derived from nature. The existence of knots is also an inhomogeneous appearance. The current study only focused on the physiological and psychological effects of knots when used as visual stimuli. Thus, the other outward features of wood, which might induce some physiological and psychological responses, should be excluded. Therefore, well-regulated wooden-wall images, not the genuine wood, were utilized as visual stimuli.

Several pieces of flat-sawn lumber from Japanese cedar (*Cryptomeria japonica*; length: 1000 mm, width: 110 mm, and thickness: 12 mm) were sorted based on the size of knots. Images of the lumber were taken using a digital still camera (D1x with Nikkor 50 mm f/1.4D lens, Nikon, Tokyo, Japan). To ensure that all images with the same size could be displayed on a screen, the images were reduced and cropped to obtain a final size of 970 × 100 mm^2 (1990 × 205 pixels).

If these lumber images had been used to compose wooden-wall images without any image processing, completed wall images could have dark and irregular appearances, as shown in the top row of Fig. 1. Therefore, each board image was retouched to adjust and standardize for color and contrast. That is, each lumber image was

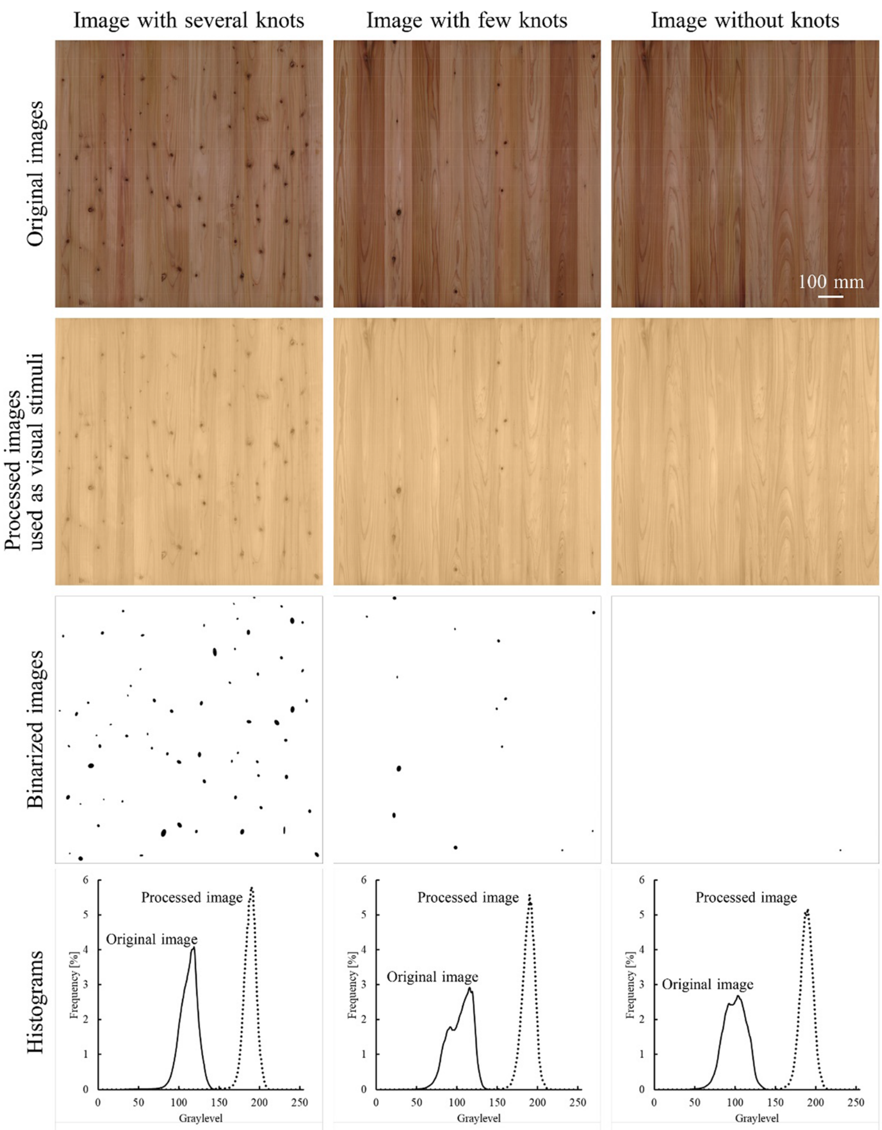

Fig. 1 Image processing and visual stimuli analysis. Histograms in the bottom row are gray-level distributions of the original (top row) and processed (second row) images. The numerical data of binarized images (third row) are shown in Table 1

transformed to a statistically equivalent one with a specific mean gray level and standard deviation. In total, 30 lumber images were retouched and included in the analysis. Then, 10 of 30 images had a lot of small knots, and another 10 had a low number of small knots. Moreover, 10 images did not have knots, except for a few pin knots. Small knot was defined as < 20 mm in diameter based on the Japan Agriculture Standards for lumber. A virtual wall image with a resolution of 1990 × 2050 pixels was established by consecutively and randomly setting 10 lumber images of either type. A square area with a resolution of 1990×1990 pixels was trimmed from the center of the virtual wooden-wall image. Three square wooden-wall images (i.e., those with several knots, those with few knots, and those without) were utilized as visual stimuli (second row in Fig. 1). The gray-level histograms of the original images and the processed images (visual stimuli) are shown in the bottom row of Fig. 1. These histograms confirmed that the abovementioned image processing controlled variations involved in the original images and facilitated well-controlled visual stimuli. Each wall image had a resolution of 1990×1990 pixels, and each pixel had 24-bit color information corresponding to red, green, and blue. All image processes were performed by self-made FORTRAN programs.

Via an image analysis using the ImageJ software (version 1.53c) (Rasband, 1997–2018), the number of knots, mean area of knots, and area fraction of knots to the whole image (knot ratio) of each wooden-wall image were calculated. Binarized wooden-wall images utilized to calculate image characteristics are shown in the third row of Fig. 1, and the image characteristics of three wall images are summarized in Table 1.

Presentation of visual stimuli

The three wooden-wall images, as shown in the second row of Fig. 1, were presented to each participant. The images, with a size of 970×970 mm^2, were projected into a large liquid–crystal display (LCD) (width: 1872 mm, height: 1053 mm, and 4 K-resolution: 3840×2160 pixels [0.49 mm/pixel, 85 V type, TH-85AX900; Panasonic, Osaka, Japan]).

The monitor was installed in a dim experimental chamber. Each participant sat on an office chair placed 1.1 m away from the monitor. The brightness of the monitor was adjusted to a relatively low level to prevent eyestrain among participants who were consecutively observing wooden-wall images displayed on the monitor. The luminance of knot areas and the surrounding areas of knots were measured using a color meter (CS-100A; Konica Minolta, Tokyo, Japan), and the illuminance at eye level was measured using an illuminance spectrophotometer (CL-500A; Konica Minolta, Tokyo, Japan). This device could measure the correlated color temperature of the images displayed on the monitor. These optical measurements, which are summarized in Table 1, assured that all wooden-wall images had almost the same luminance, illuminance, and correlated color temperature.

Study protocol

To assess physiological and psychological responses, wooden-wall images were used as visual stimuli, and this was the protocol applied in previous studies (Ikei et al. 2020; Nakamura et al. 2019). The participant was informed about the experiment at the anteroom and was then led to an artificial climate chamber with a temperature maintained at 24 °C, relative humidity of 50%, and lux illumination of 50.

Table 1 Image characteristics of the three visual stimuli and optical characteristics of the monitor

			Several knots	Few knots	No knots
Image characteristics	Number of knots		66	14	1
	Mean area of knots [cm^2]		0.983	0.835	0.285
	Circle equivalent diameter of knots [cm]		1.05	0.97	0.60
	Knot ratio (area fraction of knots) [%]		0.689	0.124	0.003
Optical measurements of monitor	Luminance [cd/m^2]	Knot area	7.4	7.6	–
		Surrounding	10.4	10.4	10.1
	Illuminance [lx]		7.6	7.6	7.6
	Correlated color temperature [K]		3834	3843	3839

First, as shown in Fig. 2, the sensors were attached to the participant's forehead and chest for physiological measurement. Then, the measurement procedure was explained to the participant who sat on a chair. After the participant calmed down, the logging of physiological signals was started. Prior to the main assessment, a training measurement was taken using a dummy image (red-brown brick wall).

Next, the main measurements were taken as follows: After the chamber was dimmed, the participants viewed a gray background for 60 s while seated (rest period). Then, one of three wooden-wall images (wooden-wall image with several knots [Fig. 3A], those with few knots [Fig. 3B], and those without [Fig. 3C]) was shown in the LCD in front of the participant. The participants viewed each wooden-wall image individually for 90 s. To eliminate potential influence correlated with the order of presentation, such as adaptation and fatigue, the three wooden-wall images were displayed in a counterbalanced manner. During the observation, the participant's physiological responses were continuously recorded. After visual stimulation for 90 s, the image displayed on the LED was switched to a dark background, and the lights were turned on. Then, a subjective evaluation was conducted.

Evaluation of physiological and psychological responses

Near-infrared time-resolved spectroscopy (TRS)

The brain activities of participants during visual stimulation were monitored using the TRS (Ohmae et al. 2006, 2007). The oxy-Hb concentration in the left and right prefrontal cortex was measured within a 60-s rest period and 90-s visual stimulation period using the TRS-20 system (Hamamatsu Photonics, Shizuoka, Japan). As the sampling rate of the TRS-20 system fluctuated between 1.08 and 1.18 s, all data points were converted to 1-Hz data using a linear interpolation technique.

Other measuring procedures and settings were performed in the same manner as described in a previous study (Ikei et al. 2020).

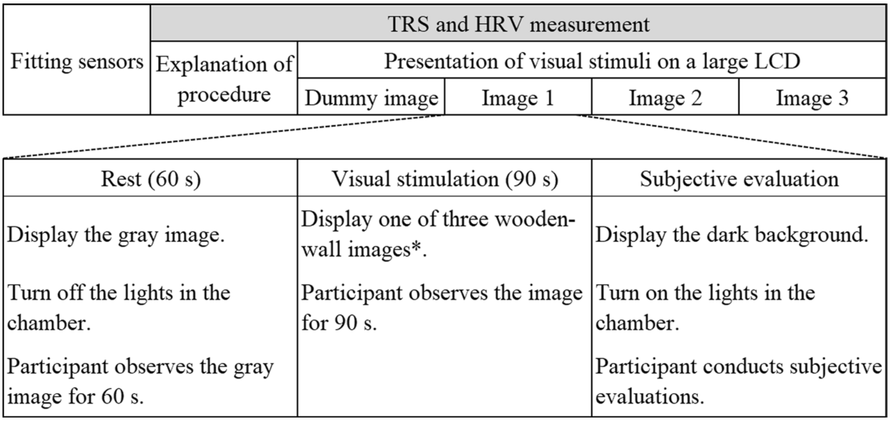

Fig. 2 Experimental procedure. To eliminate potential influence in the order of presentation, three wooden-wall images were displayed in a counterbalanced manner. *TRS* near-infrared time-resolved spectroscopy, *HRV* heart rate variability, *LCD* liquid–crystal display

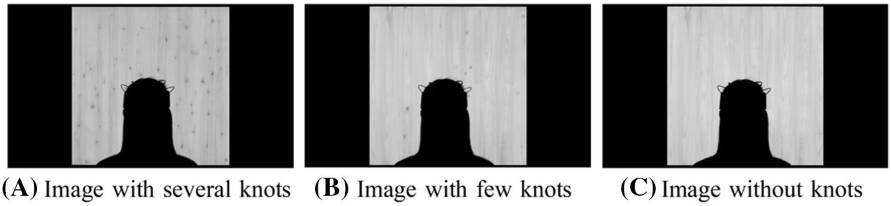

Fig. 3 Scene during visual stimulation. **A** Wooden-wall image with several knots. **B** Wooden-wall image with few knots. **C** Wooden-wall image without knots. The properties of the monitor presenting each wooden-wall image are shown in Table 1

HRV

As an indicator of autonomic nervous system activity, the HRV of each participant was measured (Task Force of the European Society of Cardiology and the North American Society of Pacing and Electrophysiology 1996; Kobayashi et al. 1999). To analyze fluctuations between consecutive R waves (RR intervals), electrocardiography was performed using a portable electrocardiograph (ActivTracer AC-301A; GMS, Tokyo, Japan), with a sampling frequency of 1 kHz. Then, the power spectrum of the obtained signal was calculated using the maximum-entropy method (MemCalc/Win; GMS, Tokyo, Japan).

Other measuring procedures and settings were used in the same manner as described in a previous study (Ikei et al. 2020).

Psychological measurements

The modified semantic differential (SD) method and the Profile of Mood State 2nd Edition (POMS2) were used for psychological measurements. The SD method could assess a participant's subjective evaluations of the appearance of visual stimuli using a questionnaire comprising 13-point psychological scales. A pair of opposing adjectives was distributed at both ends of each scale (Osgood et al. 1957). In the current study, four adjective pairs (comfortable–uncomfortable, relaxed–awakening, natural–artificial, and varied–ordered) were used to evaluate the degree of comfort, relaxation, natural, and homogeneous feelings, respectively. The former three adjective pairs have been used in previous studies consistently to investigate the association between the physiological and psychological responses of the participants who were exposed to various stimuli (e.g., Ikei et al. 2015; Song et al. 2018). The last one adjective pair (varied–ordered) was used in recent studies to evaluate the psychological effect of visual inhomogeneity involved in the surface of wood (Nakamura et al. 2019; Ikei et al. 2020). Considering the consistency of the studies, the four bipolar scales were employed in this study.

The POMS2, which was established by McNair and Lorr (1964), is a questionnaire used to evaluate psychological distress, and it has high reliability and validity (Lin et al. 2014; Yokoyama and Watanabe 2015; Heuchert and McNair 2012). In this study, the POMS2 brief version was used. In this questionnaire, the participants are asked to evaluate their present mood or mental state from 35 items rated on a 5-point scale from 0 to 4. By summing these self-evaluations for each of the five items, the POMS2 enables us to derive seven subscales ("anger–hostility" (A-H), "confusion–bewilderment" (C-B), "depression–dejection" (D-D), "fatigue–inertia" (F-I), "tension–anxiety" (T-A), "vigor–activity" (V-A), and "friendliness" (F)) and one comprehensive scale (total mood disturbance, TMD) for each participant. The score range of each subscale is 0 to 20, and the TMD score is calculated from the following formula: [A–H] + [C–B] + [D–D] + [F–I] + [T–A] − [V–A] − [F]. Therefore, the TMD score can be a negative value.

Other measuring procedures and settings were performed using the same method as described in a previous study (Ikei et al. 2020).

Statistical analysis

Physiological responses to the three visual stimuli were compared using paired *t* tests with the Holm correction. To examine differences in the psychological indices among three wall images, the Wilcoxon signed-rank test was applied with the Holm correction. All statistical tests were performed using the Statistical Package for the Social Sciences software version 21.0 (IBM Corp., Armonk, NY, the USA), and a p-value of < 0.05 was considered statistically significant.

Results

Physiological effects

TRS

The changes in oxy-Hb concentrations in the left and right prefrontal cortex within the last 30 s of the rest period (baseline) and every 30 s during the stimulation period were presented as mean. There was no significant difference between the three visual stimuli at baseline (left prefrontal cortex: wooden-wall image with several knots = 46.18 ± 1.21 μM, with few knots = 46.41 ± 1.08 μM, without knots = 46.80 ± 1.08 μM; right prefrontal cortex: with several knots = 47.79 ± 1.36 μM, with few knots = 47.63 ± 1.28 μM, and without knots = 47.96 ± 1.28 μM; mean ± standard error). The unit M indicates molar concentration (mol/dm^3).

The changes in oxy-Hb concentrations were compared according to the three visual stimuli. However, there was no significant difference in oxy-Hb concentrations. The mean oxy-Hb concentrations in the left and right prefrontal cortex during the 90-s visual stimulation period decreased during assessments using the three visual stimuli (left prefrontal cortex: with several knots = − 0.06 ± 0.11 μM, with few knots = − 0.17 ± 0.12 μM, and without knots = − 0.12 ± 0.13 μM; right prefrontal cortex: with several knots = − 0.01 ± 0.11 μM, with few knots = − 0.05 ± 0.11 μM, and without knots = − 0.09 ± 0.14 μM; mean ± standard error). Result showed that there was no significant difference in oxy-Hb concentrations.

HRV

It has been noted that the respiratory rate has a significant effect on HRV measurement, especially on HF, because the frequency bandwidth of respiration during resting overlaps the HF domain (Kobayashi et al. 1999). In this study, four participants were found whose respiratory rate differed significantly among the visual stimuli and their HRV data were excluded to avoid contamination of the impact of respiratory rate on HRV. The remaining participants ($n = 24$) showed no significant difference between the assessments using the three visual stimuli and pre- and mid-measurements of the mean respiratory rate (wooden-wall image with several knots: pre-measurement, 17.2 ± 0.8 times/min, and post-measurement, 17.0 ± 0.8 times/min; with few knots: pre-measurement, 17.9 ± 1.2 times/min, and post-measurement, 17.2 ± 0.9 times/min; and without knots: pre-measurement, 18.1 ± 0.9 times/min, and post-measurement, 17.3 ± 0.8 times/min; mean ± standard error, $p > 0.05$). However, there were no significant differences in HF value (ln[HF], an index of parasympathetic nervous activity; with several knots = 5.4 ± 0.2 ln[ms^2], with few knots = 5.5 ± 0.2 ln[ms^2], and without knots = 5.4 ± 0.2 ln[ms^2]; mean ± standard error) and the LF/HF ratio (ln[LF/HF], an index of sympathetic nervous activity; with several knots = 0.42 ± 0.22, with few knots = 0.18 ± 0.25, and without knots = 0.58 ± 0.21; mean ± standard error) among the three visual stimuli.

Psychological effects

The results of the modified SD method are shown in Fig. 4. Each wooden-wall image was found to facilitate slight to moderate comfort. However, the wooden-wall images without knots and those with few knots were significantly associated with a more comfortable feeling compared to those with several knots (Fig. 4A $p < 0.05$). Moreover, there was no significant difference in terms of comfort between the assessments using wooden-wall images without knots and those with few knots. In addition, each wooden-wall image facilitated slight to moderate relaxation, and images without knots and those with few knots were associated with a more relaxed feeling compared with those with several knots (Fig. 4B $p < 0.05$). There was no significant difference in terms of relaxed feelings between assessments using images without knots and those with few knots. There were slight variations in homogeneity after observing each wooden-wall image (Fig. 4D). In particular, the wooden-wall images with several and few knots were significantly associated with more varied impressions compared with those without ($p < 0.05$). Moreover, there was no significant difference in homogeneous feelings between images with several and few knots. Furthermore, there was no significant difference in terms of naturalness between assessments using the three wooden-wall images. However, these images were correlated with slight to moderate naturalness (Fig. 4C).

In the POMS2 test, negative mood subscales of the "confusion—bewilderment" (without knots: 1.1 ± 0.4 [mean ± SE], several knots: 2.2 ± 0.7) and "fatigue—inertia" (without knots: 0.7 ± 0.3, several knots: 1.5 ± 0.5) were significantly lower for the wooden-wall image with no knot than for those with several knots (Fig. 5, $p < 0.05$). On the contrary, the positive mood subscales of the "vigor—activity" (without knots: 3.9 ± 0.7, several knots: 2.3 ± 0.5) and "friendliness" (without knots: 5.0 ± 0.8, several knots: 3.2 ± 0.7) were significantly higher in the wooden-wall image without knots than in those with several knots. Furthermore, the score of the wooden-wall image with few knots in the F subscale (4.5 ± 0.7) was significantly

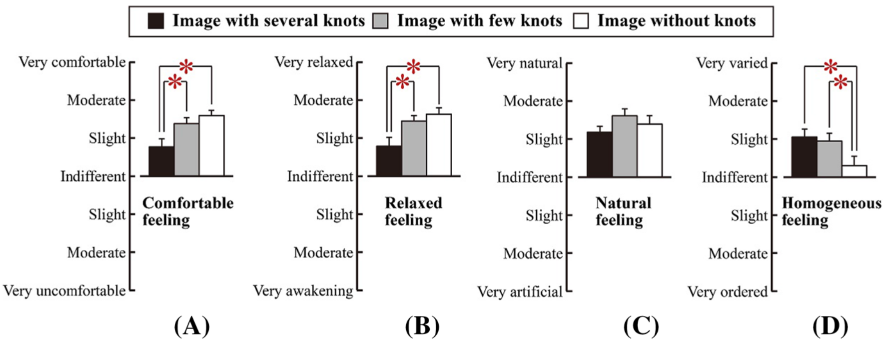

Fig. 4 Subjective evaluations of participants based on the modified semantic differential method questionnaire. Values are presented as means ± standard errors ($N = 28$). *$p < 0.05$ (Wilcoxon singed-rank test with the Holm correction)

higher than that of the wooden-wall image with several knots (Fig. 5, $p < 0.05$). The total mood disturbance score of the wooden-wall image without knots was significantly lower than that of the wooden-wall image with several knots (without knots: -0.7 ± 1.1, several knots: 5.0 ± 2.0, Fig. 5, $p < 0.05$).

Discussion

Several studies that conducted subjective evaluations had shown that knotty woods have lower psychological benefits than clear ones. Hence, compared with the latter, the former may reduce not only psychological but also physiological responses. To validate this assumption, as in a previous study (Ikei et al. 2020), the effects of visual stimulation using knotty and clear woods on physiological responses among humans were compared. Results showed significant physiological differences between gray (control) and knotty and clear wooden-wall images. However, there were no significant differences between the effects of knotty and clear wooden-wall images on physiological responses.

Therefore, the current study aimed to elucidate the impact of the presence or absence and the number of knots on physiological responses among humans. Three full-size wooden-wall images with several and few knots and those without were used as visual stimuli. Then, the oxy-Hb concentrations in the left and right prefrontal cortex and the HRV of participants who were viewing the visual stimuli were assessed. Moreover, subjective evaluations of wooden-wall images using the modified SD method and POMS2 were conducted. Nevertheless, no significant differences could be found in terms of physiological responses induced by the observation of three wooden-wall images. The current and previous studies had similar results.

The contrast (irregularity of color) of knotty wooden-wall images used in this study might be considerably lower than that of real knotty surfaces. The differences

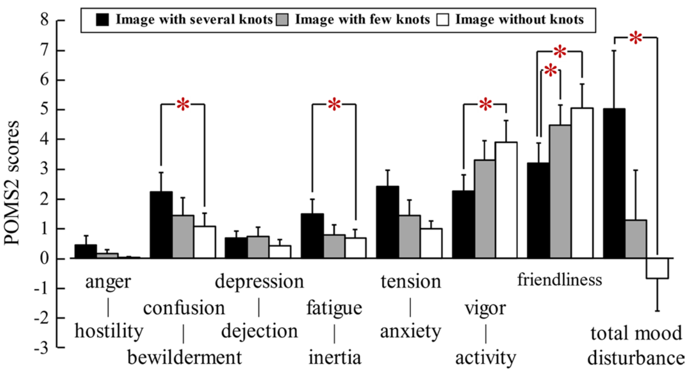

Fig. 5 Subjective feelings based on the Profile of Mood State 2 (POMS2). The seven subscales of the POMS2 test and total mood disturbance score were assessed after observing each wooden-wall image. Values are presented as mean ± standard errors ($N=28$). *$p < 0.05$ (Wilcoxon singed-rank test with the Holm correction)

in physiological responses might not have been observed because of the differences between real knotty surfaces and images of the knotty wood. To reduce undesirable irregularities in wooden-wall images, color differences in inter- or intralumber images and contrasts between knots and its surroundings were significantly controlled, as shown in the histograms in the bottom row of Fig. 1. In addition, all knots on the wooden-wall images were tiny (diameter: < 20 mm). Therefore, knots might not be sufficiently noticeable as a characteristic of wooden-wall images, and the effect of knotty wooden-wall images might have been extremely mild.

By contrast, the current study found that the psychological benefits decreased with the increase in the number of knots, and the clear wooden-wall image had the most significant psychological benefits. These results were consistent with those of other studies (Masuda and Nakamura 1987; 1993, Broman 1995; 1996; 2001, Matsumoto et al. 2016a, b) about the effects of knots based on subjective evaluations. However, there was no correspondence between physiological and psychological responses in the current study.

Such mismatch between physiological and psychological responses indicates two possibilities, which are as follows:

1. Knotty wood can only affect psychological responses, that is, subjective evaluation by the modified SD method and subjective feeling by the POMS2. Therefore, there was no significant difference between physiological responses induced by viewing knotty and clear wooden-wall images.
2. Physiological responses showed no significant changes possibly because the knotty wooden-wall images prepared in the current study demonstrated very mild visual stimuli and the responsivities of the measuring system used were insufficient for detecting slight changes in the physiological responses.

In terms of the first possibility, it should be pointed out that a typical cultural appraisal of knotty woods (which is inferior to clear surfaces commercially and aesthetically) might affect subjective evaluations and subjective feelings, because traditional values like religious faith that lumber without knots is the best have been manifested in Japan for a long time (although not as much as before these days). The effect of cultural appraisal of knotty woods could be assessed via a subjective evaluation of non-Japanese participants who are not aware of such appraisal or screened participants based on their likes and dislikes for knotty wood.

From the perspective of the second possibility, the negative physiological effect of knotty woods could be confirmed if we prepared new visual stimuli, as shown in Fig. 6. That is, to enhance the noticeability of knots, the wooden-wall image should include another lumber with large knots (top row, Fig. 6), and the contrast of grain patterns must be emphasized (bottom row, Fig. 6). To identify whether knotty woods had physiological effects, further experiments must be conducted using the same visual stimuli in the future.

Moreover, in this study, only young women in their twenties were included. To generalize the findings, larger studies with more diverse samples should be conducted.

Conclusion

The physiological and psychological effects of viewing knotty and clear woods were investigated. The three visual stimuli were found to promote comfort and relaxation. The wooden-wall image with few knots, similar to the clear wooden-wall image, had similar effects on psychological responses. Moreover, the

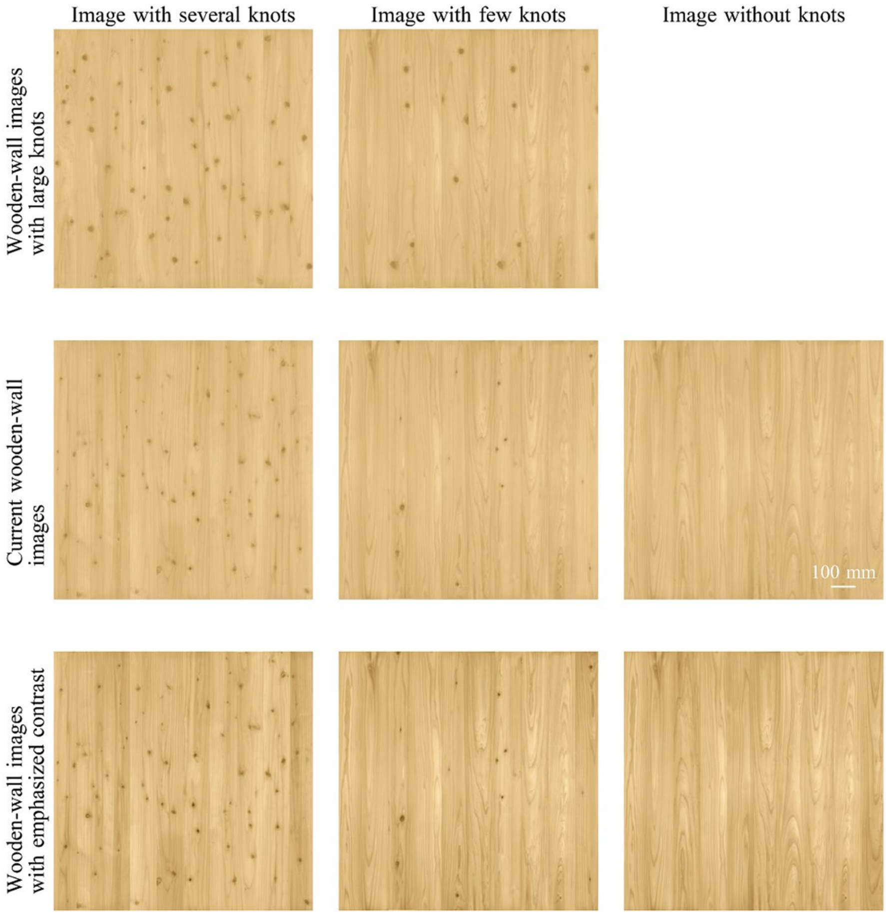

Fig. 6 Example of the modified visual stimuli. To enhance the noticeability of knots, the current wooden-wall images (middle row) were reorganized using another lumber with large knots (top row) or emphasized via contrast enhancement (bottom row)

wooden-wall image with several knots significantly reduced psychological benefits compared with the clear wooden-wall image. However, the presence or absence of knots and the number of knots had no significant effect on oxy-Hb concentrations in the left and right prefrontal cortex and HRV. The physiological effect caused by knotty woods was not confirmed. Nevertheless, it does not indicate an actual absence. Hence, more studies using images with prominent knots as visual stimuli should be performed.

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Declarations

Conflict of interests The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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