



TITLE:

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## ORIGINAL ARTICLE

## Open Access



# Physiological effects of visual stimulation with full-scale wall images composed of vertically and horizontally arranged wooden elements

Masashi Nakamura<sup>1†</sup>, Harumi Ikei<sup>2,3†</sup> and Yoshifumi Miyazaki<sup>3\*</sup>

## Abstract

Wood is a raw material that is used not only in the production of structural members for various buildings, but also in the interior finishes that are directly seen and touched by the occupants. Wood has also been recognized as a human-friendly material, but few studies have experimentally confirmed the physiological benefits it brings to humans. Therefore, the aim of the present study was to investigate the physiological effects of visual stimulation with wood. Two types of full-scale square, wooden-wall images composed of vertically or horizontally arranged lumber, were prepared using computer graphics and projected onto a large display to create the visual stimuli, and a gray image was also prepared as a control. Twenty-eight female Japanese university students participated in the study. The participants initially spent 60 s viewing the gray background (rest period) and then observed each of the wooden-wall images and the gray image separately in a random order for 90 s each. During the visual stimulation, the oxyhemoglobin (oxy-Hb) concentration as an indicator of prefrontal brain activity and heart rate variability as an indicator of autonomic nervous activity were continuously measured in each participant. Subjective evaluation of each visual stimulus was then performed using a modified semantic differential method and the Profile of Mood States 2nd Edition test. It was found that visual stimulation with either of the wooden interior wall images induced a significant decrease in oxy-Hb concentration in the left and right prefrontal cortex compared with the gray image. Furthermore, the subjective evaluation showed that the wooden-wall images provided a significantly more “comfortable,” “relaxed,” and “natural” impression than the gray image and decreased the negative mood states, with the vertically arranged wooden-wall image having a more positive effect than the horizontally arranged image.

**Keywords:** Wood, Wooden interior wall, Horizontally arranged wall, Vertically arranged wall, Visual stimulation, Near-infrared spectroscopy, Heart rate variability, Physiological relaxation, Psychological benefit

## Introduction

Wood is one of the most important natural materials in modern-day human living environments. Wood is used not only as a structural material in various architectural buildings, but also an interior material that is directly seen and touched by building occupants. One plausible

explanation for why wood has been used by humans for such a long time is that it brings various psychological and physiological benefits, as the warm color and various grain patterns of wood stimulate humans visually, while its low thermal conductivity and moderate hardness and stiffness bring tactual warmth and softness.

In modern society, people spend a considerable length of time indoors. Consequently, research has been undertaken to better understand the positive psychological and physiological effects of the natural environment on humans [1–3], which has led to an increased focus on creating natural environments indoors to improve

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occupants' well-being [4], and the use of wood for interior treatments may be considered one way of bringing nature indoors [5–7].

The progress of studies on the relationships between wood and human has been still insufficient to date. However, the psychological benefits that wood brings to humans have been relatively well examined [5, 8]. These studies have mainly focused on the psychological responses evoked by visual, haptic, and/or olfactory stimulation by wood using sensory evaluation methods [9–16]. A part of these studies was developed into the marketing research of wood products [17–20]. Some multi-modal studies have also been carried out [21, 22].

By contrast, few studies have experimentally investigated the physiological benefits of wood to humans. In a recent review of approximately 50 published articles on psychophysiological responses to interior wood treatments, Burnard et al. [4] attempted to classify the research into three categories: “environmental,” “psychological,” and “biological.” However, only four of the 50 articles were placed in the biological (i.e., physiological) category. Furthermore, while Ikei et al. [23] commented that the amount of research on the physiological effects of wood on humans was gradually increasing, only five of the 41 articles published between 1992 and 2016 that they reviewed focused on the physiological effects of visual stimulation with wood, compared with 20 articles that considered olfactory stimulation by wood. In addition, Nakamura [24] found that only 8 of 60 articles published between 1986 and 2011 that focused on wood and wooden interiors as visual stimuli used some kind of physiological indices to evaluate the human responses that were evoked by wood.

Due to this lack of research, the physiological effects of visual stimulation with wood and wooden products are almost completely unknown, despite the frequent use of wood for interior walls, floors, ceilings, and furniture. Consequently, several important questions still remain unanswered, such as does wood act as a visual stimulus and provide humans with physiologically positive effects? How much wood is needed in the interior space to bring a physiologically positive effect on occupants? Do knots, which are often avoided for visual aesthetic reasons [25, 26], actually lead to physiologically negative effects on observers? Does a different lumber arrangement on the interior walls (i.e., vertical vs. horizontal) affect the physiological effect on observers?

The aim of the present study was to examine the physiological effects of visual stimulation with wood. To do this, participants were asked to observe different wooden interior wall images, during which time the activities in the left and right prefrontal cortex and heart rate

variability were measured as indices of their central and autonomic nervous system activities, respectively.

## Methods

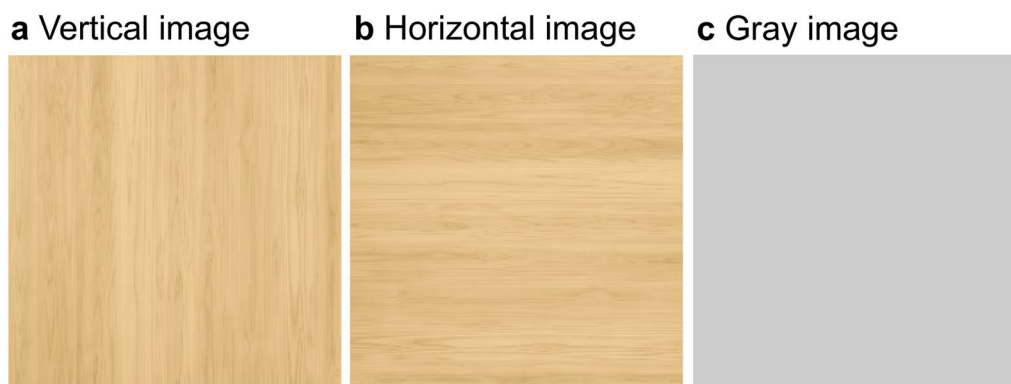
### Participants

Twenty-eight female Japanese university students participated in the present study. These participants had a mean age ( $\pm$  standard deviation) of  $22.3 \pm 2.1$  years, mean right and left eyesight scores of  $1.0 \pm 0.2$  and  $1.0 \pm 0.3$  (including corrected), a mean height of  $158.8 \pm 6.0$  cm, and a mean weight of  $51.9 \pm 5.9$  kg. Individuals who smoked were being treated for any disease, or had their menstrual period during the study period were excluded from the study. All participants were informed about the aim and procedures of the study, following which they gave written consent to participate. 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 35) and was registered in the University Hospital Medical Information Network of Japan (UMIN; unique ID: UMIN000034011).

### Visual stimulation

#### Preparation of wooden-wall images

Fifteen high-definition color photographs of individual boards of flat-sawn clear lumber of Japanese cedar (*Cryptomeria japonica*; length 2500 mm, width 170 mm) were taken using a digital still camera (Powershot G7 X Mark II; Canon, Tokyo, Japan). To ensure that all of the images would be displayed on a screen at the same size, the images were reduced and clipped to give a final size of 1053 mm  $\times$  125 mm (2160  $\times$  256 pixels). Photoretouching was also applied to the lumber images to adjust and standardize their color and contrast. Namely, every lumber image was transformed to a statistically equivalent image that had a given mean gray level and standard deviation. Nine lumber images, which had relatively consistent grain patterns, were selected as wall components. A virtual wall image of 2160  $\times$  2304 pixels was created by consecutively and randomly arranging the lumber images. A square wall image of 2160  $\times$  2160 pixels was obtained from the center of the virtual wall image to prepare two types of square wooden-wall images: a vertical type and a horizontal type, which was produced by rotating the vertical type 90° to the right (Fig. 1). In addition, a gray wall image whose brightness was the same as the wooden-wall images was prepared as a control. Each wall image had a resolution of 2160  $\times$  2160 pixels, and each pixel consisted of three kinds of 8-bit gray levels corresponding to red, green, and blue, respectively.



**Fig. 1** Three images that were used as the visual stimuli. **a** Wooden interior wall image arranged vertically; **b** wooden interior wall image arranged horizontally; **c** gray image (control)

**Table 1** Physical properties of the three images that were projected on the large display

	Vertical image	Horizontal image	Gray image
$L$ (cd/m <sup>2</sup> ) <sup>a</sup>	11.4 ± 0.4	11.6 ± 0.4	11.1 ± 0.4
$E_v$ (lx) <sup>b</sup>	5.2	5.2	5.2

$L$  luminance of the display,  $E_v$  illuminance at eye level for the participants

<sup>a</sup>  $L$  was measured at five points at equal intervals in the vertical and horizontal directions using a color meter (CS-100A; Konica Minolta, Tokyo, Japan) and the mean and standard deviation were calculated (mean ± SD)

<sup>b</sup>  $E_v$  was measured three times at eye level for the participants using an illuminance spectrophotometer (CL-500A; Konica Minolta, Tokyo Japan) and the average value was calculated. The variation in  $E_v$  values was very low (from 5.21 lx to 5.26 lx)

### Presentation of visual stimuli

The three images shown in Fig. 1 were presented to each of the participants as visual stimuli. The images were projected at a size of 1053 mm × 1053 mm onto a 4 K-compatible high-vision liquid-crystal display that was 1872 mm wide, 1053 mm high, and had a resolution of 3840 × 2160 pixels (85 V type, TH-85AX900; Panasonic, Osaka, Japan).

The display was set in a dark experimental chamber and each participant sat in an office chair located 1.1 m away from the display. The brightness of the display was adjusted to a relatively low level to avoid eyestrain of the participants who were observing the visual stimuli consecutively. The luminance of the display and illuminance at eye level for the participants were measured using a color meter (CS-100A; Konica Minolta, Tokyo, Japan) and an illuminance spectrophotometer (CL-500A; Konica Minolta, Tokyo Japan), respectively, which showed that all images provided almost the same luminance and illuminance (Table 1).

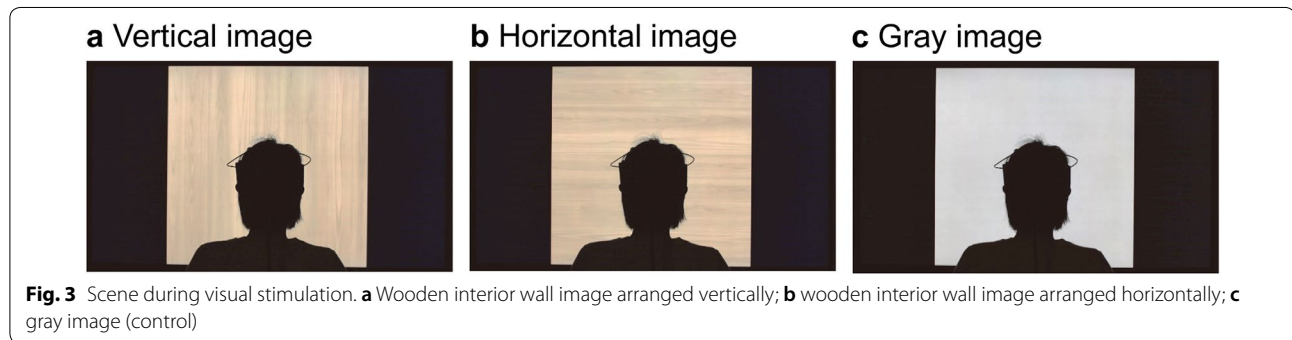
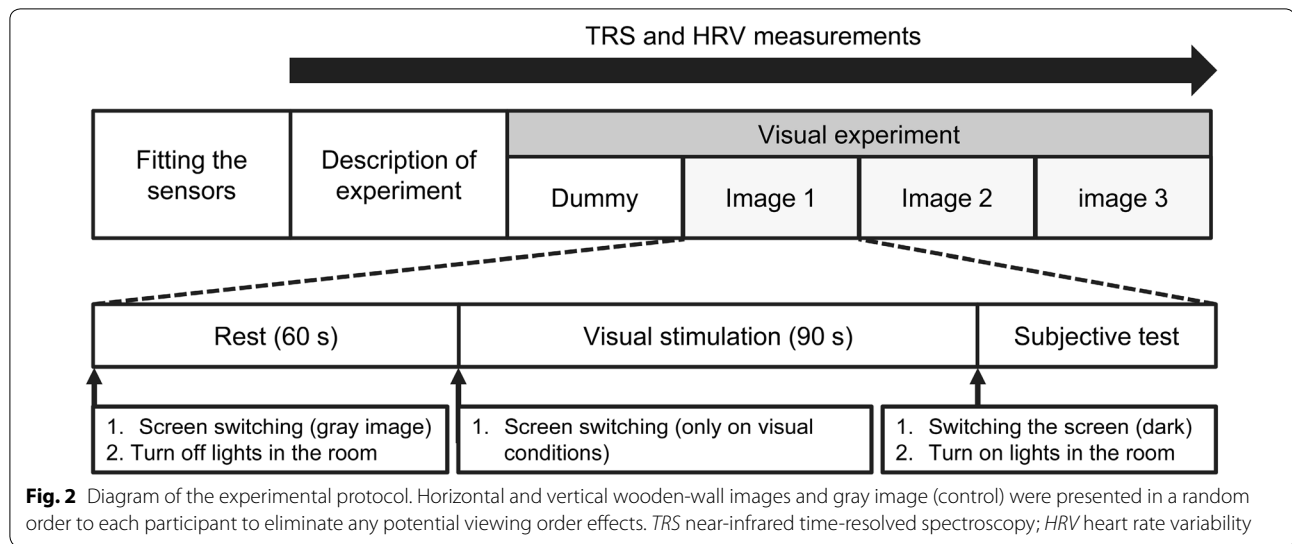
### Study protocol

Physiological measurements were performed in an artificial climate chamber that was maintained at 24 °C, 50% relative humidity, and 50 lx illumination at the Center for Environment, Health and Field Sciences, Chiba University. Each participant received an exposition of the experiment in a waiting room before entering the chamber. After fitting the sensors for physiological measurement, each participant received a description of the measurement procedure while seated and observed a dummy image (a brick wall) as an experimental rehearsal. The display was then switched to a gray background and the lights in the room were turned off. The participants viewed the gray background for 60 s (rest period), following which they observed each of the wooden-wall images and gray image separately for 90 s each while remaining seated. The wooden-wall images and gray image were presented in a random order for each participant to eliminate any potential viewing order effects. During the visual stimulation, the participants' physiological responses were continuously measured. Following the visual stimulation, the display was switched to a dark background, the lights were turned on, and a subjective evaluation was conducted. Figure 2 outlines the experimental procedure that was used, while Fig. 3 shows three scenes during the visual stimulation.

### Physiological measurements

#### Near-infrared time-resolved spectroscopy (TRS)

TRS was used to indicate the participants' brain activities during the visual stimulation [27, 28]. This method is based on the principle that an increase in local brain activity causes the blood flow to the brain to increase, leading to significant perfusion, such that the quantity of brain blood flow exceeds oxygen consumption [29].



Consequently, the oxyhemoglobin (oxy-Hb) concentration increases, which can be detected by the change in absorbance of near-infrared light irradiating the brain. Hoshi et al. [30] reported that increases or decreases in the quantity of blood flow in the brain are consistent with changes in oxy-Hb. After its discovery in 1992, Ferrari et al. [31] presented a brief historical overview of functional near-infrared spectroscopy in 2012 that functional activation of the human cerebral cortex associated with oxygenation and hemodynamic changes can be explored using near-infrared spectroscopy (NIRS). TRS was one of the NIRS approaches that progressed over these 20 years.

The prefrontal cortex is a part of the brain that is responsible for higher order judgements, such as problem-solving and decision-making. Cui et al. [32] scanned participants using simultaneous NIRS (placing NIRS probes over the frontal brain region including the prefrontal region) and functional magnetic resonance imaging during a battery of cognitive tasks and found that NIRS signals were highly correlated with functional magnetic resonance imaging measurements. This finding suggests that NIRS enables the detection of

brain activity in the prefrontal cortex region. Some previous studies reported that the oxy-Hb concentration in the prefrontal cortex significantly reduced and the subjective relaxed feeling significantly improved simultaneously in participants who had been exposed to visual [33–35], tactile [36–38], auditory [39], or olfactory [40] stimulation.

Considering these findings, in the present study, sensors were mounted on each participant's forehead at approximately Fp1 and Fp2 of the international 10–20 system for electroencephalography, and the oxy-Hb concentration in the left and right prefrontal cortex was measured during the 60-s rest period and each 90-s visual stimulation period using the TRS-20 system (Hamamatsu Photonics, Shizuoka, Japan). Since the data-sampling interval of the TRS-20 system fluctuated from 1.07 to 1.12 s, the interval was converted to 1.0 s for each data point using a linear interpolation technique to obtain 1-Hz data for the oxy-Hb concentration in the left and right prefrontal cortex. The difference of each data point from the mean value during the last 30 s of the rest period was then calculated. In addition, the overall mean

value during each 90-s visual stimulation period was calculated.

#### Heart rate variability (HRV) and heart rate

The HRV and heart rate of each participant were measured as indicators of the autonomic nervous system activity [41, 42]. HRV was analyzed for the periods between consecutive R waves (RR intervals) on an electrocardiogram that was measured using a portable electrocardiograph (Activtracer AC-301A; GMS, Tokyo, Japan), with a sampling frequency of 1 kHz. The power levels of the low-frequency (LF; 0.04–0.15 Hz) and high-frequency (HF; 0.15–0.40 Hz) components of HRV were then calculated using the maximum-entropy method (MemCalc/Win; GMS, Tokyo, Japan). The HF power was considered to reflect parasympathetic nervous activity, which is generally enhanced during relaxation, while the LF-to-HF ratio (LF/HF) was considered to reflect sympathetic nervous activity, which is enhanced at the time of awakening or in stressful situations. To normalize the HRV parameters across the participants, a natural logarithmic transformation was applied to the calculated values [43]. Changes in the values of HF and LF/HF every 30 s and the overall mean during each 90-s visual stimulation period were determined.

#### Psychological measurements

Psychological measurements were performed using a modified semantic differential (SD) method and the Profile of Mood State 2nd Edition (POMS 2). The SD method subjectively assesses the mental state of a participant through a questionnaire that is composed of pairs of opposing adjectives, each of which is evaluated on a 13-point scale [44]. In the present study, the four adjective pairs “comfortable–uncomfortable,” “relaxed–awakening,” “natural–artificial,” and “varied–ordered” were used to evaluate the extent of feeling comfortable, relaxed, natural, and homogeneous, respectively.

The POMS 2 is a well-established measure of psychological distress derived from factor analysis that has been shown to have high levels of reliability and validity [45–48]. This test simultaneously evaluates seven moods: tension–anxiety (T–A), depression–dejection (D–D), anger–hostility (A–H), fatigue–inertia (F–I), confusion–bewilderment (C–B), vigor–activity (V–A), and friendliness (F). The total mood disturbance (TMD) score is then calculated from the formula [(T–A) + (D–D) + (A–H) + (F–I) + (C–B) – (V–A)]. The TMD score reflects the general mood state, whereby the higher the score is, the more negative are the feelings of the participant and vice versa. In the present study, the Japanese

version of the POMS 2 was used, which is a shortened form with 35 questions, to reduce the burden on the participants.

#### Statistical analysis

Physiological responses to the three visual stimuli (the vertically and horizontally arranged wooden-wall images and the gray wall image) were examined by comparing changes in the physiological indices and the overall mean values over the 90-s visual stimulation periods 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 used with the Holm correction. In both cases, two-sided tests were used, because it was unknown which wooden-wall image would bring the more restful state to the participants physiologically and psychologically. All statistical analyses were performed using the Statistical Package for the Social Sciences software (SPSS version 21.0; IBM Corp., Armonk, NY, USA), and a *p* value of less than 0.05 was considered statistically significant.

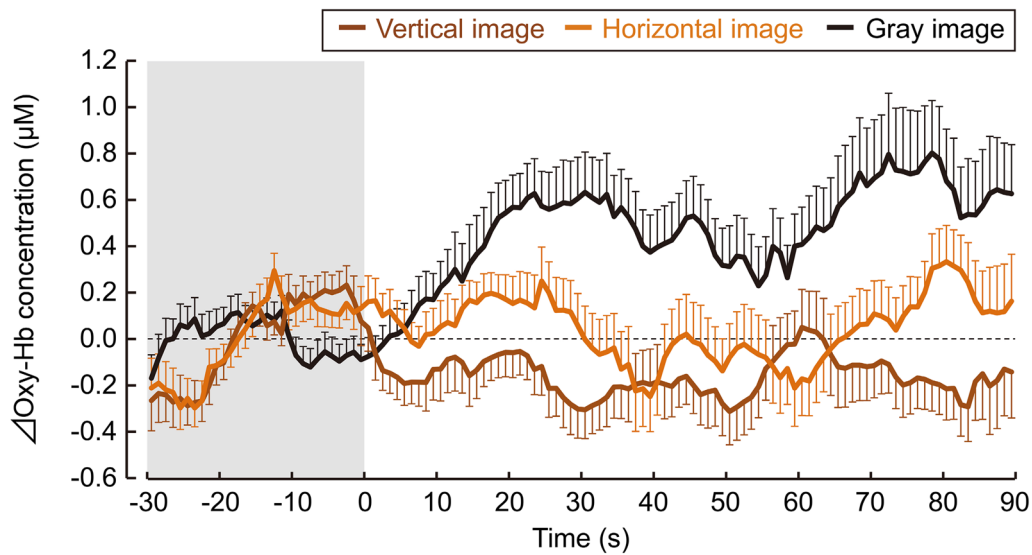
## Results

### Physiological effects

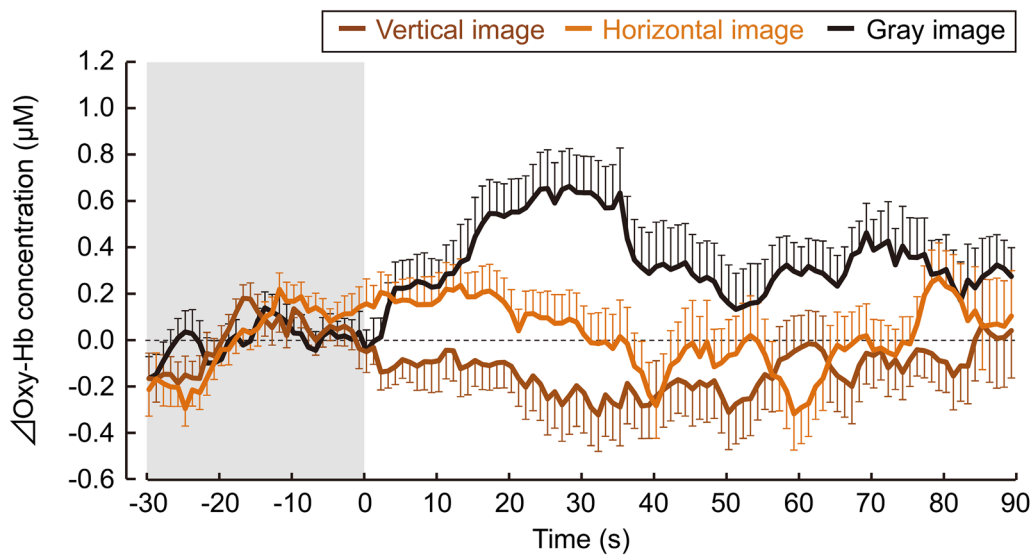
#### TRS

Changes in the oxy-Hb concentrations in the left and right prefrontal cortex during visual stimulation are shown in Figs. 4 and 5, respectively. During observation of the vertical wooden-wall image, the Oxy-Hb concentration gradually decreased in the first half of the observation period and then mostly remained below zero thereafter. By contrast, when the gray image was observed, the oxy-Hb concentrations in the left and right prefrontal cortex immediately increased at the start of the observation period and remained higher than the initial levels with the two wooden-wall images throughout the observation period. Finally, in the case of the horizontal wooden-wall image, the oxy-Hb concentration laid between that of the gray and vertical wooden-wall images and was slightly greater than zero during most of the visual stimulation period. There was no significant difference in the mean oxy-Hb concentration baseline during the last 30-s rest period (gray areas in Figs. 4, 5) among the three visual stimuli [left prefrontal cortex: vertical image =  $44.92 \pm 1.13$   $\mu\text{M}$  (mean  $\pm$  standard error), horizontal image =  $45.36 \pm 1.16$   $\mu\text{M}$ , gray image =  $45.42 \pm 1.22$   $\mu\text{M}$ ; right prefrontal cortex: vertical image =  $43.90 \pm 1.23$   $\mu\text{M}$ , horizontal image =  $44.57 \pm 1.20$   $\mu\text{M}$ , and gray image =  $43.67 \pm 1.33$   $\mu\text{M}$ ]. The unit M indicates molar concentration, and it equals to mol/dm<sup>3</sup>.

The overall mean oxy-Hb concentrations in the left and right prefrontal cortex during the 90-s visual stimulation periods with the two wooden-wall images and



**Fig. 4** Changes in the oxyhemoglobin (oxy-Hb) concentrations in the left prefrontal cortex. The oxy-Hb concentrations of participants during visual stimulation with vertical and horizontal wooden-wall images and a gray image (control) were measured every second over a 90-s period. The difference in each data point from the mean value during the last 30 s of the rest period (gray area) is presented in this chart. Data are expressed as means  $\pm$  standard errors ( $N=28$ )



**Fig. 5** Changes in the oxyhemoglobin (oxy-Hb) concentrations in the right prefrontal cortex. The oxy-Hb concentrations of participants during visual stimulation with vertical and horizontal wooden-wall images and a gray image (control) were measured every second over a 90-s period. The difference in each data point from the mean value during the last 30 s of the rest period (gray area) is presented in this chart. Data are expressed as means  $\pm$  standard errors ( $N=28$ )

the gray image are shown in Fig. 6. Observation of the wooden-wall images led to significantly lower oxy-Hb concentrations than observation of the gray image in the left and right prefrontal cortex (left prefrontal cortex: vertical image =  $-0.16 \pm 0.09 \mu\text{M}$ , horizontal

image =  $0.04 \pm 0.10 \mu\text{M}$ , gray image =  $0.46 \pm 0.14 \mu\text{M}$ ; right prefrontal cortex: vertical image =  $-0.14 \pm 0.09 \mu\text{M}$ , horizontal image =  $0.03 \pm 0.09 \mu\text{M}$ , gray image =  $0.35 \pm 0.11 \mu\text{M}$ ). Although the overall mean oxy-Hb concentration was lower during observation of the vertical wooden-wall

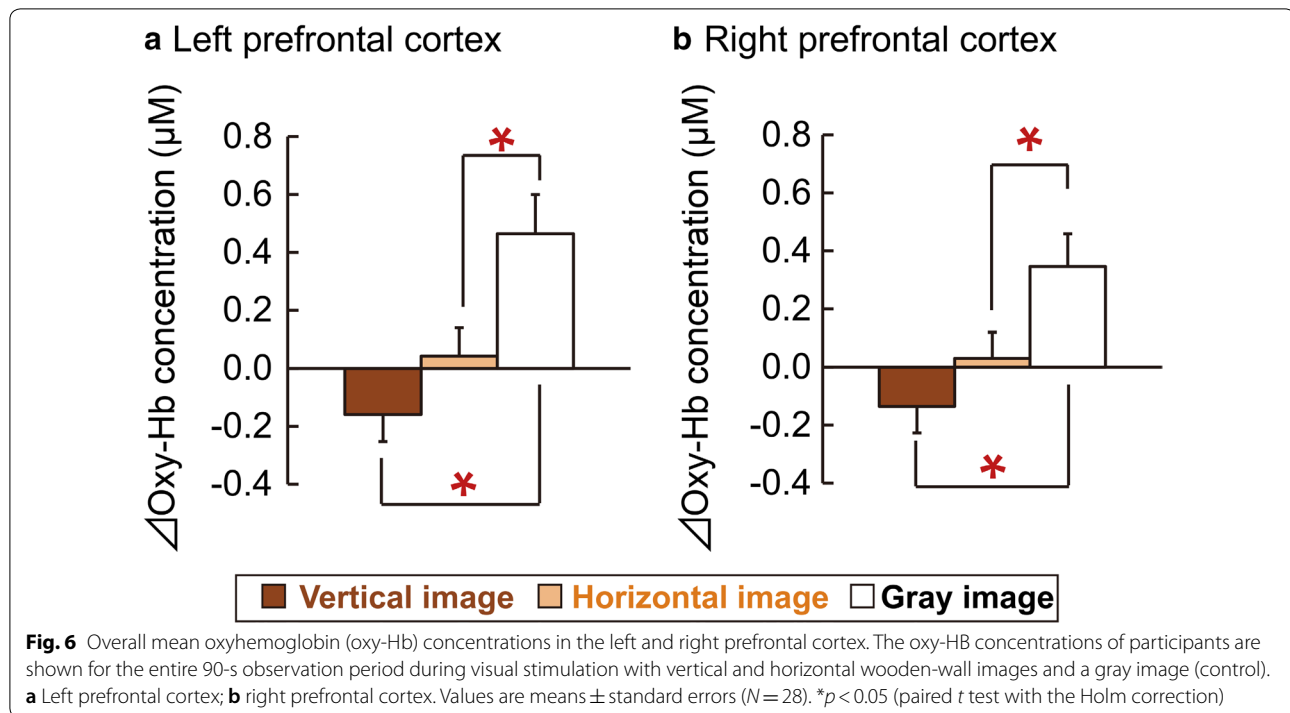


image than during observation of the horizontal wooden-wall image, this difference was not significant.

#### HRV and heart rate

There were no significant differences in the HF value (an index of parasympathetic nervous activity), the LF/HF ratio (an index of sympathetic nervous activity), or the heart rate of participants among the three visual stimuli (i.e., the horizontal wooden wall, vertical wooden wall, and gray images). The changes in the 30-s means and overall means of the HF value, LF/HF ratio, and heart rate are shown in Additional file 1: Figs. S1–S3, respectively.

#### Psychological effects

Figure 7 shows the results of the modified SD method, which was used to evaluate the subjective feelings of “comfortable–uncomfortable,” “relaxed–awakening,” “natural–artificial,” and “varied–ordered” among participants after the observation of each image. The participants had significantly more “comfortable,” “relaxed,” “natural,” and “varied” feelings after they had observed the wooden-wall images compared with the gray image ( $p < 0.05$ ). Furthermore, observation of the vertical wooden-wall image evoked a significantly more “relaxed” feeling than the horizontal wooden-wall image and the gray image ( $p < 0.05$ ).

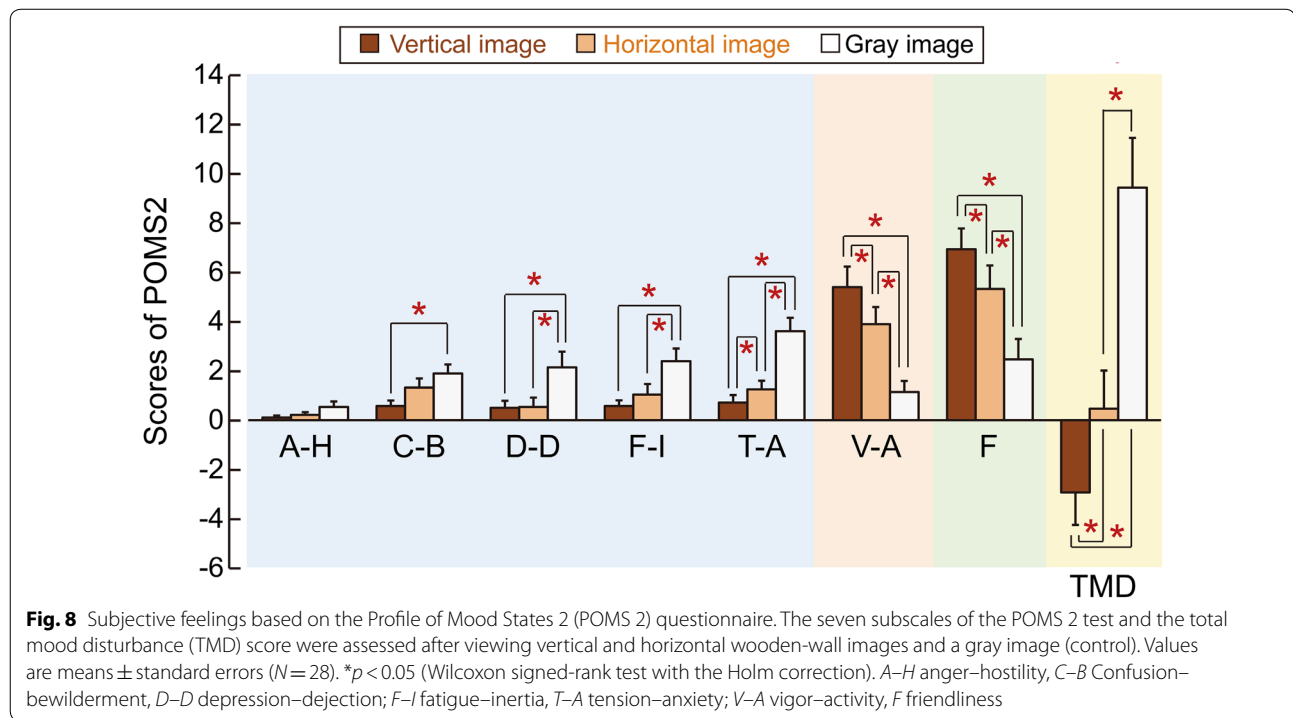
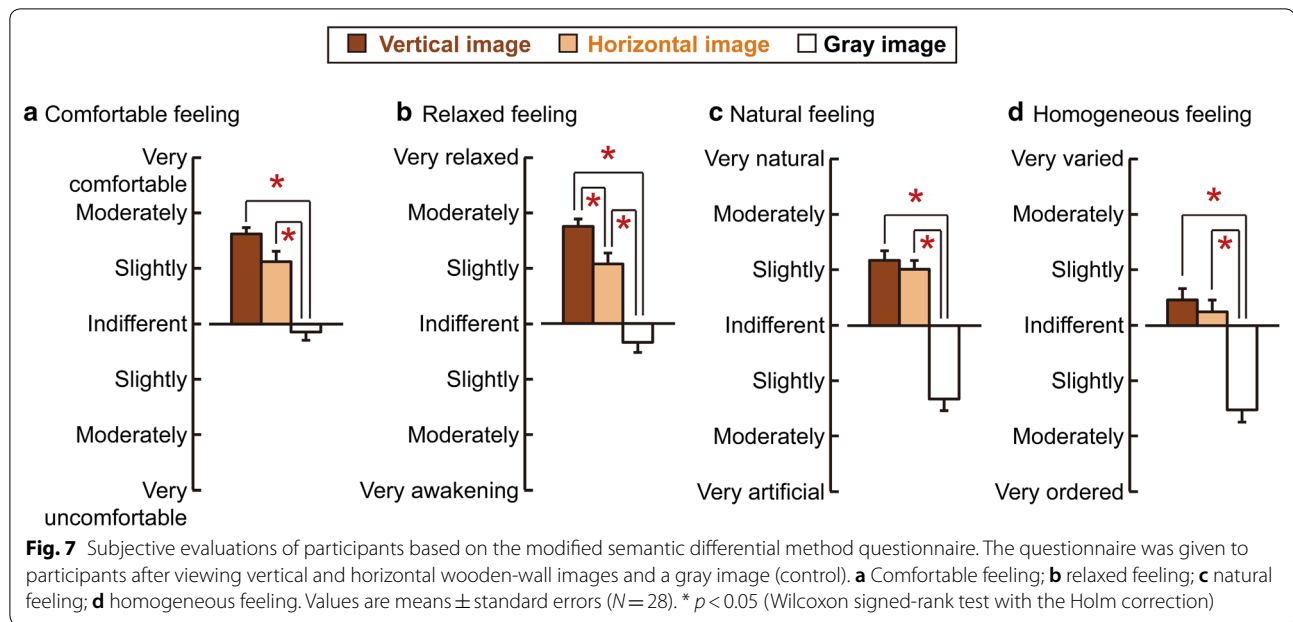
In the POMS 2 test, significant differences were detected among the wooden wall and gray images for

all POMS 2 subscales except A–H (Fig. 8). The negative mood state scores of the D–D, F–I, and T–A subscales were significantly lower for the wooden-wall images than for the gray image ( $p < 0.05$ ), while the negative mood state score of the C–B subscale was significantly lower for the vertical wooden-wall image than for the gray image ( $p < 0.05$ ). Furthermore, in the T–A subscale, the score was also significantly lower for the vertical wooden-wall image than for the horizontal wooden-wall image ( $p < 0.05$ ). By contrast, the positive mood state scores of the V–A and F subscales were significantly higher for the wooden-wall images than for the gray image ( $p < 0.05$ ), as well as for the vertical wooden-wall image compared with the horizontal wooden-wall image ( $p < 0.05$ ). The TMD score, which provides a comprehensive assessment of the negative mood state, was significantly lower for the wooden-wall images than for the gray image ( $p < 0.05$ ) and was also significantly lower for the vertical wooden-wall image than for the horizontal wooden-wall image ( $p < 0.05$ ) (Fig. 8).

#### Discussion

The present study examined the physiological effects of visual stimulation with wooden-wall images by assessing the left and right prefrontal cortex activities through measurement of the oxy-Hb concentrations using TRS and the autonomic nervous activity through measurement of HRV and the heart rate. In addition, the psychological effects were also examined through subjective assessments by the participants.





It was found that visual stimulation with wooden-wall images projected on a large display significantly decreased the oxy-Hb concentrations in the left and right prefrontal cortex based on the overall mean values during the 90-s observation period, but had no significant effect on the autonomic nervous activities of the participants

(HRV and heart rate). Similarly, Song et al. [35] reported that a significant decrease in the oxy-Hb concentration in the right prefrontal cortex of the observers who were visually stimulated with a forest image projected on a large screen compared with that of the observers who were visually stimulated with a city image. However, they found

no significant effect on autonomic nervous system activities. In a screen image study on oxy-Hb concentration changes in the prefrontal cortex, Hoshi et al. [49] showed that pleasant feelings decrease oxy-Hb concentrations, whereas unpleasant feelings increase its concentrations. Taken together, the significant decrease in oxy-Hb concentrations in the left and right prefrontal cortices found in the present study suggests that visual stimulation with wooden-wall images can effectively calm prefrontal cortex activities while having no impact on autonomic nervous system activities.

In the present study, significant decreases in the oxy-Hb concentration were noted in the left and right prefrontal cortices. In the previous TRS studies using various sensory stimuli, significant differences were noted in only the left prefrontal cortex [34, 37, 50], only the right prefrontal cortex [33, 35, 39, 40, 51, 52], or both cortices [36, 38, 53–55]. Thus, it is not clear whether a significant decrease in the oxy-Hb concentration occurs in the right prefrontal cortex, left prefrontal cortex, or both cortices, and further investigations are needed in the future.

As the significant effects of visual stimulation on the autonomic nervous activities of participants (HRV and heart rate) have been confirmed many times previously [34, 52, 56–58], measurements and analyses similar to those in the previous studies were adopted in the present study. However, no significant differences were noted in the HF value, LF/HF ratio, and heart rate of participants in the present study. It is possible that the visual stimulation used in the present study was insufficient to induce significant changes in autonomic nervous activities, although it was sufficient with regard to prefrontal cortex activity. The suspected impact of some factors, such as the spectral characteristics of the large display to present the visual stimuli, type of grain pattern, and magnitude of the contrast of grain pattern, on the results should be verified in the future experiments. Nevertheless, the present study provides the first evidence of the physiological effects produced by visual stimulation with full-scale wooden-wall images presented on a large display.

The results of the subjective evaluations were consistent with those for the prefrontal cortex activities. With the modified SD method, the scores for “comfortable,” “relaxed,” “natural,” and “varied” feelings were significantly higher for the wooden-wall images than for the gray image (Fig. 7), while in the POMS 2 test, the negative mood state scores of the D–D, F–I, and T–A subscales and the TMD score were significantly lower and the positive mood state scores of the V–A and F subscales were significantly higher for the wooden-wall images than for the gray image (Fig. 8). These findings support the observed calming down of the prefrontal cortex activities by the observation of the wooden-wall images, as

this would lead to these positive psychological responses. One particularly interesting finding was that the wooden-wall images were evaluated as being slightly “varied”—i.e., were neither “ordered” nor excessively “varied” visually—which probably affected the physiological and/or psychological responses of the participants.

In terms of the two wooden-wall images, the vertical wooden-wall image had a significantly higher score for “relaxed” feeling with the modified SD method (Fig. 7) and significantly lower scores on the T–A subscale and for TMD and significantly higher scores on the V–A and F subscales in the POMS 2 test (Fig. 8) than the horizontal wooden-wall image. In addition, the oxy-Hb concentrations in the left and right prefrontal cortex tended to be lower during the 90-s observation of the vertical wooden-wall image than during observation of the horizontal wooden-wall image (Figs. 4, 5), although the difference in the overall mean oxy-Hb concentrations in both wooden-wall images was not statistically significant (Fig. 6), indicating that the psychological effect of the visual stimulation with the vertical wooden-wall image was consistent with the prefrontal brain activity. As shown in Fig. 6, visual stimulation involving the vertical wooden-wall image provided negative values of the overall mean oxy-Hb concentrations in the left and right prefrontal cortices, whereas the horizontal wooden-wall image provided slightly positive values. This difference in the activities of the prefrontal cortex between vertical and horizontal wooden-wall images might affect the above-mentioned subjective evaluations.

The vertical and horizontal wooden-wall images were essentially identical, originating from the same image rotated by 90 degrees, and yet they elicited different physiological and psychological responses. This strongly suggests that the strength of the positive effect of visual stimulation with natural materials such as wood will depend on the design of the interior walls. This is the first observation of the vertical and horizontal arrangements of wooden-wall images having different physiological and psychological effects, so the mechanism that causes this difference is currently unknown. Therefore, a different experimental design and new visual stimuli should be used in the future to confirm this finding.

Another limitation of the present study is that all participants were female. Although many previous studies have reported the existence of differences in various human physiological responses according to sex, the TRS findings, HRV, and heart rate of male participants with regard to wood assessed using the same procedures are unknown at present. Thus, for complementing the knowledge obtained from the present study, an additional study to obtain the physiological and psychological data of male participants should be considered in the near future.

## Conclusions

Visual stimulation with wooden-wall images significantly decreased the oxy-Hb concentrations in the left and right prefrontal cortex compared with observation of a gray image, indicating a calming of the prefrontal cortex activities. Furthermore, the observation of the wooden-wall images had a positive psychological effect on participants, significantly improving the perception of “comfortable,” “relaxed,” and “natural” feelings, and bringing about positive mood states and significantly repressing negative mood states, which is consistent with the observed changes in the prefrontal cortex activities. Together, these findings indicate that the observation of a wooden-wall image induces physiological and psychological relaxation.

## Supplementary information

**Supplementary information** accompanies this paper at <https://doi.org/10.1186/s10086-019-1834-0>.

**Additional file 1.** Additional figures.

## Abbreviations

TRS: near-infrared time-resolved spectroscopy; oxy-Hb: oxyhemoglobin; HRV: heart rate variability; HF: high frequency; LF: low frequency; SD: semantic differential; POMS 2: profile of mood state 2nd edition; T-A: tension-anxiety; D-D: depression-dejection; A-H: anger-hostility; F-I: fatigue-inertia; C-B: confusion-bewilderment; V-A: vigor-activity; F: friendliness; TMD: total mood disturbance.

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## Authors' contributions

MN contributed to the conceptualization, investigation, methodology, visualization, and writing of the original draft. HI contributed to the conceptualization, data curation, formal analysis, investigation, methodology, visualization, and review and editing of the report. YM contributed to the conceptualization, data curation, funding acquisition, investigation, methodology, project administration, supervision, validation, visualization, and review and editing of the report. All authors read and approved the final manuscript.

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## Availability of data and materials

The data sets used and/or analyzed during the current study are available from the corresponding author on reasonable request.

## Competing interests

The authors declare that they have no competing interests.

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