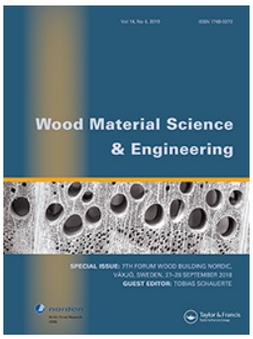

Wood Material Science & Engineering

ISSN: 1748-0272 (Print) 1748-0280 (Online) Journal homepage: informahealthcare.com/journals/swoo20

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To cite this article: Elaheh Jalilzadehazhari & Jimmy Johansson (2019) Material properties of wooden surfaces used in interiors and sensory stimulation, Wood Material Science & Engineering, 14:4, 192-200, DOI: 10.1080/17480272.2019.1575901

To link to this article: https://doi.org/10.1080/17480272.2019.1575901

WOOD MATERIAL SCIENCE & ENGINEERING
2019, VOL. 14, NO. 4, 192–200
https://doi.org/10.1080/17480272.2019.1575901

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REVIEW ARTICLE

Material properties of wooden surfaces used in interiors and sensory stimulation

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ABSTRACT

By covering interiors, such as walls, ceilings and floors, with wooden surfaces, one can change the quality of indoor environments and thereby affect both psychological and physiological responses. Psychological responses refer to individuals' emotional reactions toward interiors, while physiological responses include changes in the activity of the brain, the autonomic nervous system, the endocrine system, and the immune system. The above-mentioned responses considered in this study are those caused by visual, auditory, olfactory and tactile stimulation from interior wooden surfaces. Although earlier studies have presented valuable information on this subject, questions remain about the material properties of wood which are associated with the stimulation. Specifying the material properties can support architects, designers and engineers who intend to use wood in interiors for improving psychological and physiological responses. A literature study therefore has been conducted to determine (i) the material properties of wood which are associated with sensory stimulation, and (ii) to specify relevant recommendations or requirements which should be fulfilled when covering interiors with wooden surfaces. The results show a lack of knowledge regarding the material properties of wood and the degree in which it affects sensory stimulation.

ARTICLE HISTORY
Received 7 March 2018
Revised 22 January 2019
Accepted 25 January 2019

KEYWORDS
Wooden surfaces; indoor environmental quality; psychological responses; physiological responses; material properties

1. Introduction

The use of wood in construction has endured for centuries in Sweden. According to Schauerte (2010), in 2010 wooden single-family houses in Sweden accounted for about 90% of the market share. There has also been an upward trend in using wood for constructing multi-family houses in the country (Mahapatra and Gustavsson 2009). Historically, the accessibility of wood materials has had a profound influence on the popularity of wooden buildings in Sweden (Schauerte 2010). Furthermore, wood materials generally have a lower environmental impact when compared with other construction materials (Hemström *et al.* 2010). A study by Gustavsson *et al.* (2006) showed that the net carbon dioxide emissions of a wooden building with a coal-fired condensing plant for generating electricity were about 66.8 tonnes less than in a similar building with a concrete frame. during its 100-year lifetime.

In addition to environmental impacts, several studies have analysed how covering interiors with wooden surfaces[1] can change the quality of indoor environments and thereby affect people's health and their psychological and physiological responses. Psychological responses signify individuals' emotional reactions towards wooden surfaces in interiors (Nyrud and Bringslimark 2010). Nyrud and Bringslimark (2010) have summarised psychological responses to wood materials into three main categories: (i) the perception of wood, which involves cognition and sensation processes, (ii) preferences regarding wooden surfaces in interiors, which concerns aesthetic evaluations, and (iii) emotions produced, based on changes in physiology due to exposure to wooden surfaces in interiors.

Psychological responses to wooden surfaces in interiors comprise changes in the activity of the brain, the autonomic nervous system, the endocrine system and the immune system (Ikei *et al.* 2017). These changes are caused by visual (Nordvik *et al.* 2009, Fujisaki *et al.* 2015), auditory (Fujisaki *et al.* 2015), olfactory (Bysheim *et al.* 2016) and tactile stimulation (Bhatta *et al.* 2017), in this case associated with wooden surfaces in interiors.

Although previous studies have analysed the role of sensory stimulation in changing the psychological (Nyrud *et al.* 2010, Jiménez *et al.* 2016, Rice *et al.* 2007) and physiological responses (Sueyoshi *et al.* 2004b, Li *et al.* 2006, Sakuragawa *et al.* 2008, Burnard and Kutnar 2015, Park *et al.* 2017), they provide no explanation of how the material properties of wood cause these changes. Determining these properties is essential, since it may provide possibilities for the development of further wood treatments (Strobel *et al.* 2017). Furthermore, it allows replacing other materials with wood, which leads to an improvement in indoor environmental quality and health. According to Kats *et al.* (2003), Fisk and Seppanen (2007), Seppänen and Fisk (2006), and Wargocki (2003), improving health can also bring economic benefits. For this purpose, this literature study aims to determine the material properties of wood which are associated with sensory stimulation. In

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addition, this literature study specifies relevant recommendations provided by previous studies, by Swedish standards and by building rating certifications regarding the use of interior wooden surfaces.

2. Methodology

This study was based on a systematic literature review. The literature review aimed to search for studies which analysed only the correlation between sensory stimulation associated with wooden surfaces in interiors and related changes in physiological responses. The literature study was carried out in the Scopus database using four main keywords and phrases: "wood", "human psychology", "human physiology" and "material property". The primary search terms resulted in almost 153 studies. The search terms were subsequently narrowed down to include only English-language studies published between 2000 and 2018 (Table 1).

In addition, the subject area was limited to "medicine", "neuroscience", "biochemistry, genetics and molecular biology", "psychology", "material science", "social science", "pharmacology, toxicology and pharmaceutics", "immunology and microbiology" and "nursing". The evaluated studies included published journal articles, conferences, review articles, reports, and book chapters.

The abstracts of the studies found were read, and the relevant ones were selected for critical evaluation. After applying the pre-selection limitations, 52 studies were found eligible and analysed.

The search for requirements and regulations regarding the use of interior wooden surfaces was accomplished by reviewing the related Swedish standards, including "Light & Room, the guide for planning of indoor lighting" (Månsson 2003), SS25667 and SS25668 (Swedish Standard Institute 2018), and chapters from Building Regulation 2015 (National board of housing building and planning 2015a). Furthermore, three building rating certifications were reviewed, including Sweden Green Building Council certification (*Miljöbyggnad* in Swedish) (SGBC 2017), WELL certification from the International WELL Building Institute (IWBI 2018), and the Living Building Challenge standard from the International Living Future Institute (LBC 2016).

3. Results

First, the material properties of wood, which are associated with visual, olfactory, auditory and tactile stimulation are discussed. Later, the available recommendations and requirements for covering interiors with wooden surfaces are presented.

Table 1. Search terms used in the Scopus database.

	Search terms	Found studies	Eligible after pre-selection
Scopus	wood AND (human AND physiology OR human AND psychology OR material AND property)	153	52

Material properties associated with visual stimulation

Visual stimulation from a wooden surface is dependent on the colour, structure, surface treatment and the presence of knots[2] (Nyrud and Bringslimark 2010). The characteristics of knots vary among different species of tree, including their size, shape, homogeneity, colour, distance between knots and the number of knots on the surface of the wood (Høibø and Nyrud 2010, Ross 2010). A study by Nakamura and Kondo (2007) shows a positive linear relationship between the number of knots exposed in wooden surfaces in interiors and eye fatigue, which can be accompanied by eye strain and headaches (Aries *et al.* 2015). Eye strain occurs due to the tightness of the ciliary muscles, which changes the shape of the lens in the eye (Aries *et al.* 2015) and can cause difficulties in learning and information processing (Edwards and Torcellini 2002). Furthermore, eye fatigue can lead to higher levels of stress and anxiety (Edwards and Torcellini 2002).

The colour of the wood depends on the direction of radiated light and the chemical composition, including extractives, lignin, cellulose, and hemicellulose (Hon and Shiraishi 2000, Strobel *et al.* 2017). One part of the radiated light enters the wood cells and is absorbed by voids and pigments, while the other part is emitted through reflection and transmission (Hon and Shiraishi 2000). In general, wood emits long-wave light and is therefore perceived as having a yellow-to-red hue (Nyrud and Bringslimark 2010). Light falling in the eyes reflected from interior wooden surfaces can trigger the visual cortex in the brain and thereby affect cognition performance, including analysing, memorising and reasoning processes (Dzulkifli and Mustafar 2013, Aries *et al.* 2015). Dzulkifli and Mustafar (2013) have claimed that long-wave colours with a yellow-to-red hue can improve cognitive performance. Furthermore, the aromatic lignin component in wood can absorb a high amount of ultraviolet light (Kutz 2005), creating a comfortable environment for the eye. According to Van Kuijk (1991), ultraviolet exposure can cause degradation of the retina (the innermost layer of the eye). Multiple studies have discussed the benefits of the colour of wood on cognition performance and eye health.

On the structure of wood, Hirata *et al.* (2012) say that "the anatomical level relief structure of wood surfaces induces light to scatter and diminish surface glare". Scattering the light can decrease perceived glare and increase luminance value (Watchman *et al.* 2016). In general, reduced glare and an adequate luminance value can decrease the incidence of eye fatigue, eye strain and headaches (Aries *et al.* 2015), thereby reducing perceived stress (Edwards and Torcellini 2002). In a similar way, wood surface treatments can provide uniform light distribution and thereby decrease perceived glare (Watchman *et al.* 2016). According to Tell (1990), wood stain, clear varnish, and film-forming paint are the three main surface treatment techniques in Sweden. Applying surface treatments to wooden surfaces used in interiors can change their light emittance and absorption (Keeler and Vaidya 2016, Kreith and Chhabra 2017). The emittance of a surface comprises the surface transmittance and reflectance values. The Room and Light standard demands a reflectance value of 60%, 80% and 20% for walls, ceilings,

and floors in office buildings respectively, while it provides no requirements for reflectance values in residential buildings (Månsson 2003).

Although multiple studies analysed the changes in physiological responses associated with visual stimulation from interior wooden surfaces, they provided no information regarding the material specifications of the wood used in the experiments. To draw a conclusion as to whether changes in physiological responses are associated with the colour, structure, surface treatment or knots in wood, is therefore amiss. For instance, Tsunetsugu *et al.* (2002) and Tsunetsugu *et al.* (2007) analysed the effects of visual stimulation from the wooden surfaces in different living rooms on blood pressure, heart rate and rCBF. The rCBF refers to the specific amount of blood being circulated in a particular part of the brain (Sharma 2011). Sakuragawa *et al.* (2005) evaluated changes in blood pressure associated with visual stimulation from wood surfaces and white steel surfaces on walls. The wood species had not been specified in the studies mentioned above. Generally, visual stimulation associated with wooden surfaces in interiors was found to have positive effects on physiological responses, which resulted in a reduction in respondents' perceived stress. The small sample size of respondents, and the short exposure time in performing experiments, limited the derivation of a conclusion based on evidence. According to Kansara (2013), respondents' reactions should be evaluated over short-, medium- and long-term periods. Furthermore, Sakuragawa *et al.* (2005) included only male respondents in the experiment, which causes concerns when interpreting the results.

The Swedish Green Building certification evaluates the visual environment based on the amount of daylight coming through the windows. Although the amount of daylight is affected by the reflectance value of the walls, ceiling, and floor, it is also highly dependent on window size.

The WELL building certification evaluates visual environments by quantifying the amount of light, glare, uniformity and colour rendering index of electrical lighting (IWBI 2018). Furthermore, the certification recommends designers to ensure a minimum glazing area, along with a shading and lighting control system (IWBI 2018).

The Living Building Challenge standard emphasises biophilia theory in building design by incorporating environmental features, natural shapes and forms, natural patterns and processes, light and space, place-based relationships and evolved human-nature relationships (LBC 2016). For this purpose, the certification encourages the use of wood in interiors. However, the current Living Building Challenge standard, which was applicable at the time of conducting this literature review (2018), did not present an approach for evaluating visual environment.

The above-mentioned studies and certifications provide no recommendation regarding knots, colour or structure of interior wooden surfaces which can affect visual stimulation and improves the visual environment (Tsunetsugu *et al.* 2002, Sakuragawa *et al.* 2005, Tsunetsugu *et al.* 2005, Tsunetsugu *et al.* 2007, LBC 2016, SGBC 2017, IWBI 2018).

Material properties associated with auditory stimulation

The auditory stimulation from interior wooden surfaces depends mainly on the wood's acoustic performance. The acoustic performance of wood can be determined by its composition, surface treatment, type of mounting, geometry (Bucur 2006) and density (Wegst 2006). The composition of wood includes its anisotropic, hygroscopic and viscoelastic composition (Rowell 2012). Anisotropy refers to the variations in wood properties in three different directions: longitudinal, radial and tangential. In the presence of moisture, the longitudinal swelling is negligible (Wood Handbook 2010), but the tangential grain direction can swell about twice as much as in the radial grain direction, due to its higher density (Rowell 2012). A higher moisture content can deteriorate the acoustic properties of wood, since it changes the microstructure of the cell walls (Wegst 2006, Rowell 2012). The viscoelastic composition of wood refers to polymers in the cell walls; this includes crystalline cellulose polymers as the elastic phase, and nanocrystalline cellulose polymer as the viscous phase (Rowell 2012). A vibration in the wood is transmitted more quickly through the elastic phase of the cell walls than through the viscous phase (Rowell 2012). The crystalline cellulose polymers are oriented in the longitudinal direction (Kurjatko *et al.* 2006). Therefore, a vibration in the longitudinal direction travels faster in comparison with the other two directions. The hygroscopic composition refers to the influence of absorbed water molecules in reducing the elastic properties of the cell walls (Ozyhar *et al.* 2013). Various treatments were previously used to control the moisture content in the wood, including heat treatments (Dubey *et al.* 2012, Esteves *et al.* 2017) and chemical treatments (Obataya *et al.* 2001). According to Standard SS-EN 14298 (2017) issued by the Swedish Standard Institute, the moisture content for wooden floors should be between 7% to 9%. However, it provides no requirement regarding moisture content in wooden surfaces used on walls and ceilings.

Surface treatments including wood stain, clear varnish, and film-forming paint, can affect acoustic performance by modifying damping, stiffness, and mass (Bucur 2006). Damping refers to the dissipation of sound in wood (U.S. Department of Agriculture *et al.* 2007). Results presented by Trichkov and Bardarov (2010) show that damping was increased by increasing the quantity of clear vanish. Additionally, the type of mounting (Godshall and Davis 1969) and the geometry of the wood, including its thickness (Seddeq 2009), can affect the sound absorption coefficient and thereby modify the acoustic performance of wood. Density is the other important factor which characterises the acoustic performance of wood (Wegst 2006). Accordingly, treatments which can alter the density of the wood can change its acoustic performance. Compression in the transverse direction of wood and impregnation methods are two examples which can increase the density of wood materials (Sandberg *et al.* 2013). In general, wood has poor acoustic insulation properties when compared with other construction materials (Bucur 2006). However, sound absorbing panels, such as perforated wooden panels,

were previously used to absorb sound in interiors, such as in cinemas (Song *et al.* 2016, Shengwo and Fangshuo 2010)

The National Board of Housing, Building and Planning in Sweden, which authorises policies and supervises procedural, legislative and architectural plans, provides no separate acoustic recommendations for surface treatment, type of mounting or geometry (National board of housing building and planning 2018). Instead, the authority specifies the minimum differences in sound pressure between the outside and inside of residential and office buildings and also between different spaces within the buildings (National board of housing building and planning 2015b). Furthermore, the Swedish Standard Institute has issued SS25267 and SS25268 standards for residential and office buildings respectively (Swedish Standard Institute 2018). The above-mentioned standards include four different classes for evaluating the acoustic performance of buildings: A, B, C and D (Swedish Standard Institute 2018). Class A corresponds to the best acoustic performance, while class D refers to the poorest (Swedish Standard Institute 2018). Acoustic performance class C complies with the requirements issued by the Board which should be fulfilled in the construction of new buildings (National board of housing building and planning 2018).

Several studies analysed the relationships between auditory stimulation in wooden buildings and physiological responses. However, these studies provided no information regarding material specifications of the wood used in the construction of the buildings, namely the composition, surface treatment, type of mounting and geometry of the wood.

For instance, Sueyoshi *et al.* (2004a) analysed the effects of heavy floor-impact sounds on changes in respondents' blood pressure and peripheral blood flow (the circulating blood in the body) in a wooden building. Furthermore, they evaluated respondents' sensitivity to the sounds. Sueyoshi *et al.* (2004b) studied changes in the systolic blood pressure to different prolonged floor-impact sounds in a building with wooden flooring. Park *et al.* (2017) analysed the effects of various sounds on heart rate, skin conductance and respiratory rate in a building with wooden flooring. The respiratory rate refers to the measurement of breaths per minute. The above-mentioned studies did not specify the wood species used in the construction of buildings or floor coverings. The results presented indicate that physiological responses to sound are indeed dependent on individual sensitivity more than on the sounds or their pressure levels. The findings are in accordance with the results presented by Hume and Ahtamad (2013) in that sound impact resources at different pressure levels have no significant effect on physiological responses. However, the above-mentioned studies only considered respondents identified as male or female. In addition, they provided no insight into how changing the setting for an experiment could affect the results. The inclusion of a larger sample size and a wider age range would allow for generalising the results. The risk of serial position effect[3] in these studies may also prevent derivation of a more robust conclusion.

The Swedish Green Building certification evaluates the acoustic performance of buildings by analysing four parameters: sound from indoor installations or background sound, stage sound, air sound and outside sound (SGBC 2017). The certification demands minimum requirements for these parameters in both residential and office buildings (SGBC 2017).

The WELL building certification specifies different sound level requirements for various spaces in residential, office and educational buildings (IWBI 2018). Furthermore, the certification asks designers to ensure acoustic comfort by specifying requirements for surface finishes and reverberation time based on the room functionality (IWBI 2018).

The health and happiness petal of Living Building Challenge aims to create a healthy and robust indoor environment. However, no specific recommendation was found regarding the acoustic performance of buildings (LBC 2016).

None of the studies analysed, or the certifications, provided any specific recommendations regarding the composition, surface treatment, type of mounting or geometry of wood for improving the acoustic performance of buildings.

Material properties associated with olfactory stimulation

The effects of olfactory stimulation from wood on physiological responses depend strongly on the chemical composition of the wood, including volatile extractives (Navi and Sandberg 2012) and the subjects' individual differences in sensitivity towards olfactory stimulation (Brand and Millot 2001, Lundström *et al.* 2003). The emission of extractives is mainly affected by moisture content (Huang *et al.* 2016). The monoterpenes group of substances, which include different organic extractives, represents the most volatile extractives in woods (Granström 2005). The composition and amount of monoterpenes in wood is strongly dependent upon a tree's age, its species, its genetics and the time of the year (Granström 2005). Furthermore, the monoterpenes group of substances varies among individual plants and can be found in the resin (Granström 2005). The resin in Scots pine and Norway Spruce, which are the most common conifers in Sweden, consists of about 25–30% of monoterpenes (Granström 2005). The dominant extractives of the monoterpenes group in Scots pine are α-pinene, 3-carene dominate and β-pinene, while they are α-pinene, β-pinene and 3-carene in Norway spruce in descending order of quantity (Granström 2005).

The majority of studies concentrated on volatile extractives from a single species, and analysed their effects on physiological responses. For instance, Ikei *et al.* (2015a) analysed the effects of olfactory stimulation caused by emissions from air-dried and high temperature-dried Japanese Hinoki cypress (*Chamaecyparis obtusa*) wood chips on oxygenated haemoglobin concentration (oxy-Hb) in the prefrontal cortex. In another attempt, Ikei *et al.* (2015b) analysed the effect of olfactory stimulation caused by emissions from Hinoki cypress (*C. obtusa*) leaf oil on heart rate variability (HRV), and on oxy-Hb. HRV describes the variation in time intervals between heartbeats (Marek and MD 1996). The type of the emitted extractive considered in this study remained unspecified. In another study, Ikei *et al.* (2016) studied the effect of olfactory stimulation caused by α-pinene from Japanese cedar (*Cryptomeria japonica*) wood

chips on HRV and the heart rate. Hiruma *et al.* (2002) considered only Hiba oil, extracted from Thujopsis dolabrata species, and analysed the effect of its odours on contingent negative variation (CNV). CNV is defined as "an event-related brain potential (ERP) that occurs prior to an expected stimulus that usually requires an action" (Hiruma *et al.* 2002). However, the type of the emitted extractive from Hiba oil was not specified. Joung *et al.* (2014) concentrated on D-Limonene as a single extractive and studied its effect on HRV and the heart rate. However, no information was provided about the species from which D-Limonene was extracted. Li *et al.* (2009) studied the effects of odours from an oil extracted from Hinoki cypress *(Chamaecyparis obtuse)* on the activity of natural killer cells and on concentrations of adrenaline and noradrenaline in urine, known as stress hormones. Natural killer cells contribute to the death of virus- or tumour-infected cells (Li *et al.* 2006), and thereby have an important role in boosting the immune system. Emitted extractives included α-pinene and β-pinene. Dayawansa *et al.* (2003) analysed the effect of cedrol inhalation, extracted from cedar wood oil, on the heart rate, blood pressure, respiratory rate, and parasympathetic activity. The species, from which cedarwood oil was extracted remained unspecified.

Only a single study was found which considered different species in their experiments (Bamba and Azuma 2014). The wood species included Japanese Cedar (*Cryptomeria cedar*) and Hinoki cypress *(Chamaecyparis obtuse)*. Samples were taken from trees of different ages, drying conditions and growing locations. Furthermore, Bamba and Azuma (2014) included Poplar plywood in the experiments, and analysed its effect on oxy-Hb. The extractives comprised Formaldehyde, Acetaldehyde, Acetone, Isooctane, Heptane, Toluene, Octane, Nonane, α-Pinene and Limonene. The results show a significant change in oxy-Hb when respondents were exposed to plywood. This was because plywood emitted a higher quantity of Formaldehyde than the other samples. No explanation was presented whether variety in age, drying conditions or growing location, affected any changes in oxy-Hb.

Brand and Millot (2001), and Lundström *et al.* (2003), studied individuals' sensitivity toward olfactory stimulation. The results presented showed a tendency for women to be more sensitive towards olfactory stimulation than men. The role of gender in sensitivity towards olfactory stimulation may have an evolutionary basis (Brand and Millot 2001).

The above-mentioned studies used various odours from different wood species in their experiments, which led to inconsistency in the results. Furthermore, the studies considered mostly respondents identified as only male or female. Evaluating a larger age range, extending the exposure time, and analysing the correlation between individual sensitivity and physiological response, can strengthen the results and help to arrive at a conclusion. Furthermore, the above-mentioned studies provided no information on how the variety in age, genetics and the time of the year, could change the composition and amount of extractive, and thereby affect the physiological responses.

The Swedish Green Building certification sets requirements for ventilation systems to improve indoor air quality and to ensure a comfortable environment for occupants in residential and office buildings (SGBC 2017). However, the certification provides no recommendations regarding the chemical composition of wood, including volatile extractives which influence olfactory stimulation.

The WELL building certification considers holistic design strategies to improve air quality by mitigating harmful contaminants and volatile organic compounds (IWBI 2018). However, the certification provides no recommendations about levels of volatile extractives in wood, which can affect olfactory stimulation.

The Living Building Challenge aims to promote good indoor air quality by (i) adopting the latest version of American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) 62; (ii) prohibiting smoking within buildings; (iii) monitoring indoor air quality before and nine months after occupancy; (iv) adopting the California Department of Public Health (CDPH) Standard Method v.1.1-2010 for all interior products which emit volatile organic compounds; (v) considering exhaust systems for janitorial areas, kitchens, and bathrooms; (vi) considering an entry which can reduce particulates brought in on shoes; and (vii) specifying a protocol which ensures the use of cleaning products carrying the Environmental Protection Agency (EPA) Design on their Environment label. However, the certification gives no recommendations about volatile extractives from wooden surfaces to be used for interiors.

Material properties associated with tactile stimulation

According to Wang *et al.* (2000), the effects of tactile stimulation on physiological responses, which includes skin temperature, depend on the heat flux of materials. Heat flux is controlled by the thermal conductivity of materials, and temperature differences between the skin and the material with which it is in contact (Wang *et al.* 2000). In general, the thermal conductivity of wood and wood-based materials is lower than other materials commonly used to cover interiors, such as tile, marble, and concrete (Wang *et al.* 2000, Yaşar and Erdoğan 2008).

The thermal conductivity of wood depends on its moisture content, density, grain direction, the content of extractives, and its structural irregularities, including knots, checks, and temperature (Glass and Zelinka 2010). The thermal conductivity of wood is increased by augmenting either moisture content or density (Glass and Zelinka 2010). However, in a stable condition, the thermal conductivity of wood in the longitudinal direction can be 1.5–2.8 times greater than in the radial or tangential directions (Glass and Zelinka 2010).

The thermal conductivity of wood can be altered by applying heat treatments, chemical treatments and surface treatments (Rowell 2012, Olarescu *et al.* 2015, Sair *et al.* 2017), which can modify or preserve the moisture content in wood and thereby affect its thermal conductivity (Obataya *et al.* 2001, Fredriksson 2010, Dubey *et al.* 2012, Esteves *et al.* 2017).

The majority of the studies analysed the effect of tactile stimulation on changes in physiological responses through contact with various materials with different thermal conductivity. For instance, Wang *et al.* (2000) analysed the effect of tactile stimulation caused by different materials on changes

in the temperature of the skin at the tip of the middle finger, on the palm and on the back of the hand. The materials comprised nine types of solid woods, five types of wood-based materials, four types of inorganic materials and three types of other material. Morikawa *et al.* (1998) studied the effects of tactile stimulation on systolic blood pressure through contact with Sugi woods *(C. japonica)* with planed and sawn surfaces, Hinoki woods *(Charnaecyparis obtusa)* with a sawn surface, stainless steel board of 4 mm thickness, denim, silk, and a vinyl bag of 0.8 mm thickness filled with cold water at 6°C. Sakuragawa *et al.* (2008) conducted a similar study and analysed the effects of tactile stimulation caused by various materials on systolic blood pressure. The materials used were a 20°C Sugi wood specimen *(Cryptomeria japonica)*, a 20°C Hinoki wood specimen *(Charnaecyparis obtusa)*, 20°C and 5°C oak wood specimens *(Quercus crispula),* 20°C and 5°C acrylic plastic samples, and aluminium samples at 20°C and 30°C. According to Jeong *et al.* (2014), variation in blood pressure after touching different materials may occur due to changes in skin temperature which can affect blood flow and blood vessels.

The results from the studies mentioned above show that touching wooden surfaces has mainly positive effects on physiological responses, and can reduce perceived stress. However, they mostly considered respondents identified as only male or female. Evaluating a large sample size and a wide age range helps to derive robust conclusions. Furthermore, no information was provided on how the variations in the moisture content, density, grain direction, the content of extractives, and the structural irregularities of wooden materials, could change thermal conductivity and thereby affect physiological responses.

Wang *et al.* (2000) recommend the use of wood in interiors, since it has lower thermal conductivity and is perceived as a warm and pleasant material. However, no recommendation or requirement was found in Swedish standards or in the three reviewed building certifications which suggested the use of wood in interiors due to its low thermal conductivity.

4. Discussion

The results presented by earlier studies show that sensory stimulation associated with wooden surfaces in interiors have mainly positive effect on physiological responses and can reduce respondents' perceived stress. However, the results are mainly limited due to the small sample size, the small age range and the short exposure time; accordingly, it is difficult to derive a robust conclusion from the results obtained. Furthermore, the majority of the studies provided neither insight into how changing experiment settings could affect the results, nor described the correlations between the respondents' sensitivity toward sensory stimulation. In addition, earlier studies provided no explanation regarding the material properties of wood which are associated with sensory stimulation. This limits the inference of the results and confines one to correlate the physiological responses to material properties. The latest statement necessitates the evaluation and description of material specifications in future studies.

Furthermore, several factors can change the indoor environmental quality and thereby affect respondents' physiological responses, including artificial lighting, air quality and sounds. Future studies can consider the issues related to the quality of indoor environments and provide information regarding the settings in which the experiments have been performed. In addition, more studies should be conducted in different environments, such as in residential, educational or commercial buildings and hospitals. The sensory stimulation from wooden surfaces in these environments can have different effects on physiological responses. Finally, conducting longitudinal studies could provide further information about the effects of sensory stimulation on physiological responses over a longer period of time. Specifying material properties of wood associated with sensory stimulation along with longitudinal studies could provide useful information for architects and designers, who intend to use wooden surfaces in interiors.

5. Conclusion

Covering interiors with wooden surfaces can improve indoor environmental quality and thereby affect individuals' health and their psychological and physiological responses. The above-mentioned responses can be generated by vision, auditory, olfactory, and tactile stimulation, each one associated with wooden surfaces in interiors.

The result of the literature study shows that visual stimulation is dependent on the existence of knots, colour, structure and the surface treatment of the wooden surfaces in interiors. No recommendation or requirement, presented by Swedish standards, Swedish Green Building, and Well-building certification, was found which discussed the above-mentioned properties. But, Living Building Challenge standard prohibit any use of wood treatments which contain Creosote, Arsenic or Pentachlorophenol chemicals.

Furthermore, the results show that physiological responses towards auditory stimulation are strongly dependent on the individuals' sensitivity rather than sound impact sources or their pressure levels. The material properties of wood associated with its acoustic performance include wood compositions, surface treatment, types of mounting, and geometry. No recommendation or requirement has been found about the above-mentioned properties.

The material properties of wood, which affect olfactory stimulation, depend strongly on the chemical composition on wood, including volatile extractives. Earlier studies, which analysed the effect of olfactory stimulation on physiological responses, used various odours from different wood species in their experiments, which led to an inconsistency in the results. A stronger experiment design could help to overcome the above-mentioned limitations and strengthen the results. In addition, earlier studies provided no explanation regarding material properties of wood which could cause changes in physiological responses. Meanwhile, no recommendation or requirement, presented by Swedish standards, Swedish Green Building, Well-building certification or Living Building Challenge standard has

been found which discussed olfactory stimulation of wooden surfaces and the degree to which it should be used in interiors.

The tactile stimulation depends on the heat flux of materials. Heat flux is controlled by the thermal conductivity of materials, and temperature differences between the skin and the material with which it is in contact. Wood has a small thermal conductivity. Accordingly, touching wooden surfaces causes only minor variations in the skin temperature in comparison with other materials, such as tiles or concrete. The results presented by earlier studies indicate that variations in skin temperature should be large enough to increase the perceived stress. Earlier studies recommended covering interiors with wooden surfaces. But no recommendations or requirements have been found which persuade the use of wood in interiors.

6. Future work

The future work of this study could focus on olfactory stimulation caused by interior wooden surfaces, that is those which can affect physiological responses and thereby improve people's health and reduce perceived stress. Furthermore, the economic benefits due to improved health and reduced stress will be analysed.

Notes

1. In this literature study, covering interiors with wooden surfaces refers to the installation of wooden panels on walls, ceiling, and floor.
2. Individuals have mainly a positive attitude towards wood due it's naturalness. Positive attitudes can intensify individuals' preferences to use wood in interiors (Nyrud and Bringslimark 2010). However, there are some indications that individuals can indeed separate various properties of wood and have different preferences towards them. For instance, the existence of multiple knots can have a negative impact on people's preferences (Nyrud and Bringslimark 2010). To understand how individuals develop different preferences relies on the exploration of differences in the attitude domain across cultural contexts (Riemer *et al.* 2014) and life domain factors (Diener 1984), which is out of the scope of this study.
3. The serial position effect describes the possibility of recalling first and last experiments best while having a weak recollection of middle experiments (Mack *et al.* 2017).

Disclosure statement

No potential conflict of interest was reported by the authors.

Funding

This work was supported by Knowledge Foundation: [Grant Number 20130245].

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