Journal of Environmental Psychology 110 (2026) 102925

Contents lists available at ScienceDirect

Journal of Environmental Psychology

journal homepage: www.sciencedirect.com/journal/journal-of-environmental-psychology

The psychological effects of Scots pine (*Pinus sylvestris*) wood scent, virtual wooden walls, and their combined stimuli on humans

Tuula Jyske [a,b,*], Valtteri Kutvonen [b], Janne Kaseva [c], Mika Kurkilahti [d], Heidi Hellén [e], Toni Tykkä [e], Emilia Rosenborg [a], Madli George [a], Saša Tkalčan [f], Jutta Kauppi [g]

[a] Department of Forest Sciences, Faculty of Agriculture and Forestry, PO Box 27, University of Helsinki, 00014, Finland
[b] Natural Resources Institute Finland, Food and Bioproducts, Production Systems Unit, Viikinkaari 9, Helsinki, 00790, Finland
[c] Natural Resources Institute Finland, Applied Statistical Methods, Natural Resources Unit, Tietotie 4, Jokioinen, 31600, Finland
[d] Natural Resources Institute Finland, Applied Statistical Methods, Natural Resources Unit, Itäinen Pitkäkatu 4 A, Turku, 20520, Finland
[e] Finnish Meteorological Institute, Erik Palménin Aukio 1, Helsinki, 00560, Finland
[f] Services for Digital Education and Continuous Learning, PO Box 59, University of Helsinki, 00014, Finland
[g] Natural Resources Institute Finland, Research and Customer Relationships, Latokartanonkaari 9, Helsinki, 00790, Finland

ARTICLE INFO

Keywords:
Mood
olfactory
Virtual
Visual
VOCs
Wood

ABSTRACT

Wood construction uses forest biomass effectively and stores carbon. As a biophilic material, wood provides wellbeing benefits; however, its sensory properties, particularly those of Scots pine (*Pinus sylvestris*), one of the most commonly used wood species in construction, remain under-researched. A study involving 50 participants examined the effects of wood scent and visual stimuli on wellbeing. Participants visited a control room and rooms featuring scent, virtual walls, or both, completing tests and questionnaires. The results indicated that virtual walls combined with wood scent significantly reduced stress and enhanced restoration, with a mean Restoration Outcome Scale (ROS) score 0.47 points higher than the control and 0.30 points higher than with scent alone. There is a 96 % and 92 % confidence that ROS values are greater with both stimuli. While no significant difference was found between single stimuli, there is a 92 % certainty that ROS is higher with virtual walls compared to the control. These findings suggest that wooden virtual environments and wood scent could support cognitive training and emotional regulation. However, further research is needed to explore long-term effects and optimal stimulus levels.

1. Introduction

The relationship between humans and nature has been studied from various disciplinary perspectives, including environmental science, ecopsychology, and sociology. Research indicates that regular contact with nature can significantly reduce stress and enhance mood (Aerts et al., 2018; Giusti, 2019; Ojeda et al., 2022). In contrast, the influence of the built environment and different construction materials on individual's perceived wellbeing has not been as extensively explored, although the volume of relevant studies is increasing (Ige et al., 2019; Nyrud & Bringslimark, 2010). As people continue to spend more time indoors, it is essential to place greater emphasis on the comfort of living spaces.

Ulrich (1983) introduced the stress recovery theory on the influence of natural environments and materials on human stress levels. According to the theory, environmental factors, particularly natural surroundings and materials, positively impact human wellbeing. His landmark study demonstrated that patients with views of natural landscapes from their hospital rooms recovered more quickly than those whose views were of concrete walls. The theory posits that natural environments stimulate the parasympathetic nervous system, promoting relaxation and stress reduction. Elements of nature, such as vegetation, wood, and water, create a calming atmosphere, which can lower blood pressure, reduce stress, and enhance mood (Ulrich, 1983). This theory has been used in numerous studies (e.g., Tsunetsugu et al., 2013) and has been expanded through recent research highlighting nature's role in mental wellbeing (Corazon et al., 2019). Corazon et al. (2019) analyzed 36 studies focusing on the effects of natural environments on stress relief, revealing that time spent in nature significantly reduced stress and improved mood.

* Corresponding author. Department of Forest Sciences, Faculty of Agriculture and Forestry, PO Box 27, University of Helsinki, 00014, Finland.
E-mail address: tuula.jyske@helsinki.fi (T. Jyske).

https://doi.org/10.1016/j.jenvp.2026.102925
Received 23 June 2025; Received in revised form 22 January 2026; Accepted 22 January 2026
Available online 29 January 2026

The biophilia hypothesis suggests that humans have an inherent need to connect with nature and other forms of life (Wilson, 1984). Initially introduced by Fromm (1973), Wilson later refined the concept with an evolutionary perspective. Research indicates that exposure to nature positively influences physical and mental health, reducing stress and enhancing wellbeing through activities like outdoor recreation and exposure to natural sounds (van Riper et al., 2019). Unfortunately, urbanization has reduced individuals' contact with natural environments, potentially harming urban residents' wellbeing (van Riper et al., 2019.

Biophilic design aims to create indoor spaces that evoke natural settings by incorporating elements such as natural materials, wood, houseplants, natural light, and even the scents associated with these materials (Ryan et al., 2014). This design approach has gained popularity in response to urbanization and middle-class expansion, seeking to promote wellbeing in built environments (Africa et al., 2019). Biophilia is also integral to ecopsychology, which investigates human-environment interactions and the impact of nature on psychological health and attitudes toward issues like climate change (Africa et al., 2019). Limited contact with nature can lead to feelings of alienation, particularly among those living in urban areas (Soga & Gaston, 2020).

The decline in accessible natural areas, exacerbated by urbanization and population growth, threatens childhood experiences that foster a connection to nature (Molinario et al., 2020; Seymour, 2016). If this trend continues, the biophilia concept may need re-evaluation. However, advancements in technology could offer new ways to experience nature, including through virtual and indoor environments, which may also provide benefits similar to real interactions with nature (Mollazadeh & Zhu, 2021).

Research into the wellbeing benefits of virtual natural environments has been conducted (e.g., Adhyaru, 2022; Lakhani et al., 2020; Meuwese et al., 2021; Owens & Bunce, 2023). However, in most cases, the focus is solely on virtual nature such as forests or parks. Virtual reality has also been used to study the effect of room interior designs (e.g., Tawil et al., 2021), albeit not regarding wood use. In contrast, research using virtually created complete wooden structures and walls imitating real wood with large monitors or projectors appears to be rare, likely because facilities where such research could be conducted are limited in number and a relatively new phenomenon. Studies showing pictures of wood and wooden rooms on smaller singular monitors have been conducted, however (e.g., Li et al., 2021; Nakamura et al., 2019, 2022), giving promising results for the suitability of such virtual methods.

Studies examining physical interior wood coverage have reported dose-sensitive responses: moderate to high wood coverage has been found to often enhance perceived warmth and comfort and modulated physiological indices, although optimal levels may vary by context and user (Tsunetsugu et al., 2002, 2005; 2007; Kwak & Choi, 2025).

Recent research has shown that virtual environments can be used for different purposes to impact on individuals' wellbeing, such as supporting emotion regulation (Macey et al., 2022) providing therapeutic settings (Yen et al., 2024), relieving stress (Ladakis et al., 2024), and having positive impact on mental wellbeing (Navarro-Haro et al., 2016). Most of the recent experiments in virtual environments rely on monitoring the human-technology-interaction, using virtual technologies, devices, sound, visualization, artificial sounds, and odors to induce, record, and explore individual's psycho-physiological responses. According to Pallavicini and Bouchard (2019), individual's emotion regulation by using virtual reality tools and enhancing individual's cognitive abilities plays an important role in human-technology-interaction, especially in virtual environments that can contribute to individual's positive emotions and wellbeing.

Research on the effects of woody scents on humans has become increasingly common. However, this research is often limited by small sample sizes and a division in focus between studies of actual wood material scents and those examining needle or leaf scents, as well as a limited number of wood species investigated. For instance, the scent of Scots pine (*Pinus sylvestris*) wood material, chosen for this study, seems to have been investigated in only a few studies in previous human research (e.g., Muilu-Mäkelä et al., 2025; Schreiner et al., 2018, 2020a). Nevertheless, Scots pine is one of the most significant tree species in the boreal region, both ecologically and economically (Ruotsalainen et al., 2022). Its long-term importance, especially in Finland, is evidenced by its continued use in construction, where it has served as an essential material for generations (Jussila & Lähtinen, 2020; Dalheimer & Aakala, 2024; Ilgin & Karjalainen, 2022). Even today, Scots pine remains as one of the most frequently used wood species for construction in the region (OSF, 2025a, 2025b; Puuinfo, 2025). Therefore, understanding the olfactory and visual impacts of pine timber-based materials on occupants and their wellbeing is important.

Olfactory research has been conducted on needles of another pine species, *Pinus densiflora* (Jo et al., 2010), and its primary odor compound, α-pinene (Ikei et al., 2016), yielding results on induction of physiological relaxation. However, studies on this topic often focus on trees and materials readily available in the local region, resulting in a lack of research on many other globally significant tree species. Much of the existing literature appears to originate from Japan, leading to a relative overabundance of findings concerning Japanese tree species. In the present study, participants will not be informed about the specific scent to reduce the risk of cognitive bias; for instance, a study by Yu et al. (2022) demonstrated that cognitive bias related to wood scents could potentially skew results.

Furthermore, research examining the interplay between visual and olfactory stimuli remains relatively limited (Cornelio et al., 2021), particularly in relation to wooden materials. A lack of research on combined stimuli is due to the difficulty of controlling overlapping effects from multiple stimuli, where, for example, real wooden walls may still emit scents and volatile organic compounds (VOCs), even if they are not being studied. Therefore, this study aims to evaluate the effects of Scots pine wood scent (VOCs), visual impacts of wood materials by using virtually created full wooden walls, and the combination of their stimuli at the same time on human participants in a classroom type environment.

To reach these goals, the research questions were set as follows: (1) Does the scent of wood reduce self-reported stress levels and improve mood in participants? (2) Do virtually created wooden walls reduce self-reported stress levels and improve mood in participants? and (3) Does the combination of wood scent and virtually created wooden walls reduce self-reported stress levels and improve the mood in participants?

Based on the research questions and what is already known from previous similar research, three hypotheses were established, which are as follows: (H1) Wood scent should reduce stress levels and improve mood of participants; (H2) Virtually created wooden walls should reduce stress levels and improve mood of participants; and (H3) A combination of wood scent and virtually created wooden walls should reduce stress levels and improve mood of participants, with the expectation that increasing the number of stimuli increases the effect. The current study is a unique approach to study the effects of a full virtual wooden room while simultaneously being able to control the wood material derived VOC-emission variables that real wooden walls would undoubtedly have.

This study investigated the impact of wood scent and visual effects of virtually generated wooden walls on wellbeing among 50 participants. These individuals experienced a control room and rooms enhanced with either Scots pine wood scent, virtual pine wood walls, or both. The impacts were monitored by using Restoration Outcome Scale (ROS).

2. Materials and methods

2.1. Participants

Experimental participants were recruited for the study, based on prior power calculations to determine the minimum relevant sample size, using the main dependent variable, the Restoration Outcome Scale, ROS (Korpela et al., 2008). The ROS variable was chosen for the power analysis and sample size estimation based on earlier studies (Tyrväinen et al., 2014; Ojala et al., 2023). See **Supplementary Data (D1)** for detailed documentation of the data generating process, power analysis model, and recommended sample size.

Before the study began, the participants were asked to fill in a background questionnaire (**Supplementary Data D2**). The 50 recruited participants, on average 27.5 (±7.0) years old, included 23 men and 27 women, with 52 % born in Finland and 48 % from 16 other countries, and 46 % having attained a master's degree or higher. The participants were also asked to evaluate their connection to nature using the Inclusion of Nature in Self (INS) scale (Kleespies et al., 2021; Schultz, 2002), and their preference for the type of working environment they would prefer to use. The 50 participants evaluated their connection to nature as moderate to high on average, with a working environment of a shared room of two to three people being chosen as the preferred type most often. A public place, such as a library or a café, was the least commonly chosen option. Upon completing all the visits, the participants were given a 25 € grocery store gift card as compensation for using their time for the study. The study was conducted in accordance with the ethical guidelines of the University of Helsinki for human research.

2.2. Study design

The participants were recruited to visit the study environment three times, with four possible different stimuli settings (control, with virtual wooden walls, with scent, and with both virtual wooden walls and scent; Fig. 1). The research was carried out as a cumulative effect study, where the number of studied stimuli (0,1, or 2) was increased by one at each visit, under the expectation that the effect would increase with each added stimulus. The participants were divided into two groups roughly the same size, with the added stimuli being the same in the first and last visit and different in the second visit for both groups. Due to time and resource limitations, only three visits were possible for each participant. The four different stimuli settings were as follows:

All 50 participants visited the control setting, which served as a baseline for other settings, and 48 participants visited the combination setting with both scent and virtual walls (Fig. 1). A total of 23 participants visited the setting with only wood scent, and 20 participants visited the setting with only virtual wooden walls. Altogether, seven participants did not partake in the intermediate second visit (either with scent or virtual walls), and two participants did not partake in the final third visit because of scheduling conflicts. However, these participants who missed the second or third visit were included in the analysis due to ability of our model to handle some random missing values (see more in the statistical analysis chapter).

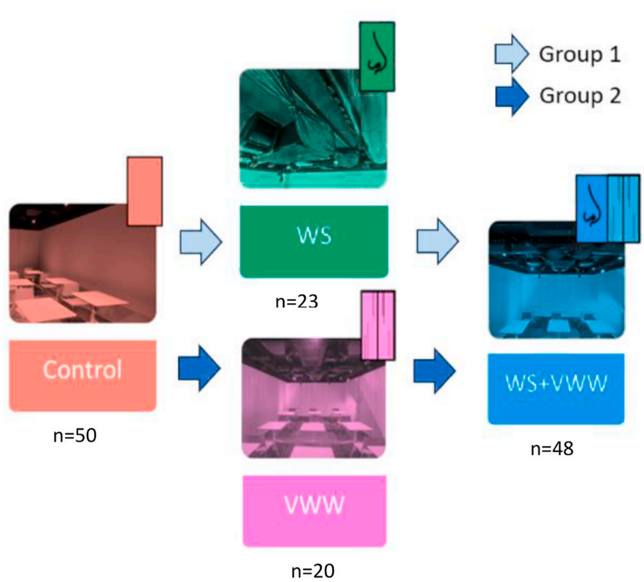

Fig. 1. Study design illustrating the sequence of visits for two groups across four different stimuli settings. Each participant (n = 50) was planned to visit once in three out of four settings: Control, wood scent (WS), virtual wooden wall (VWW) and combined stimuli of wood scent and virtual wooden wall (WS + VWW). However, seven participants missed the second visit and two missed the third visit.

2.3. Virtual laboratory (VirtuLab) environment as a study setting

The study took place in the Natural Resources Institute Finland (Luke) VirtuLab, located on the Viikki campus of the University of Helsinki. VirtuLab is a facility where 360° imagery and/or videos can be projected in high quality onto the walls to create a realistic virtual environment for use in a variety of research (Fig. 2). The room is 30.6 m^2 with a height of 2.9 m and imagery is projected onto the four walls with six projectors (EB-PU1007W, Epson, Japan) fitted with ultra short-throw lenses (ELPLX01S, Epson, Japan). The air conditioning in the room is centrally controlled and set at a constant level, changing the air in the room 8.1 times an hour. The virtual wooden walls used for this study were four images of real Scots pine features taken from within the University of Helsinki Think Corner building stairwell combined into a single 360° image. The images were captured in 8K, however when in use within VirtuLab they were somewhat zoomed in. The wooden structures and virtual environment were built to mimic the real-life wooden environments (Fig. 2). For the control setting and the wood scent setting, the virtual projections were turned off and the walls had a neutral structure and gray appearance. The control setting (and wood scent setting) with turned off virtual walls can be seen in Fig. 2, albeit with an alternative seating arrangement being tested prior to the beginning of the study.

2.4. Wood scent generation

For the wood scent setting and the combination setting which had the scent, the scent was generated by using wood chippings and sawdust suspended from the ceiling in porous fabric ("Dancer's net", made of 82 % polyamide and 18 % elastane, Great Britain; purchased from Eurokangas) pouches spread evenly across the room (Fig. 2). The pouches were fluffed between visits, and fresh material was changed into the pouches at the start of each study day. Fig. 2C shows a close-up of some of the scent pouches. The material used was dried Scots pine wood chippings and sawdust (Siekkelin Saha Ky, Kouvola, Finland) with the possibility of very minor amounts (less than 10 %) of Norway spruce wood chippings mixed in, due to possible impurities in industrial source. As the VOC-emission profiles of these two tree species have been found to be very similar, with the Scots pine emitting significantly higher amounts of VOCs in total (Kovačević et al., 2023), this was not considered an issue for the purposes of the study.

2.5. Cognitive tests and psychological surveys of emotion regulation and mood change

During each visit, the participants answered questions in a survey and performed a cognitive test, all on an individual laptop. The survey and the cognitive test embedded within it were created using PsyToolkit, a free website for creating cognitive tests and surveys (Stoet, 2010, 2017). The flow of the study during each visit is also illustrated in Fig. 3. Each visit started in a separate meeting room near VirtuLab, where before starting the study and the whole process was briefly explained to the participants. Before the first visit, the participants also signed a research consent form, affirming their participation in the study. Then, to start each visit, all participants were instructed to relax for a few

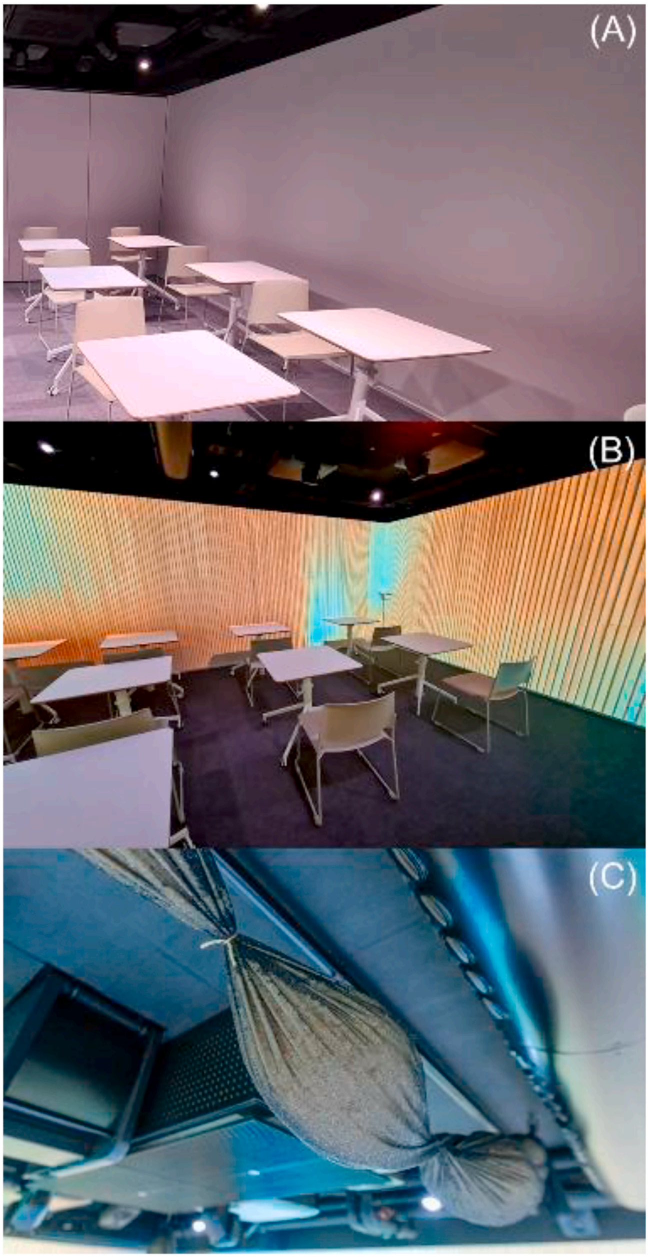

Fig. 2. The VirtuLab with the virtual walls turned off (A). The virtual wooden walls projected inside VirtuLab (B). Example of the suspended fabric pouches that were filled with Scots pine wood chippings and sawdust to create the wood scent (C).

minutes. Following this, the participants answered a psychological questionnaire rating their overall mood for that day and questions regarding their current mood and stress levels (i.e., the baseline measurement). The participants were then asked to move to VirtuLab, where psychological questionnaire was repeated (i.e., the immediate effect measurement). Following this, the participants performed the cognitive test, after which the psychological questionnaire was repeated a third time (i.e., the main measurement).

On the second and third visits, the participants were also instructed to choose a seat they had not previously sat in, if they could recall their previous seating locations. During each of the visits, the seating location for each participant was recorded to confirm this, with the room layout and seat numbering during the study illustrated in **Supplementary Data (D3)**. During each visit, an observer sat at the back of the testing room, to give instructions to the participants as well as to assist in the cases of possible technical difficulties with the testing program.

The cognitive test performed during each visit was chosen to be the Stroop Color Word Test (CWT) (Stroop, 1935). The test was chosen because we wanted the participants to experience some cognitive stress to simulate classroom type situation. In previous studies, the test has been found to reliably induce a higher level of cognitive stress in participants (e.g., Renaud & Blondin, 1997). The test has originally been envisioned as a method to test cognitive interference in people. It has also been described as a test that measures different cognitive functions and emotion regulation, as well as general concentration (e.g., Bench et al., 1993; Macleod, 1991; Scarpina & Tagini, 2017). During the cognitive test, text writing out the name of one of four random colors (red, green, blue, or yellow) will flash on the screen, with the letters also being colored in one of the four colors at random. The participants are then instructed to press a button corresponding to the color of the letters, regardless of what color is written out. This was repeated 200 times each visit, taking around 6–8 min, depending on the response speed of the study participant. The Psytoolkit cognitive test program then recorded the number of correct answers and the response times for possible further use (excluded from this study).

The Restoration Outcome Scale (ROS) was used in the psychological questionnaires as the primary measure of treatment effects. ROS was completed by participants in all conditions, allowing comparisons between visual and olfactory stimuli, as well as their combination.

The psychological data was collected from the participants at three points during each visit embedded within the survey: before starting in the waiting room (i.e., baseline), right after entering the experiment room (i.e., immediate effect), and right after performing the cognitive test (i.e., main measurement). The data was collected in the form of short questionnaires based on the (ROS) (Hartig et al., 1998; Korpela et al., 2008). In the questionnaires, participants answered six statements on a 5-point Likert scale (Likert, 1932), choosing an option from agree to disagree, to evaluate their mood and stress levels at that specific moment. The 5-point data was recorded in numeric values (1–5), where a higher value indicates a higher level of restoration and a better mood (i.e., a lower level of stress). Participants were given the option to answer the statements in either Finnish or English based on their own preference. The six statements in English were as follows: *1) I feel calm, 2) I feel alert and that I can concentrate well, 3) I have enthusiasm and energy, 4) I feel restored and relaxed, 5) I feel like I can forget everyday worries, and 6) My thoughts are clear and bright.*

2.6. *Post-experiment survey for qualitative feedback*

Upon completing all study visits, participants were invited to participate in an online post-experiment survey with both closed-ended and open-ended questions. In this survey, they were instructed to compare their experiences across visits numbered 1 to 3, rather than evaluating the specific conditions associated with each visit. Consequently, the anonymous responses collected cannot be directly linked to the specific conditions of the different visits.

Participants were prompted to describe their impressions of the test room for each visit, with their feedback categorized as positive, negative, neutral, or other. This qualitative feedback was designed to provide insights into the participants' overall experiences and perceptions of the experimental environment. It is important to note that the survey results for the main variable of interest – i.e., the ROS – were collected in each condition, enabling comparisons between visual-only and olfactory-only effects as outlined in Section 2.5.

2.7. *Collecting volatile organic compounds (VOCs)*

During all the visits, ambient air concentrations of VOCs were measured from the VirtuLab room before and after the visiting groups, as well as in-between the groups. The measurements were conducted with a pocket pump (loo, SKC Ltd., UK) and a flow meter (Thermal mass

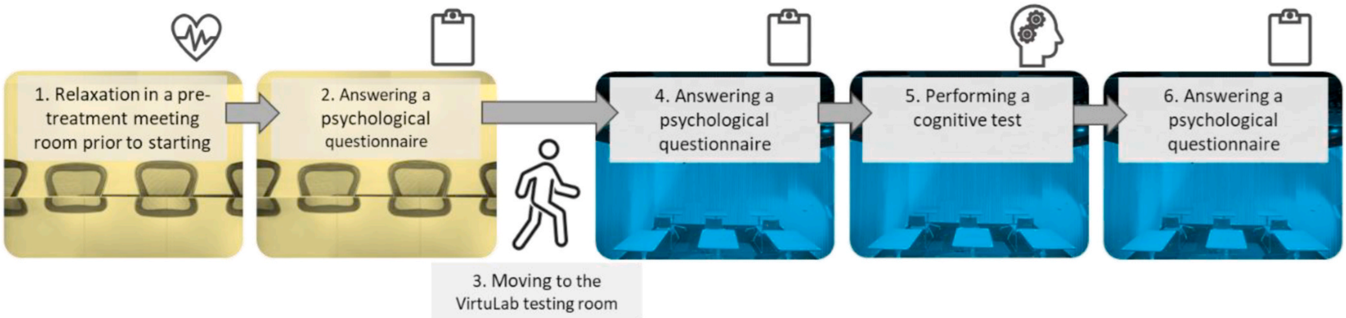

Fig. 3. The six different stages of each visit to VirtuLab. The Restoration Outcome Scale, ROS, was used in psychological questionnaire and the Stroop Color Word Test in cognitive test. The cognitive test with ROS was done in all the setting conditions, and in the pre-setting meeting room. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

flowmeter 4140F, TSI Inc., USA), collecting air samples for 10 min into dual absorbent (Tenax TA & Carbopack B, 60/80 mesh) sorbent tubes (Markes international Ltd., UK) at an average rate of 0.107 L/min. The goal of the VOC concentration data was to confirm the existence and quantify the amount of terpenoids, the main wood scent compound group, during the experiment sections with scent. The same data was also collected during the sections without scent, to find out the ambient level and to confirm that no significant wood scent residue from previous activities existed within the air. A total of 30 VOC samples were taken during the study. The samples were taken at the approximate center of the testing room from a height of about 20 cm above the desk surfaces.

2.8. Thermal desorption–gas chromatography–mass spectrometry analysis of VOCs

The VOC samples taken during the study were analyzed using thermal desorption–gas chromatography–mass spectrometry (TD–GC–MS) at the Finnish Meteorological Institute (Helsinki, Finland). A thermal desorption instrument (TurboMatrix 350, PerkinElmer Inc., USA) was used, connected to a gas chromatograph (Clarus 680, PerkinElmer Inc., USA) which in turn was connected to a mass spectrometer (Clarus SQ 8 T, PerkinElmer Inc., USA). The system was calibrated using multiple sorbent tubes injected with a known standard solution, placed before, after half, and after all the regular VOC sample sorbent tubes, so that any changes in the responses during analysis could be noticed and corrected. The detailed method used for analyzing the VOCs with the TD–GC–MS was based on and explained in detail in Helin et al. (2020). The results obtained from the TD–GC–MS were analyzed, and the VOCs were quantified, using TurboMass GC/MS software (PerkinElmer Inc., USA).

From the results, the average sum and standard deviation of VOCs were calculated for each setting based on the VOC measurement taken right after each visit. The VOCs most strongly emitted from the Scots pine material are α-pinene, β-pinene, 3-carene, camphene, and limonene (e.g., Kovačević et al., 2023). An identical average sum and standard deviation were acquired for comparison from 20 VOC measurements taken from a new real wooden (Norway spruce) building at the University of Helsinki, Hyytiälä forest station (Juupajoki, Finland). The measurements were taken as a part of the Hyytiälä living lab project to measure the time-dependent changes in the VOC emissions from the building materials. The 20 measurements were taken between June and October 2023 from four different wooden residence rooms of a similar size at the station. These measurements had a longer collection time and a slightly higher pumping rate; however, this was considered when calculating the concentrations. The analysis method for these samples was the same, using TD–GC–MS at the Finnish Meteorological Institute, except for ultimately quantifying a larger number of different VOCs.

2.9. Room environmental conditions

Indoor air conditions (temperature, carbon dioxide, relative humidity) were measured using a stationary air quality monitor (Loop One Basic, Loopshore Oy, Finland). The sensor provided continuous monitoring with a measurement at 10-min intervals throughout the study period. The R statistical computing software package ggplot2 was used for the time series analysis of the data (R Core Team, 2024; Wickham, 2016).

Additionally, light level measurements were taken from the room with a commercial handheld digital lux meter (MT-30, RZ, China). The measurements were taken from four different points inside the room at approximately the same heights and angles from a setting without the virtual walls enabled and from a setting with the virtual walls enabled. An average of these four points would then be used. The measurements were taken only once during each relevant setting, as it was determined that the likelihood that the light levels of the luminaires or the projectors changed during the 2 weeks of this study was miniscule. An average light intensity value was calculated from the light intensity measurements for both the setting with virtual walls enabled and with them disabled.

2.10. Statistical analysis

Statistical analysis was performed with a Bayesian approach (Gelman et al., 2013) using the BGLIMM procedure in SAS 9.4 (SAS Institute Inc., Cary, NC, USA). The number of burn-in iterations was set to 25,000, with 100,000 Monte Carlo samples drawn and every 20th sample retained to reduce autocorrelation resulting to 5000 posterior samples. All priors were specified as weakly informative default values, as detailed in the SAS BGLIMM documentation.

Setting and group were used as fixed effects in the model. The ROS value, measured before entering the setting room, was used as a baseline covariate for each respondent. Also, the logarithm of VOCs, measured in each hour, was used as a covariate for wood scent. The models were fitted both with and without the control variables, age, and gender. Repeated visits within each respondent were accounted for using the most flexible, unstructured covariance structure that estimates covariances between all visits. Informally, the fitted model was:

Response variable = setting(F) + group(F) + log(VOC)(F) + baseline covariate(F) + age(F) + gender(F) + visit (R),

where F denotes for fixed value and R denotes for the repeated measure random variable. Covariance type is unstructured and study person (id) as subject. To assess the normality of continuous variables, skewness and kurtosis values were calculated. All values ranged from -0.97 to 0.52, indicating approximately symmetric and mesokurtic distributions. These values fall well within the commonly accepted thresholds for normality (e.g., skewness $< |2|$ and kurtosis $< |7|$; Curran et al., 1996), supporting the suitability of the Bayesian modelling approach used. Although the study design is unbalanced with respect to settings, the study hypothesis can be answered with linear contrasts. The primary hypotheses were one-sided (see 1, 2, 4, 5, 6 below). The primacy of settings for one stimulus (WS or VWW) could not be anticipated, so a two-sided test was used for that (see 3 below). Therefore, the statistical comparisons made were:

1) Control < VWW
2) Control < WS
3) VWW ≠ WS
4) VWW < VWW + WS
5) WS < VWW + WS
6) Control < VWW + WS

In Bayesian statistics, the findings are interpreted using the parameters' posterior probability distributions rather than *p*-values, but they have much in common. For example, the 95 % probability intervals (95 % PI) fulfill a similar purpose to the 95 % confidence intervals in frequentist statistics. One-way and two-way hypotheses were taken into account in the interpretation.

The model fit for fixed parameters were checked from trace plots which were smooth and from the shape of posterior distributions which were unimodal and symmetric. For random variables, trace plots were smooth, and distributions were unimodal but right skewed, which is a common result. All effective sample sizes were larger than 4700.

3. Results

3.1. VirtuLab environmental conditions

The logarithm of VOCs, measured in each hour, was used as a covariate for wood scent. This was found to be especially important due to the diluting effect of wood scent during the day (Fig. 4), which was found out afterwards.

The other monitored room conditions were rather stable during the study period as seen in Figs. 5 and 6.

3.2. Settings impacts on participants' mood

The mean ROS after the visit was 0.47 points higher with the combined setting of wood scent and virtual wooden walls (H6) compared to the control, and 0.30 higher compared to the wood scent setting (H1). Therefore, we can be 96 % and 92 % certain, respectively, based on the probability intervals, that the ROS value would be higher with two stimuli (Fig. 7). No clear difference was observed between the cases of one stimulus (H3, MD = 0.08, 90 % probability interval 0.42–0.58), but we can be 92 % certain that the ROS value would be higher with virtual wooden walls compared to the control (H5, MD = 0.25). The addition of demographic variables (age, gender) did not change the main results. The three probabilities mentioned above weakened only by 0.5–1.5 %-unit.

The model included covariates of baseline ROS and Scots pine VOC level, which influenced the setting means. Notably, the range of

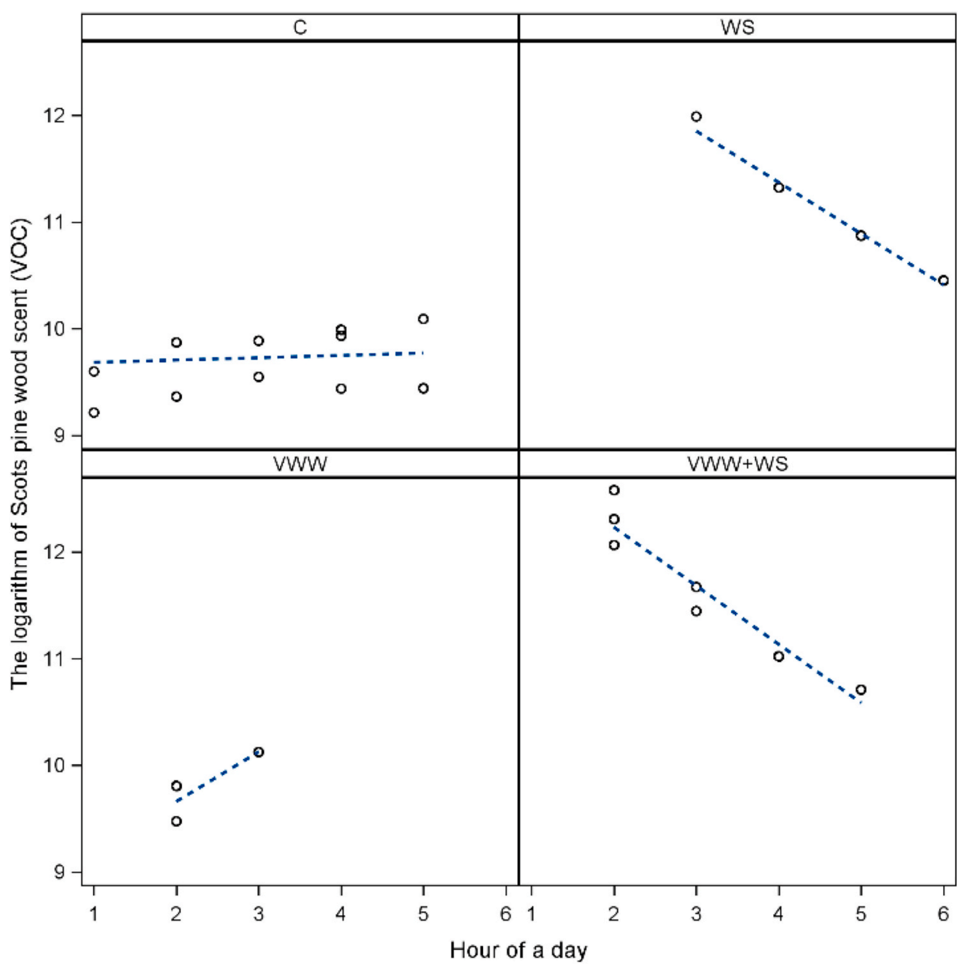

Fig. 4. The mean logarithm values of Scots pine VOCs used as a covariate for wood scent, depending on the hours of study room usage under different settings: C, control; WS, wood scent; VWW, virtual wooden wall; VWW + WS, combined stimuli of wood scent and virtual wooden wall. No effect was expected in the control and WWW settings due to the absence of wood scent.

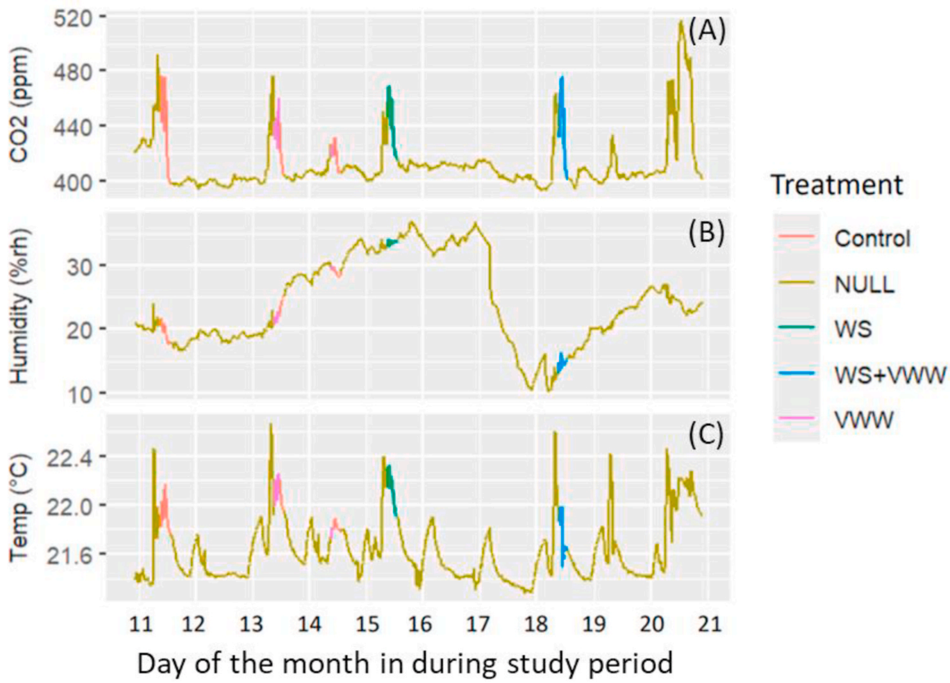

Fig. 5. Indoor air conditions in the VirtuLab during the study period in March 2024: (A) CO2, (B) relative humidity, and (C) air temperature in different settings: Control; WS, wood scent; VWW, virtual wooden wall; WS + VWW, combined stimuli of wood scent and virtual wooden wall. NULL refers to the times without settings.

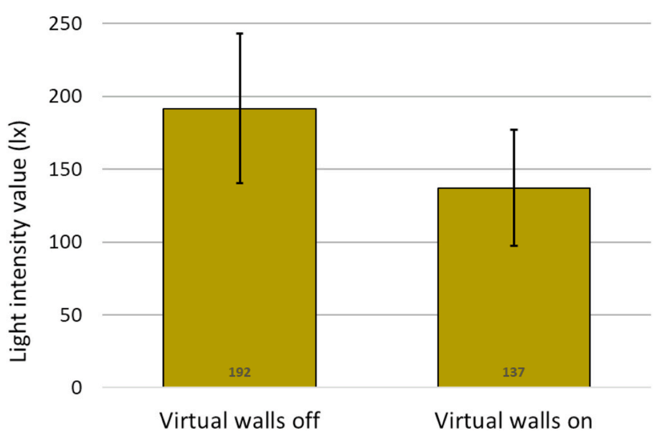

Fig. 6. Light intensity values (lx) with and without virtual walls on, with ±1 standard deviations.

individual responses varied across participants. On average, the two-stimuli setting resulted in a 0.14-point higher score compared to the control. However, individual differences were substantial: the largest observed difference in favor of the two-stimuli setting was 0.98 points, with the upper quartile at 0.38 points and lower quartile at −0.17 points. The lowest observed difference favored the control setting by 0.65 points.

3.3. Post-experimental survey

Altogether 48 participants completed a post-experimental survey with closed and open-ended questions. The perception of the pre-experiment meeting room was rated as "neutral" by 50 %, "comfortable" by 29 %, "stressful" by 10 %, and "other" by 11 % of participants (data not shown). The average stress level in response to the stress test was 2.6 on a 5-point scale (1 = no stress; 5 = high stress). The impact of other participants on the ability to focus was rated 2.1 on the same scale (data not shown).

Participants described their impressions of the test room for each visit, categorized as positive, negative, neutral, or other. Fig. 8 shows that the feedback for the settings tends to be neutral to positive, with variability noted across different sensory experiences.

Positive responses included comments such as "*It was relaxing*" and "*Room was silent and easy to focus*". Negative responses highlighted issues like "*The light was irritating*" and "*The silence was oppressive*". Mixed responses were labeled as "other", meaning that they included both positive and negative aspects or it was unclear whether an impression was more positive, average, or negative. Comments classified as "other" included, for example, statements indicating no perceived difference between the spaces across visits, without elaboration on emotional response ("*The same as the first time*"), or responses that combined both positive and negative elements ("*Calm, but very alert. The visuals made me calm, but the confined space kept me alert*"). The question presented to the participants was: "What was your first impression of the VirtuLab environment during your 1st/2nd/3rd visit? Consider points like visual conditions, scent, acoustics, and possibilities to focus."

Lighting and acoustics were frequently mentioned, with opinions varying widely. Some found the room acoustics pleasant, while others found the silence oppressive. Similarly, the lighting received mixed reviews, with some finding it too bright and others finding it perfect. The projection of virtual wooden walls was described as "*warmer and brighter*" by some participants. Scent was the least mentioned aspect, often not perceived at all, with responses such as "*No obvious scent felt*". Many participants reported that their impression of the room was similar over the course of the experiment, while others noticed differences in, for example, visual conditions and/or scent.

4. Discussion

4.1. Impacts of wood scent and virtual wooden walls on mood

In a simulated, stress-inducing indoor environment of this study, both virtual wooden walls and wood scent improved mood and

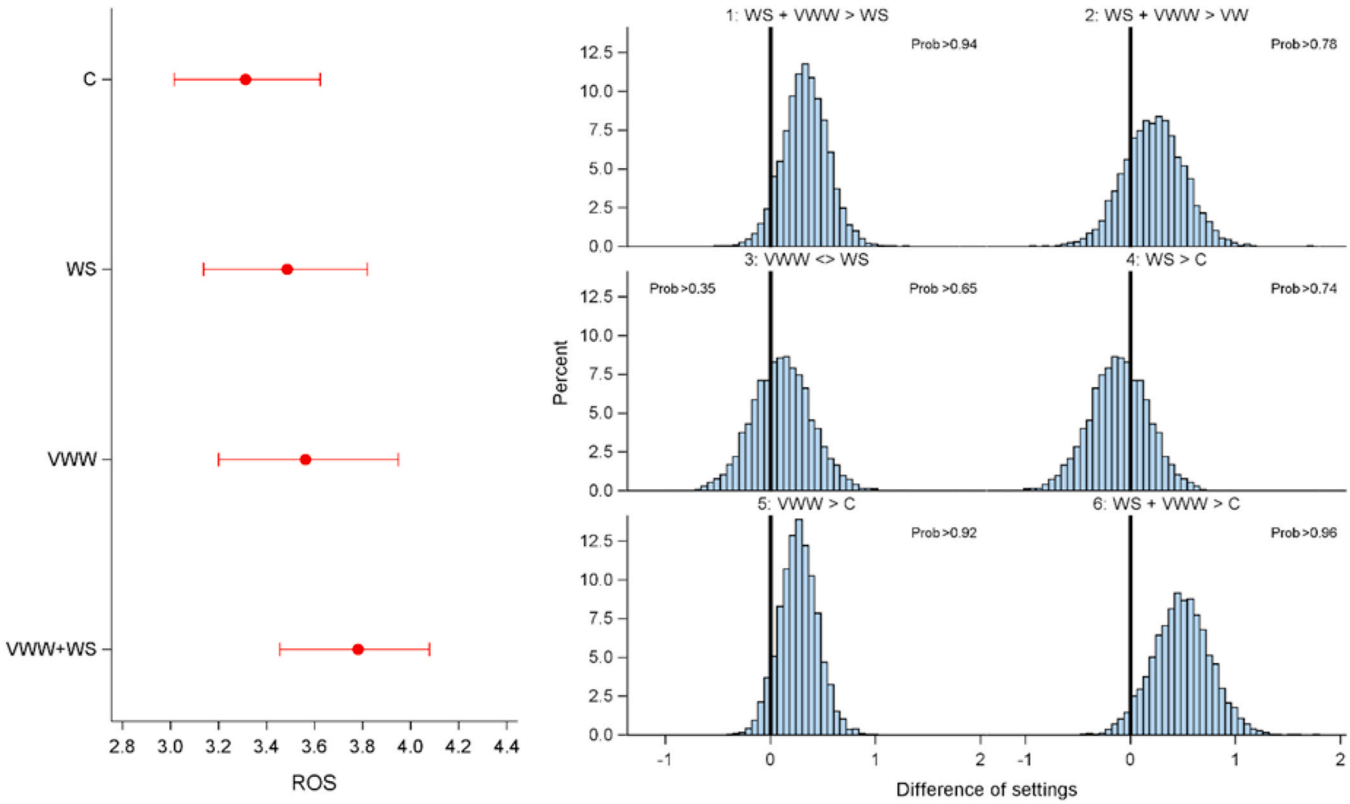

Fig. 7. The estimated restorative outcome score (ROS) predictions and their 95 % probability intervals for the settings fitted with covariates are shown on the left. C refers to the control, VWW to virtual wooden walls, WS to wood scent, and VWW + WS to the combined stimuli of virtual wooden walls and wood scent. On the right, the six research hypotheses regarding differences between settings and their posterior distributions are presented.

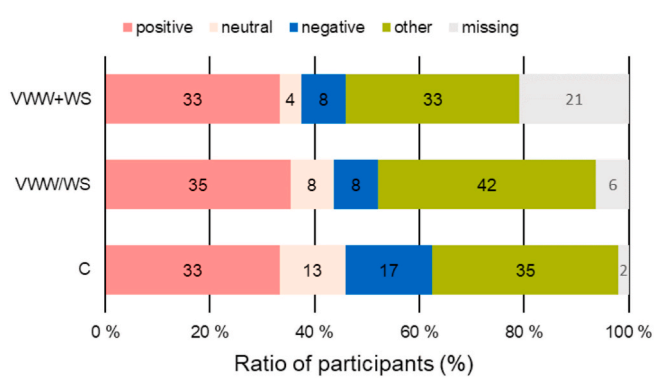

Fig. 8. Impressions of participants of the VirtuLab environment after visiting all the different settings: control (C), virtual wooden wall (VWW), wood scent (WS), combined stimuli of virtual wooden wall and wood scent (VWW + WS). The impressions were divided into four categories: "positive", "neutral", "negative", and "other". Mixed responses were labeled as "other", meaning that they included both positive and negative aspects or it was unclear.

perceived restoration, with visual stimuli exerting the stronger effect, and the combined condition yielding a modest incremental gain. These results align with evidence that visual wood cues can reliably elicit positive affect and reduce stress, including shown preferences for authentic wood over laminate (Jiménez et al., 2016) and reduced blood pressure in planed-wood rooms compared to non-wood rooms (Sun et al., 2020). Prior work showing that high-quality images or virtual renderings of wood can approximate the affective impact of real wood (Nyrud et al., 2011; Nakamura et al., 2019; Li et al., 2021) is also consistent with our finding that large, projection-based virtual walls were sufficient to enhance restoration.

We acknowledge that full wooden wall projections selected for this study may not be universally optimal; the most beneficial coverage likely varies by individual and cultural context (Butter et al., 2025; Wilder, 1957). Given study constraints, multiple coverage treatments were, however, not feasible. We therefore used full wooden walls as a high-salience manipulation to probe the upper bound of visual wood exposure, isolate effects relative to non-wood control, and establish an empirical baseline for subsequent work.

The modest synergy of scent plus visuals accords with multimodal nature-exposure studies pairing forest imagery with leaf-derived scents (and sometimes sounds) that have enhanced affective outcomes (Song et al., 2019, 2021). Our findings extend this pattern to wood-themed, built interiors: visually salient simulations delivered most of the benefit, with olfactory cues providing context-sensitive gains. The absence of significance in some pairwise contrasts is interpretable through two well-noted dynamics in environmental psychology: brief exposures privilege rapid visual appraisal over slower olfactory processing, and perceived restoration can rise even when physiological changes are subtle or moderated by uncontrolled VOC backgrounds (cf. Sun et al., 2020). Overall, visual wood cues appeared to be a robust lever for immediate affective relief, with scent acting as a contingent enhancer.

4.2. *The role of wood scent in perceived restoration*

Scent alone improved perceived restoration, albeit less strongly than visuals. This pattern corroborates olfactory research showing relaxation and stress reduction from tree-derived scents via heart rate variability (HRV) and self-reported restoration (Ikei, Song, & Miyazaki, 2015; Matsubara & Ohira, 2018; Song et al., 2019). Scots pine contains odor-active compounds (e.g., α-pinene, vanillin, (E,E)-nona-2,4-dienal) (Schreiner et al., 2018), and wood-related odors have been associated with elevated happiness and contentment even when physiological effects were indistinct (Schreiner, Karacan, et al., 2020). Our modest effect sizes suggest that exposure duration, inter-individual variability, and odor composition moderated the outcomes.

Contextual determinants likely shaped the outcomes of the current study. Pleasantness and familiarity of the wood scent vary with VOC profile, and the gender and cultural background of individuals experiencing the wood scent; also, congruent visuals can increase perceived pleasantness (Butter et al., 2025). Wood processing methods have shown to alter the odor quality of wood – for example, high-temperature drying has been found to reduce the pleasantness of wood scents of some wood species (Ohira et al., 2009), though findings are not uniform among the different species (Ikei, Song, Lee, & Miyazaki, 2015). Indoors, terpene oxidation can also produce less pleasant or harmful byproducts and fine particles (Abbatt & Wang, 2020), potentially damping the wood scent benefits. In light of these considerations – and our observation of predominant visual effects plus modest, context-dependent scent contributions – we recommend that future research standardize and monitor scent composition, dose, and delivery kinetics; broaden the range of wood species and wood processing methods; and stratify participants by relevant profiles to delineate boundary conditions and specify for-whom and under-what-conditions effects.

4.3. The effectiveness of multimodal stimuli

The combined visual-plus-scent condition yielded a small yet reliable benefit over unimodal exposures, reinforcing the multisensory principle that convergent inputs amplify affective and stress-related outcomes (Ikei et al., 2017; Lopes & Falk, 2024). Our results complemented prior demonstrations with forest imagery and olfactory/auditory cues (Song et al., 2019, 2021) by showing analogous advantages in wood-themed interiors. The constrained increment is consistent with (1) dominance of strong, congruent visuals under brief exposure, and (2) added variability and cross-modal interactions in multimodal designs that can dilute the detectable impacts (Ikei et al., 2017).

Our non-headset, full–wall projection setup addressed an underexplored area in human–environment interaction (cf. Wang, 2024). Projected, visual wood augmentations – optionally complemented by calibrated wood scent – appeared to deliver measurable affective gains without the logistical and ergonomic burdens of immersive VR headsets, supporting scalable applications in classrooms and offices.

4.4. Personal and cultural differences in optimizing environmental conditions

Inter-individual variability in our data aligned with documented personal and cultural differences in sensory preferences. Butter et al. (2025) reported that pine-dominant odors were most familiar and pleasant for German participants and that congruent images increased odor pleasantness – a pattern consistent with our finding that adding visuals to scent improved outcomes. Design-focused studies further clarify that person-to-person optimization is needed: greater wood coverage has been linked to increased perceived warmth and reduced stimulation, with gender-linked differences in texture appraisal (Kwak & Choi, 2025); and varying coverage has shown to modulate physiological activation while remaining subjectively comfortable (Tsunetsugu et al., 2002, 2005, 2007). In VR contexts, wood and red brick have shown to enhance emotional comfort and creativity, whereas concrete and white paint supported cognition and concentration (Zhou et al., 2025). Our pattern – stronger benefits from visual wood, with scent amplifying effects for those who found it pleasant – fits this broader evidence base.

Practically, based on our findings and the previous literature, designers should prioritize high-quality, context-appropriate visual representations of wood to deliver rapid, broadly acceptable mood benefits. Where acceptable and well controlled, practitioners may incorporate congruent wood scents to enhance outcomes for receptive subgroups and evaluate non-immersive versus immersive implementations to balance efficacy, comfort, and feasibility.

4.5. Study limitations

Time constraints in the Virtual Laboratory (VirtuLab) dictated an unconventional sequence. Expecting wood scent to persist for several days, we scheduled wood-scent conditions later to avoid carryover into non-scent settings. Only three visits per group were feasible, resulting in an unbalanced design. To avoid identical sequences, the second visit was either VWW or WS. These constraints shortened the study timeline, which could introduce a memory effect and order effects nested within the cumulative stimuli. These limitations required the use of cumulative stimuli; ideally, a cross-over or small Latin square design would have been preferable.

4.6. Future directions

Future research could prioritize high-quality visual wood cues and consider supplementing them with calibrated, congruent wood scents where acceptable, given indications that combined sensory inputs may enhance affective outcomes (Ikei et al., 2017; Song et al., 2019, 2021). It may be beneficial to pair self-reported measures with physiological indices, such as heart rate variability and cortisol levels, to triangulate restoration and reduce one method bias (Tyrväinen et al., 2014). Also stratifying results by likely moderators – including baseline arousal consistent with the law of initial value (Wilder, 1957), odor familiarity and preference, and cultural background of the participants (Ojala et al., 2023; Butter et al., 2025) – should be considered in further studies to illuminate for-whom and under-what-conditions effects.

Experimental designs could aim to improve sensory congruence and immersion while maintaining ecological validity through non-headset, screen-based, scalable setups; incorporate multimethod outcomes spanning self-report, psychophysiology, and behavior; and plan for adequate statistical power to detect the small-to-moderate increments typical of multimodal add-ons (Ascone et al., 2025). Longitudinal approaches may be useful for evaluating durability of effects and potential habituation or sensitization to repeated exposures. Given indications of a dose–response function with a likely "sweet spot", future work needs to systematically vary visual wood coverage and scent concentration and gather detailed participant feedback to map preference and tolerance thresholds, thereby clarifying mechanisms such as visual dominance and cross-modal congruence and informing guidelines for classrooms and offices.

Finally, because VOC composition and indoor oxidation processes can alter odor quality and health-relevant byproducts, it will be advantageous to characterize and control scent composition and delivery kinetics by monitoring indoor air quality parameters and compare wood species and wood processing methods to facilitate translation from laboratory findings to diverse real-world interiors (Abbatt & Wang, 2020).

5. Conclusions

This study found that virtual wooden walls and wood scent improved mood and perceived restoration in a simulated, stress-inducing indoor environment, with visual cues exerting the stronger effect and the combination yielding a modest, reliable gain. These results aligned with prior evidence on the affective benefits of visual wood cues and extended multimodal nature-exposure research to wood-themed, built contexts, demonstrating that even projection-based implementations can produce measurable benefits. Practically, designers should prioritize high-fidelity visual wood cues for broad, immediate effects and, where acceptable and well controlled, add congruent wood scents to enhance outcomes for receptive subgroups. Because baseline arousal, odor familiarity, and material preferences vary across individuals and likely moderate responses, customizable environments tuned to user profiles and cultural contexts are advisable. Such tailoring can help optimize comfort while avoiding overstimulation or scent-related aversion. Future research should employ multimethod and longitudinal designs, standardize scent composition and delivery (including dose and kinetics), and map dose–response functions for both visual wood coverage and scent concentration to establish evidence-based guidelines. Comparative tests across wood species and processing methods, alongside monitoring of indoor air quality, will improve ecological validity. Overall, customizable virtual environments that emulate natural materials – visually and olfactorily – show promise as scalable, flexible tools for supporting wellbeing in urban indoor settings.

CRediT authorship contribution statement

Tuula Jyske: Writing – review & editing, Writing – original draft, Supervision, Resources, Project administration, Investigation, Funding acquisition, Conceptualization. **Valtteri Kutvonen:** Writing – review & editing, Writing – original draft, Investigation, Formal analysis. **Janne Kaseva:** Writing – review & editing, Writing – original draft, Visualization, Methodology, Formal analysis, Data curation. **Mika Kurkilahti:** Writing – review & editing, Writing – original draft, Methodology, Formal analysis. **Heidi Hellén:** Writing – review & editing, Writing – original draft, Supervision, Methodology. **Toni Tykkä:** Writing – review & editing, Writing – original draft, Methodology, Formal analysis. **Emilia Rosenborg:** Writing – review & editing, Writing – original draft, Investigation. **Madli George:** Writing – review & editing, Writing – original draft, Visualization, Data curation. **Saša Tkalčan:** Writing – review & editing, Writing – original draft, Visualization, Software. **Jutta Kauppi:** Writing – review & editing, Writing – original draft, Resources, Funding acquisition, Conceptualization.

Ethical approval

The Ethics Committee of the University of Helsinki, Helsinki, Finland, waived the need for ethics approval for this fully anonymous study on perceived wellbeing of voluntary adults with a study design that did not include any health data, and physical integrity was not violated.

Data availability statement

Data will be openly available upon request.

Funding

This work was supported by the BIOSYS project co-funded by the EU via North Karelia region in Finland, and BY the University of Helsinki, Finland (tenure track starting grant for TJ).

Acknowledgements

We would like to thank MSc Eliisa Löyttyniemi for valuable advice when planning the study design. We thank Tuomas Kari for skillful technical assistance in the virtual laboratory. Pauliina Piilola is acknowledged for helping in the experiments. We would like to thank Luke and Dr. Ann Ojala for the insightful advice on human-related studies.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jenvp.2026.102925.

References

Abbatt, J. P. D., & Wang, C. (2020). The atmospheric chemistry of indoor environments. *Environmental Science: Processes & Impacts, 22*, 25–48. https://doi.org/10.1039/C9EM00386J

Adhyaru, J. S. (2022). Virtual reality as a tool to promote wellbeing in the workplace. *Digital Health, 8*. https://doi.org/10.1177/20552076221084473

Aerts, R., Honnay, O., & Van Nieuwenhuyse, A. (2018). Biodiversity and human health: Mechanisms and evidence of the positive health effects of diversity in nature and green spaces. *British Medical Bulletin, 127*(1), 5–22. https://doi.org/10.1093/bmb/ldy021

Africa, J., Heerwagen, J., Loftness, V., & Ryan Balagtas, C. (2019). Biophilic design and climate change: Performance parameters for health. *Frontiers in Built Environment, 5*, 28. https://doi.org/10.3389/fbuil.2019.00028

Ascone, L., Mostajeran, F., Mascherek, M., Tawil, M., Knaust, T., Samaan, L., & Kühn, S. (2025). Multi- vs. unimodal forest-bathing in VR to enhance affective and cognitive recovery after acute stress. *Journal of Environmental Psychology, 105*(2025), Article 102637. https://doi.org/10.1016/j.jenvp.2025.102637

Bench, C. J., Frith, C. D., Grasby, P. M., Friston, K. J., Paulesu, E., Frackowiak, R. S. J., & Dolan, R. J. (1993). Investigations of the functional anatomy of attention using the stroop test. *Neuropsychologia, 31*(9), 907–922. https://doi.org/10.1016/0028-3932(93)90147-R

Butter, K., Hucke, C. I., Ohlmeyer, M., & van Thriel, C. (2025). The impact of visual context on the perception of wood odours. *Building and Environment, 280*, Article 113129. https://doi.org/10.1016/j.buildenv.2025.113129

Corazon, S. S., Sidenius, U., Poulsen, D. V., Gramkow, M. C., & Stigsdotter, U. K. (2019). Psycho-physiological stress recovery in outdoor nature-based interventions: A systematic review of the past eight years of research. *Int J Environ Res Public Health, 16*(10), 1711. https://doi.org/10.3390/ijerph16101711, 2019 May 16.

Cornelio, P., Velasco, C., & Obrist, M. (2021). Multisensory integration as per technological advances: A review. *Frontiers in Neuroscience, 15*, Article 652611. https://doi.org/10.3389/fnins.2021.652611

Curran, P. J., West, S. G., & Finch, J. F. (1996). The robustness of test statistics to nonnormality and specification error in confirmatory factor analysis. *Psychological Methods, 1*(1), 16–29. https://doi.org/10.1037/1082-989X.1.1.16

Dalheimer, F., & Aakala, T. (2024). Availability and consumption of wooden resource for the construction of late medieval roof structures in Finland. *Mirator, 24*(1), 42–55. https://doi.org/10.54334/mirator.v24i1

Fromm, E. (1973). *The anatomy of human destructiveness*. Holt, Rinehart and Winston.

Gelman, A., et al. (2013) Gelman, A., Carlin, J. B., Stern, H. S., Dunson, D. B., Vehtari, A., & Rubin, D. B. (2013). *Bayesian data analysis* (3rd ed.). New York: Chapman and Hall/CRC.

Giusti, M. (2019). Human-nature relationships in context. Experiential, psychological, and contextual dimensions that shape children's desire to protect nature. *PLoS One, 14*(12), Article e0225951. https://doi.org/10.1371/journal.pone.0225951

Hartig, T., Lindblom, K., & Ovefelt, K. (1998). The home and near-home area offer restoration opportunities differentiated by gender. *Scandinavian Housing and Planning Research, 15*(4), 283–296. https://doi.org/10.1080/02815739808730463

Helin, A., Hakola, H., & Hellén, H. (2020). Optimisation of a thermal desorption–gas chromatography–mass spectrometry method for the analysis of monoterpenes, sesquiterpenes and diterpenes. *Atmospheric Measurement Techniques, 13*, 3543–3560. https://doi.org/10.5194/amt-13-3543-2020

Ige, J., Pilkington, P., Orme, J., Williams, B., Prestwood, E., Black, D., Carmichael, L., & Scally, G. (2019). The relationship between buildings and health: A systematic review. *Journal of public health (Oxford, England), 41*(2), e121–e132. https://doi.org/10.1093/pubmed/fdy138

Ikei, H., Song, C., Lee, J., & Miyazaki, Y. (2015a). Comparison of the effects of olfactory stimulation by air-dried and high-temperature-dried wood chips of hinoki cypress (*Chamaecyparis obtusa*) on prefrontal cortex activity. *Journal of Wood Science, 61*, 537–540. https://doi.org/10.1007/s10086-015-1495-6

Ikei, H., Song, C., & Miyazaki, Y. (2015b). Physiological effect of olfactory stimulation by hinoki cypress (*Chamaecyparis obtusa*) leaf oil. *Journal of Physiological Anthropology, 34*(44). https://doi.org/10.1186/s40101-015-0082-2

Ikei, H., Song, C., & Miyazaki, Y. (2016). Effects of olfactory stimulation by α-pinene on autonomic nervous activity. *Journal of Wood Science, 62*, 568–572. https://doi.org/10.1007/s10086-016-1576-1

Ikei, H., Song, C., & Miyazaki, Y. (2017). Physiological effects of wood on humans: A review. *Journal of Wood Science, 63*, 1–23. https://doi.org/10.1007/s10086-016-1597-9

Ilgin, E., & Karjalainen, M. (2022). Massive wood construction in Finland: Past, present, and future. In *Wood industry-past, present and future outlook*. InTech Open Access Publisher.

Jiménez, P., Dunkl, A., Eibel, K., Denk, E., Grote, V., Kelz, C., & Moser, M. (2016). Wood or laminate? —psychological research of customer expectations. *Forests, 7*(11). https://doi.org/10.3390/f7110275. article 275.

Jo, H.-J., Eijiro, F., & Cho, T.-D. (2010). An experimental study of physiological and psychological effects of pine scent. *Journal of the Korean Institute of Landscape Architecture, 38*(4), 1–10. http://uci.or.kr/G704-000407.2010.38.4.001.

Jussila, J., & Lähtinen, K. (2020). Effects of institutional practices on delays in construction – Views of Finnish homebuilder families. *Housing Studies, 35*, 1167–1193. https://doi.org/10.1080/02673037.2019.1651831

Kleespies, M. W., Braun, T., Dierkes, P. W., & Wenzel, V. (2021). Measuring connection to nature—A illustrated extension of the inclusion of nature in self scale. *Sustainability, 13*(4). https://doi.org/10.3390/su13041761. article 1761.

Korpela, K. M., Ylén, M., Tyrväinen, L., & Silvennoinen, H. (2008). Determinants of restorative experiences in everyday favorite places. *Health & Place, 14*(4), 636–652. https://doi.org/10.1016/j.healthplace.2007.10.008

Kovačević, M., Rieder-Gradinger, C., Teischinger, A., & Srebotnik, E. (2023). Volatile organic compounds emitted from Scots pine and Norway spruce wood. *Holz als Roh- und Werkstoff, 81*(3), 699–712. https://doi.org/10.1007/s00107-022-019,09-0

Kwak, S., & Choi, K. (2025). Visual perceptions of wood-integrated material combinations: Effects on psychological and physiological responses. *Journal of Wood Science, 71*, 20. https://doi.org/10.1186/s10086-025-02191-3

Ladakis, I., Filos, D., & Chouvarda, I. (2024). Virtual reality environments for stress reduction and management: A scoping review. *Virtual Reality, 28*(50). https://doi.org/10.1007/s10055-024-00943-y

Lakhani, A., Martin, K., Gray, L., Mallison, J., Grimbeek, P., Hollins, I., & Mackareth, C. (2020). What is the impact of engaging with natural environments delivered via virtual reality on the psycho-emotional health of people with spinal cord injury receiving rehabilitation in hospital? Findings from a pilot randomized controlled trial. *Archives of Physical Medicine and Rehabilitation, 101*(9), 1532–1540. https://doi.org/10.1016/j.apmr.2020.05.013

Li, J., Wu, J., Lam, F., Zhang, C., Kang, J., & Xu, H. (2021). Effect of the degree of wood use on the visual psychological responses of wooden indoor spaces. *Wood Science and Technology, 55*, 1485–1508. https://doi.org/10.1007/s00226-021-01320-7

Likert, R. (1932). A technique for the measurement of attitudes. *Archives of Psychology, 22*, 5–55.

Lopes, M. K., & Falk, T. H. (2024). Audio-visual-olfactory immersive digital nature exposure for stress and anxiety reduction: A systematic review on systems, outcomes, and challenges. *Front. Virtual Real., 5*, Article 1252539. https://doi.org/10.3389/frvir.2024.1252539

Macey, A.-L., Macey, J., & Hamari, J. (2022). Virtual reality in emotion regulation: A scoping review. In *6th International GamiFIN Conference 2022 (GamiFIN 2022)*. Finland.

Macleod, C. M. (1991). Half A century of research on the stroop effect – An integrative review. *Psychological Bulletin, 109*(2), 163–203. https://doi.org/10.1037/0033-2909.109.2.163

Matsubara, E., & Ohira, T. (2018). Inhalation of Japanese cedar (Cryptomeria japonica) wood odor causes psychological relaxation after monotonous work among female participants. *Biomedical Research, 39*(5), 241–249. https://doi.org/10.2220/biomedres.39.241

Meuwese, D., Maas, J., Krabbendam, L., & Dijkstra, K. (2021). Viewing Nature lets your mind run free: Three experiments about the influence of viewing a Nature video on cognitive coping with psychological distress. *International Journal of Environmental Research and Public Health, 18*(16). https://doi.org/10.3390/ijerph18168842. article 8842.

Molinario, E., Lorenzi, C., Bartoccioni, F., Perucchini, P., Bobeth, S., Colleony, A., Diniz, R., Eklund, A., Jaeger, C., Kibbe, A., Richter, I., & Ruepert, A. (2020). From childhood nature experiences to adult pro-environmental behaviors: An explanatory model of sustainable food consumption. *Environmental Education Research, 26*, 1–27. https://doi.org/10.1080/13504622.2020.1784851

Mollazadeh, M., & Zhu, Y. (2021). Application of virtual environments for biophilic design: A critical review. *Buildings, 11*, 148. https://doi.org/10.3390/buildings11040148

Muilu-Mäkelä, R., Ojala, A., Harju, A., Kostensalo, J., Viik, J., Wik, I., Matilainen, H., Virtanen, L., Niemi, H., Butter, K., & Ohlmeyer, M. (2025). Impact of wooden interior surfaces on indoor environment quality and perceptions: Comparisons between wooden and non-wooden office rooms. *Journal of Building Engineering, 111*, Article 113429. https://doi.org/10.1016/j.jobe.2025.113429

Nakamura, M., Ikei, H., & Miyazaki, Y. (2019). Physiological effects of visual stimulation with full-scale wall images composed of vertically and horizontally arranged wood elements. *Journal of Wood Science, 65*(55). https://doi.org/10.1186/s10086-019-1834-0

Nakamura, M., Ikei, H., & Miyazaki, Y. (2022). Effects of visual stimulation using wooden-wall images with different amounts of knots on psychological and physiological responses. *Wood Science and Technology, 56*, 1869–1886. https://doi.org/10.1007/s00226-022-01419-5

Navarro-Haro, M. V., Hoffman, H. G., Garcia-Palacios, A., Sampaio, M., Alhalabi, W., Hall, K., & Linehan, M. (2016). The use of virtual reality to facilitate mindfulness skills training in dialectical behavioral therapy for borderline personality disorder: A case study. *Frontiers in Psychology, 7*, 1573. https://doi.org/10.3389/fpsyg.2016.01573

Nyrud, A. Q., & Bringslimark, T. (2010). Is Interior wood use psychologically beneficial? A review of psychological responses toward wood. *Wood and Fiber Science, 42*, 202–218.

Nyrud, A. Q., Bringslimark, T., & Bysheim, K. (2011). Benefits from wood interior in a hospital room: A preference study. *Architectural Science Review, 57*(2), 125–131. https://doi.org/10.1080/00038628.2013.816933

Official Statistics of Finland (OSF). (2025a). *Commercial fellings 6/2025 [web publication]*. Helsinki: Natural Resources Institute Finland [referred: 13.8.2025]. Access method: https://www.luke.fi/en/statistics/commercial-fellings/commercial-fellings-62025.

Official Statistics of Finland (OSF). (2025b). *Flows of wood material 2023, 23 Nov 2024 [web publication]*. Helsinki: Natural Resources Institute Finland [referred: 13.8.2025]. Access method: https://www.luke.fi/en/statistics/flows-of-wood-material/flows-of-wood-material-2023.

Ohira, T., Park, B.-J., Kurosumi, Y., & Miyazaki, Y. (2009). Evaluation of dried-wood odors: Comparison between analytical and sensory data on odors from dried sugi (*Cryptomeria japonica*) wood. *Journal of Wood Science, 55*, 144–148. https://doi.org/10.1007/s10086-008-1001-5

Ojala, A., Kostensalo, J., Viik, J., Matilainen, H., Wik, I., Virtanen, L., & Muilu-Mäkelä, R. (2023). Psychological and physiological effects of a wooden office room on human wellbeing: Results from a randomized controlled trial. *Journal of Environmental Psychology, 89*. https://doi.org/10.1016/j.jenvp.2023.102059. Article 102059.

Ojeda, J., Salomon, A., Rowe, J., & C Ban, N. (2022). Reciprocal contributions between people and Nature: A conceptual intervention. *BioScience, 72*(10), 952–962. https://doi.org/10.1093/biosci/biac053

Owens, M., & Bunce, H. (2023). The effect of brief exposure to virtual nature on mental wellbeing in adolescents. *Scientific Reports, 13*. https://doi.org/10.1038/s41598-023-44717-z. article 17769.

Pallavicini, F., & Bouchard, S. (2019). Editorial: Assessing the therapeutic uses and effectiveness of virtual reality, augmented reality and video games for emotion regulation and stress management. *Frontiers in Psychology, 10*. https://doi.org/10.3389/fpsyg.2019.02763

Puuinfo. (2025). https://puuinfo.fi/puutieto/finnish-forests/species-of-trees/?lang=en. (Accessed 22 April 2025).

R Core Team. (2024). *R: A Language and environment for statistical computing*. Vienna, Austria: R Foundation for Statistical Computing. https://www.R-project.org/.

Renaud, P., & Blondin, J.-P. (1997). The stress of Stroop performance: Physiological and emotional responses to color-word interference, task pacing, and pacing speed. *International Journal of Psychophysiology, 27*(2), 87–97. https://doi.org/10.1016/S0167-8760(97)00049-4

Ruotsalainen, S., Himanen, K., Viherä-Aarnio, A., Aarnio, L., Haapanen, M., Luoranen, J., Matala, J., Riikonen, J., Uotila, K., & Ylioja, T. (2022). *Puulajivalikoiman monipuolistaminen metsänviljelyssä: Synteesiraportti. Luonnonvara- ja biotalouden tutkimus 24/2022. Luonnonvarakeskus. Helsinki. 135 s* [in Finnish].

Ryan, C. O., Browning, W. D., Clancy, J. O., Andrews, S. L., & Kallianpurkar, N. B. (2014). Biophilic DESIGN PATTERNS: Emerging nature-based parameters for health and wellbeing in the built environment. *International Journal of Architectural Research: ArchNet-IJAR, 8*(2), 62. https://doi.org/10.26687/archnetijar.v8i2.436

Scarpina, F., & Tagini, S. (2017). The stroop color and word Test. *Frontiers in Psychology, 8*. https://doi.org/10.3389/fpsyg.2017.00557. article 00557.

Schreiner, L., Bauer, P., & Buettner, A. (2018). Resolving the smell of wood - Identification of odour-active compounds in Scots pine (*Pinus sylvestris* L.). *Scientific Reports, 8*, 8294. https://doi.org/10.1038/s41598-018-26626-8

Schreiner, L., Karacan, B., Blankenagel, S., Packhaeuser, K., Freiherr, J., & Loos, H. M. (2020b). Out of the woods: Psychophysiological investigations on wood odors to estimate their suitability as ambient scents. *Wood Science and Technology, 54*, 1385–1400. https://doi.org/10.1007/s00226-020-01216-y

Schreiner, L., Ortner, E., & Buettner, A. (2020a). Nosy confirmation: Reconstitution of the characteristic odor of softwood via quantitative analysis and human sensory evaluation. *Analytical and Bioanalytical Chemistry, 412*, 1137–1149. https://doi.org/10.1007/s00216-019-02339-3

Schultz, P. W. (2002). Inclusion with Nature: The psychology of human-nature relations. In P. Schmuck, & P. W. Schultz (Eds.), *Psychology of sustainable development* (pp. 61–78). Boston, MA: Springer. https://doi.org/10.1007/978-1-4615-0995-0_4.

Seymour, V. (2016). The human-nature relationship and its impact on health: A critical review. *Frontiers in Public Health, 4*, 260. https://doi.org/10.3389/fpubh.2016.00260, 2016 Nov 18 PMID: 27917378; PMCID: PMC5114301.

Soga, M., & Gaston, K. (2020). The ecology of human-nature interactions. *Proceedings of the Royal Society A: Mathematical, Physical and Engineering Sciences B., 287*, Article 20191882. https://doi.org/10.1098/rspb.2019.1882

Song, C., Ikei, H., & Miyazaki, Y. (2019). Physiological effects of forest-related visual, olfactory, and combined stimuli on humans: An additive combined effect. *Urban Forestry and Urban Greening, 44*, Article 126437. https://doi.org/10.1016/j.ufug.2019.126437

Song, C., Ikei, H., & Miyazaki, Y. (2021). Effects of forest-derived visual, auditory, and combined stimuli. *Urban Forestry and Urban Greening, 64*, Article 127253. https://doi.org/10.1016/j.ufug.2021.127253

Stoet, G. (2010). PsyToolkit - A software package for programming psychological experiments using Linux. *Behavior Research Methods, 42*(4), 1096–1104. https://doi.org/10.3758/BRM.42.4.1096

Stoet, G. (2017). PsyToolkit: A novel web-based method for running online questionnaires and reaction-time experiments. *Teaching of Psychology, 44*(1), 24–31. https://doi.org/10.1177/0098628316677643

Stroop, J. R. (1935). Studies of interference in serial verbal reactions. *Journal of Experimental Psychology, 18*(6), 643–662. https://doi.org/10.1037/h0054651

Sun, M., Nakashima, T., Yoshimura, Y., Honden, A., Nakagawa, T., Saijo, H., Watanabe, Y., Ajimi, T., Yasunari, S., Yamada, Y., Nagano, J., Okamoto, T., Ishikawa, H., Ohnuki, K., Fujimoto, N., & Shimizu, K. (2020). Effects and interactions of different interior material setting and personal preference on psychological and physiological responses in living environment. *Journal of Wood Science, 66*(63). https://doi.org/10.1186/s10086-020-01910-2

Tawil, N., Sztuka, I. M., Pohlmann, K., Sudimac, S., & Kühn, S. (2021). The living space: Psychological wellbeing and mental health in response to interiors presented in virtual reality. *International Journal of Environmental Research and Public Health, 18*, Article 12510. https://doi.org/10.3390/ijerph182312510

Tsunetsugu, Y., Lee, J., Park, B.-J., Tyrväinen, L., Kagawa, T., & Miyazaki, Y. (2013). Physiological and psychological effects of viewing urban forest landscapes assessed by multiple measurements. *Landscape and Urban Planning, 113*, 90–93. https://doi.org/10.1016/j.landurbplan.2013.01.014

Tsunetsugu, Y., Miyazaki, Y., & Sato, H. (2002). The visual effects of wooden interiors in actual-size living rooms on the autonomic nervous activities. *Journal of Physiological Anthropology and Applied Human Science, 21*, 297–300.

Tsunetsugu, Y., Miyazaki, Y., & Sato, H. (2005). Visual effects of interior design in actual-size living rooms on physiological responses. *Building and Environment, 40*, 1341–1346.

Tsunetsugu, Y., Miyazaki, Y., & Sato, H. (2007). Physiological effects in humans induced by the visual stimulation of room interiors with different wood quantities. *Journal of Wood Science, 53*, 11–16.

Tyrväinen, L., Ojala, A., Korpela, K., Lanki, T., Tsunetsugu, Y., & Kagawa, T. (2014). The influence of urban green environments on stress relief measures: A field experiment. *Journal of Environmental Psychology, 38*, 1–9. https://doi.org/10.1016/j.jenvp.2013.12.005

Ulrich, R. S. (1983). Aesthetic and affective response to natural environment. *Human Behavior and Environment: Advances in Theory and Research, 6*, 85–125.

van Riper, C. J., Browning, M. H. E. M., Becker, D., et al. (2019). Human-Nature relationships and normative beliefs Influence behaviors that reduce the spread of aquatic invasive species. *Environmental Management, 63*, 69–79. https://doi.org/10.1007/s00267-018-1111-9

Wang, Z. (2024). Discussion on the transformation of human-computer interaction in virtual reality and mixed reality. *The Frontiers of Society, Science and Technology, 6*(3), 16–20. https://doi.org/10.25236/FSST.2024.060303

Wickham, H. (2016). *ggplot2: Elegant graphics for data analysis*. New York: Springer-Verlag, ISBN 978-3-319-24277-4. https://ggplot2.tidyverse.org.

Wilder, J. (1957). The law of initial value in neurology and psychiatry. *The Journal of Nervous and Mental Disease, 125*, 73–86. https://doi.org/10.1097/00005053-195701000-00009

Wilson, E. O. (1984). *Biophilia*. Cambridge, MA: Harvard University Press. ISBN 0-674-07442-4.

Yen, H.-Y., Hsu, H., & Huang, W.-H. (2024). Virtual reality natural experiences for mental health: Comparing the effects between different immersion levels. *Virtual Reality, 28*(52). https://doi.org/10.1007/s10055-024-00958-5

Yu, C.-P., Weng, W.-C., Ramanpong, J., Wu, C.-D., Tsai, M.-J., & Spengler, J. D. (2022). Psysiological and psychological responses to olfactory stimulation by Taiwania (Taiwania cryptomerioides) essential oil and the influences of cognitive bias. *Journal of Wood Science, 68*. https://doi.org/10.1186/s10086-022-02021-w. article 12.

Zhou, Y., Zhao, X., Feng, Y., Xuan, C., Yang, C., & Jia, X. (2025). Effects of visual perception of building materials on human emotional States and cognitive functioning in a physical learning environment. *Buildings, 15*(7), 1163. https://doi.org/10.3390/buildings15071163