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Wood and human stress in the built indoor environment: a review

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Abstract Individuals spend most of their time indoors, and therefore indoor environments are important aspects of one's life. Creating healthful indoor environments should be a priority for building designers, and evidence-based design decisions should be used to ensure the built environment provides healthful benefits to occupants. This review was conducted to examine the body of research studying wood use and human stress to determine the potential fit for wood in the restorative environmental design paradigm. Previous studies on psychophysiological responses to wood are reviewed, as are current methods for assessing stress in experimental settings. To date, studies examining the psychophysiological effects of wood use in interiors have revealed reduced autonomic stress responses when compared to rooms without and with less wood. Therefore, by increasing wood use in design paradigms seeking to bring the positive health benefits of nature into the built environment, like restorative environmental design, building designers may improve the well-being of building occupants. This review reveals further studies are needed to better understand the psychophysiological responses to wood, and suggests specific aspects of wood such as colour, quantity, and grain pattern should be examined and how stress and stress recovery should be analysed.

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Introduction

Today, people spend most of their time indoors and our physical surroundings are known to affect us (USGBC 2010; Kaplan 1995; Ulrich 1991). Therefore, creating healthy indoor environments such as offices, classrooms, living rooms, dining rooms, and bedrooms is an important aspect of creating healthy environments for building occupants. Natural environments have been shown to have positive effects on psychological well-being (Tyrväinen et al. 2014; Park et al. 2007; Hartig 2004; Hartig et al. 1997; Herzog et al. 1997; Kaplan 1995; Kaplan and Kaplan 1989). Therefore, bringing nature into the built environment may improve occupant well-being. Wood is a particularly interesting material for this purpose because it is already widely used and many products already exist on the market.

Though some design mechanisms are in place to bring nature into the built environment (Kellert 2005, 2008; Wilson 2008), people often remain segregated from nature and its restorative effects while indoors. Therefore, the impetus to bring nature indoors is to bring the restorative qualities of natural outdoor environments to people where they spend most of their time. One readily available means to address the issue is to use wood as functional or decorative indoor material. Indeed, using wood for interior treatments in indoor environments has been shown to have positive impacts on occupants, especially related to indicators of human stress (Fell 2010; Nyrud and Bringlimark 2010; Rice et al. 2006; Sakuragawa et al. 2005; Tsunetsugu et al. 2002, 2007). The application of natural materials and products to indoor environments is a major tenet of biophilic design and is part of an effort to bring the restorative elements of natural environments indoors (Derr and Kellert 2013; Kellert 2005, 2008). Furthermore, wood is a sustainable building material manufactured by nature with solar energy, which stores carbon (Sinha et al. 2013; Salazar and Meil 2009). After conversion to building products (e.g., lumber, wood-based panels), wood has only a minute amount of embodied energy compared to other building materials and increases the pool of stored carbon in the built environment creating a positive impact on climate change (Sinha et al. 2013).

As people become more aware of environmental concerns, they are slowly becoming interested in and willing to change or select aspects of their home related to sustainability (Park et al. 2013; Rice et al. 2006). Currently, these aspects of the home are often related to cost-savings through energy consumption reductions. However, studies examining home-like environments and stress indicate a preference for wooden elements and suggest restoration in home-like environments with interior wood may be enhanced (Tsunetsugu et al. 2007; Rice et al. 2006). Further findings and dissemination of the healthful impacts of indoor wood applications will educate homeowners and potential homeowners about choices for healthy interiors in their homes.

The objectives of this study were to review the methodologies, designs, and results of studies dealing with fundamental research assessing the psychophysiological indicators of occupant stress to interior wood treatments and provide a summary of how wood can be used in restorative environmental design by providing a connection to nature and positive health impacts for building occupants.

This review builds on the work of Nyrud and Bringlimark (2010), but focuses more narrowly on how wood may fit within the paradigm of restorative elemental design and explores underutilized methods for measuring human stress in this field. An overview of current methods for measuring stress levels and their potential use in studying restorative interior environments is also presented.

Methods

Critically evaluated articles examining human psychophysiological stress and wood in this review were sought in peer-reviewed English-language journals found in online databases. One PhD dissertation is included in the critical evaluation and three other studies are mentioned, which may demonstrate further interest in the field but are not published in peer-reviewed journals. The latter articles are mentioned for completeness, but do not offer qualified evidence for or against stress impacts in indoor environments with wood. Searches yielded four scholarly articles and the aforementioned PhD dissertation. The limited results of the search indicate that this field is in a nascent stage. It is therefore important to review the existing work and identify helpful results and troubling trends alike in order to improve future research in the field.

The scholarly articles and book (Kaplan and Kaplan 1989) related to restorative environments were gathered through searches of scholarly databases. In addition to these articles, this review has been supplemented with information from two books published on biophilic design that represent the most robust collection of information on that subject. The framework articles related to restoration and environments (e.g., Kaplan 1995; Ulrich et al. 1991) are included as a foundation, which has been built upon by many other researchers—including those who have worked with stress and wood in the built environment. Other articles (e.g., Hartig et al. 1997; Hartig 2004 etc.) provide a framework for understanding and assessing perceptions of restorative environments. Finally, articles and books providing context for functionalising restoration theories in the built environment, especially work by Kellert (2008) and Wilson (2008) amongst others, are discussed. These books present little scientific evidence, but identify current and potential applications of the restoration theories. In these cases, they also provide context in which studies examining restoration in the built environment can be conducted.

There are many more scholarly articles reviewing the use of biological indicators in psychophysiological stress experiments, and indeed robust review articles and meta-analyses of the research (cf. Dickerson and Kemeny 2004). Two articles are presented in more detail here to demonstrate useful methods to examine stress that are applicable to future studies examining human stress in the built indoor environment.

Restoration and human stress

In order to improve occupant well-being, important design decisions must be made which balance occupant needs and health with other goals such as environmental impacts and design aesthetics. To achieve these goals, designers must understand human stress, restoration and have building design paradigms that bring those issues to the forefront in their work. Many restoration theories stem from the field of environmental psychology and have helped to lay the foundation for new building design paradigms that emphasize occupant health, nature, and sustainability. Furthermore, these building design paradigms offer an opportunity for increased wood use.

Restoration theories

Hartig (2004) defines restoration as a process of renewal that replenishes a depleted social, psychological or physical resource. These resources have most often been depleted by an individual's effort to adapt to their environment (Hartig 2004). Early restoration theories focused on recovery from psychophysiological stress (Ulrich et al. 1991) and attention restoration (Kaplan and Kaplan 1989). Psychophysiological stress recovery theory posits that natural environments, and even views of these environments, will aid recovery from stressful events, including psychological stress and physical stress (e.g., recovery from surgery) (Ulrich 1984, 1991; Ulrich et al. 1991). Attention restoration theory (ART) focuses on understanding how individuals replenish their ability to exert attention on common tasks, such as those at the workplace that require directed attention (Hartig 2004; Hartig et al. 1997; Herzog et al. 1997; Kaplan 1995; Kaplan and Kaplan 1989). Though many experiments related to ART and psychophysiological stress recovery have focused on outdoor environments (or views of outdoor environments), some experiments have examined bringing nature into the built environment. For example, a recent study examined the effect the presence of plants in an office-like environment has on attention capacity and found participants performed better in the presence of plants after performing a task approximately 25 min in the test room, but not upon entering the test room (Raanaas et al. 2011). In an extensive review of the psychological benefits of indoor plants, Bringslimark et al. (2009) determined that although the evidence suggests indoor plants can provide psychological benefits, the heterogeneity amongst the methods and results may imply the benefits are contingent on the context of the encounter with indoor plants and the participants in the experiment. These concerns extend to experiments with wood or other natural materials indoors.

Many studies have found empirical evidence to support these theories, but the theories themselves remain open to elaboration as more evidence is collected regarding the restorative effects of nature (Hartig 2004). Studying the effects of wood on attention and psychophysiological stress restoration in the built environment may produce helpful and enlightening results.

Experimental assessment of stress and psychophysiological responses to wood

Monitoring and measuring human stress

Monitoring recovery from stressful events is one way to explore and assess the restorative properties of indoor environments. However, stress is not a rigidly defined concept and there is disagreement regarding its precise definition (Cohen et al. 1995; Burchfield 1979). Despite these differences, Cohen et al. (1995) note how various definitions all refer to an interest in the process in which environmental demands exceed ones adaptive capabilities and lead to psychological and physiological changes in an individual. Excessive activations of these responses are worrisome because they may place individuals at risk for disease (Gaab et al. 2003; Lucini et al. 2002; Cohen et al. 1995).

Cohen et al. (1995) distinguish between three traditions in assessing the role of stress and note each makes different assumptions and therefore uses separate methodologies for measurements. These traditions are (Cohen et al. 1995):

- Environmental tradition—focuses on experiences triggered by one's social, natural, and cultural environment, which are objectively associated with substantial demands on the individual to adapt to the environment and uses environmental demands, stressors, or events as components of analysis.
- Psychological tradition—scrutinizes an individual's subjective assessment of their ability to cope with the adaptive demands of specific events using appraisals or perceptions of stressfulness in specific situations as metrics of stress level.
- Biological tradition—researchers determine stress levels by monitoring the activation of specific physiological systems established as responding to adaptive demands on the individual and use metrics of the activity for analysis of stress level.

Both the psychological and biological traditions have been employed to measure stress recovery in restorative environments. The methods associated with these traditions are more readily assessed in laboratory settings, and biological methods provide measures suitable for inferential comparisons. The environmental tradition is less useful in laboratory experiments because previous stress events are hard to place in relation to restorative environments and rely on self-reported assessments of the events, often at a much later date.

Psychological measures are subjective and rely on respondent assessment of their own situation. Subjective measures in this field are inherently challenging to make causal inferences from, but provide context and suggest direction for qualitative analysis (Cohen et al. 1995). On the other hand, biological methods for assessing stress often rely on monitoring the sympathetic and parasympathetic activity of the autonomic nervous system (ANS) and the output of the hypothalamic–pituitary–adrenocortical axis (HPA) of the endocrine system (Hellhammer et al. 2009;

Sztajzel 2004; Cohen et al. 1995; Kirschbaum and Hellhammer 1994). Though physiological responses to stress reveal themselves in a variety of measurable ways, these metrics are critical because they are the primary indicator of how stressed an individual becomes, and also how quickly and fully an individual recovers from stress.

Autonomic nervous system (ANS) responses to stressors include increased output of epinephrine, norepinephrine, increased blood pressure, heart rate, sweating, and constriction of peripheral blood vessels (Cohen et al. 1995). Methods for monitoring these responses have been employed in studies examining the effect wood has on occupant stress (Fell 2010; Tsunetsugu et al. 2002, 2007; Sakuragawa et al. 2005).

The HPA response is to release hormones, which help the body maintain homoeostasis when presented with a stress event (primarily cortisol, a corticosteroid, in humans) (Kirschbaum et al. 1993; Kirschbaum and Hellhammer 1994). Salivary free cortisol quantity is considered an effective, non-invasive measure of the HPA response to stress and therefore is useful to determine individual stress levels (Hellhammer et al. 2009; Gaab et al. 2003; Kirschbaum and Hellhammer 1994; Kirschbaum et al. 1993). Kirschbaum et al. (1992, 1993, 1999) and Kirschbaum and Hellhammer (1994) have extensively explored the HPA response to stress and have established cortisol levels as an effective measure of the response. Hellhammer et al. (2009) concluded salivary cortisol is useful as long as the researchers are aware of possible sources of variance in salivary cortisol and possible confounding variables are properly accounted for. These include sex, psychiatric health, and smoking (Hellhammer et al. 2009). Furthermore, cortisol levels naturally follow a circadian rythem throughout the day with peak release occurring soon after awakening and diminishing slowly throughout the day to their lowest levels in the evening (Dickerson and Kemeny 2004; Hellhammer et al. 2009). Dickerson and Kemeny (2004) note conducting experiments during the same time period for all participants and later in the day is one method to overcome this challenge. Furthermore, including a no-stressor control group or using within-subject experimental design is also suggested (Dickerson and Kemeny 2004). In addition to the circadian release cycle of cortisol, regular pulsatory cortisol releases do occur, but are quite stable within individual subjects suggesting a within-subject experimental design may compensate well for this attribute (Chrousos and Gold 1998).

Salivary free cortisol can be determined by assessing saliva samples gathered with a simple mouth swab, which can be stored and assessed at a later time (Gaab et al. 2003). Additionally, saliva samples are non-intrusive and practical for taking repeated measurements in a short period of time. Assessment of cortisol concentration in saliva can be determined by immunoassay methods described elsewhere (Dressendorfer et al. 1992).

While monitoring and assessing stress in any experiments, it is important to remember stress manifests itself in many ways, and the wide variety of autonomic and endocrine activity indicators used to monitor stress levels do not always correlate with each other. However, salivary free cortisol levels are an effective indicator of laboratory and real-world stress levels and have been found to correlate well with many other indicators of stress (Hellhammer et al. 2009; Dickerson and

Kemeny 2004; Lucini et al. 2002). Despite this, salivary free cortisol levels have not been used as an indicator of stress in experiments studying the psychophysiological responses to wood. This method has been used in monitoring restoration in outdoor environments (Tyrväinen et al. 2014; Park et al. 2007) and extensively in other stress-related experiments (Hellhammer et al. 2009; Gaab et al. 2003; Lucini et al. 2002; Kirschbaum and Hellhammer 1994; Kirschbaum et al. 1992, 1993).

Studies on psychophysiological responses to wood

Though there have been few studies directly examining the psychophysiological effects wood in the built environment has on people, they come to a similar conclusion: wood has a generally positive effect on occupants. The studies discussed here represent the extent of published scientific work on the topic. The studies all have examined biological indicators of psychophysiological stress or recovery from it and therefore provide insights into how wood use may provide benefits for stress reduction or improved recovery from stress. All but one of the following studies reported finding beneficial health impacts of wood in the built environment. In each case, the use of actual-size test environments allows easier application in practice. Many of the studies were done with limited sample sizes; however, they provide an impetus for further work in the field and a foundational framework for future studies.

Tsunetsugu et al. (2002) examined psychophysiological responses of subjects exposed to decorative wood applied to living room environments. The most basic room included white walls, with wood flooring, two covered (with drapes) windows, a coffee table, and one plant. The other room was identical to the basic room, but also included decorative wall and ceiling treatments made from wood. Ten subjects were preconditioned in a third room with a decorative wood treatment on the walls that was otherwise identical to the two test rooms. Baseline heart rate and blood pressure measurements were taken in this room. All subjects were exposed to two test environments: the basic room and the decorated test room. Subjects were randomly assigned to initial test rooms, but were exposed to both rooms consecutively. While heart rate and blood pressure decreased in the room with decorative wood application, the sample size was small and a potential serial effect could confound the findings. Furthermore, the objectives of the study were not clearly defined and therefore not clearly ascertainable in the study findings making interpretation of the findings and determining their applications challenging. Increasing sample size, clearly defined objectives and study outcomes that reflect them are critical in the early stage of defining a nascent research field.

Sakuragawa et al. (2005) assessed how material preference impacts blood pressure when viewing those materials. In this study, subjects were asked about their feelings for steel and wood and then exposed to a white steel wall and a wood wall in a random order. The study found subjects who reported liking steel maintained stable blood pressure readings during exposure to the steel wall. Those who reported disliking steel had increased blood pressure when exposed to the steel wall. Blood pressure decreased for subjects who reported liking wood when exposed to the wood wall. For those subjects who reported disliking wood, blood pressure neither increased nor decreased when exposed to the wood wall. The walls were presented in an otherwise empty room with no environmental context. The small sample size and the possibility of serial effects in this study limit inference of any findings. Additionally, the subjects were exposed to the experiment topic in the questionnaire before the test began. Avoiding the serial effect by using a within-subjects design on only two treatments for each subject could have improved the findings. Alternatively, using three subject groups (one control and one for each treatment) could have strengthened the findings as long as the sample sizes were increased. Notably, however, this study revealed how preference for materials might impact psychophysiological responses to different environments.

Tsunetsugu et al. (2007) assessed psychophysiological responses to different quantities of wood in a replicated living room environment. Four rooms were prepared for the experiment, a practice room to familiarize the subjects with the procedure of the experiment and three test rooms treated with different amounts of wood coverage. Each test room was designed to appear as a real, Japanese-style living room and was treated with 0, 45, and 90 % wood coverage. Heart rate and blood pressure were assessed as psychophysiological indicators of stress and health for 15 subjects during and after 90 s of exposure in each environment. Subjects were also asked to provide ratings of each of the three experimental environments. The 45 % covered room was the most favoured one and diastolic blood pressure was lower, but heart rate was higher in this room than the 0 % room. The 90 % room yielded the lowest blood pressure measurements, but subjects registered increased heart rates in the room. The short exposure time in each room provides only a small window into the immediate response of the subject to the environment. In this context, the results may not be indicative of the effect of spending significant time in indoor environments with wood. Though the sample size was small, the lack of correlation between preference and physiological response contradicts the preferential findings in Sakuragawa et al. (2005).

In the most robust study on the topic, Fell (2010) assessed sympathetic indicators of ANS stress responses for 119 subjects in four different office-like environments. In this factorial study, subjects were randomly assigned to only one room. The room treatments were: control (with non-wood furniture, and no plants), non-wood furniture with plants, wood furniture without plants, and wood furniture with plants. Subjects were monitored by an electrocardiogram and for electrodermal activity over three intervals: during a period of 10 min prior to the test to determine a baseline reading, throughout the test, and for a 10-min recovery period thereafter. To induce stress, subjects were given a Paced Auditory Serial Addition Test (PASAT, Gronwall 1977), which is considered a light stressor. Directly after the test period, subjects were asked to complete an environmental satisfaction questionnaire. The electrocardiogram provided analysis of cardiovascular responses to stress including inter-beat interval and heart rate variability. Electrodermal monitoring allowed for analysis of three stress responses: skin conductance levels, frequency of non-specific skin responses (F-NS-SCR), and amplitude of non-specific skin responses (A-NS-SCR). Measurements were compared between treatments during the baseline period (pre-test), testing period, and recovery period (post-test). Cardiovascular responses were not found to be significant in this study. However, there was strong evidence F-NS-SCR values were lower during the pre-test and recovery periods in the room with wood furniture and no plants, and some evidence of lower values during the test period in the same room. The study also examined the effects of indoor plants on stress responses, but neither a main effect nor interaction effect was discovered. This study provides the most robust examination of the psychophysiological effects of wood in the built environment. However, to better account for individual variations in stress responses a within-subjects design may have been useful. Similarly, profiling the individual's mood state and using a stronger stressor may have strengthened the findings.

Nyrud et al. (2010) examined restoration more directly in their study of interior wood treatments in hospital recovery rooms. This study compared recovery times, pain medication use, blood pressure, and self-reported measures of pain and stress of 197 orthopaedic patients in three different room types. Each room had either a view of nature, was treated with a piece of art, or was treated with a decorative wood element. No significant differences were found between rooms for any measure. Connecting these findings to Ulrich's (1984) prior study of hospital recovery where views of nature alone were found to have positive impacts on recovery raises questions about the amount of nature that must be visible to impact recovery times. That is, to what degree must nature be present to aid recovery times and reduce pain and are particular elements of nature more or less beneficial than others?

Additionally, studies carried out at the Human Research Institute in Austria have positively associated increased concentration, reduced strain, and reduced stress in schools with exposed wood in the built indoor environment (Grote et al. 2003, 2009; Kelz et al. 2007). These studies give further hints that humans experience positive health impacts when exposed to wooden elements indoors. However, the published scientific documentation for these studies lacks the detail necessary to fully accept the results.

Restorative environments and building design paradigms

In the case of both ART and psychophysiological stress recovery theory, the natural environment provides the individual with a means to restore themselves to a more complete state. These restorative environments exist in nature and provide a model for bringing the desired effects indoors. According to Kaplan (1995), the components of a restorative environment are:

1. Being away—the sense of being in a different environment (distance is not a necessary component of being away.)
2. Fascination—when ones attention is effortlessly focused on something.
3. Extent—feeling an area to be large. Well-designed paths can be used to make a small area seem larger.
4. Compatibility—the natural affinity humans seem to have for nature makes it a compatible environment.

While many of the elements of restorative environments may seem challenging to incorporate into building design, biophilic design provides guidance on how to bring nature indoors therefore a means to produce restorative indoor environments. Biophilic design is the incorporation of the principles of biophilia into building design (Kellert 2005, 2008). These principles are built around the concept of an innate human attraction to life and life-like processes (Kellert 2008). To create restorative indoor environments with biophilic principles, Wilson (2008) suggests being away can be addressed with indoor gardens, views of nature, and other features occupants can view or visit, which differ from a typical workstation. Similarly, design features may provide extent by varying ceiling height, including natural lighting, and other mechanisms (Wilson 2008). Natural patterns, shapes, and forms all provide targets of fascination, while compatibility is derived from evolved human relationships with nature (Kellert 2008; Wilson 2008).

There are six guiding principles of biophilic design. Briefly, they are (Kellert 2008):

1. Environmental features—making design choices, which reflect readily recognizable as aspects of nature. These features may range from views of nature, to water features within the building, to including a wide variety of indoor plants.
2. Natural shapes and forms—using elements of the built environment to replicate naturally occurring elements (such as trees).
3. Natural patterns and processes—using elements of design (such as materials, spaces, lighting, etc.), which through visual recognition, touch, scent, or sound remind occupants of growth, life, natural motion, and other elements of nature.
4. Light and space—diversity of colour, natural light, and variability in lighting levels are reminiscent of nature. Further, difference in size and shape of spaces in the built environment also remind us of nature.
5. Place-based relationships—connections to cultural and ecological elements linking geographically distinct locations with the built environment.
6. Evolved human relationships with nature—the connections humans have developed throughout the evolutionary history. For example, natural settings, such as forests, have provided shelter and safety, food and materials for survival.

One way to implement biophilic design in contemporary buildings is the restorative environmental design (RED) paradigm, which brings together the ideas of sustainable design and biophilic design (Derr and Kellert 2013; Kellert 2008). Additionally, RED attempts to promote a stronger connection between building occupants and nature, in order to inspire and motivate people to care for the environment. Derr and Kellert (2013) believe RED is the next evolution of “green” design. In principle, the goals of RED are to reduce environmental impacts of new buildings, to ensure buildings provide healthful benefits to the occupants, and to promote a stronger connection to nature.

Wood as an element of restorative environmental design

Wood is an ideal material for RED because it satisfies both general tenets of the design paradigm: sustainability and a connection to nature. Furthermore, research investigating psychophysiological responses to wood in the built environment supports the idea that indoor use of wood has positive health implications for occupants. Wood from healthy, well-managed forests is a renewable material and provides carbon storage (Hashimoto et al. 2002). It is unsurprising such a product, when used in appearance applications, also provides a connection to nature (Nyrud and Bringlimark 2010; Nyrud et al. 2010; Rice et al. 2006; Masuda 2004).

Wood is also an abundantly available material. The United Nations Food and Agriculture Organization (FAO) reports 30 % ($\sim$1.2 billion hectares) of the worlds forested area is used specifically for production purposes (FAO 2010). Another 949 billion hectares is designed as multifunction, which may include production purposes (FAO 2010). Usage from these forests includes industrial roundwood destined for wood products, fuelwood, and non-wood forest products. The majority of harvests from forests in Asia and Africa are used for fuelwood, while in Europe, North America and Oceania fuelwood harvests account for less than 20 % of the total (FAO 2010).

Furthermore, wood is known to sequester carbon throughout its lifetime when product lifetimes are sufficiently long (Salazar and Meil 2009; Tonn and Marland 2007; Hashimoto et al. 2002). In many industrialized countries, carbon storage in wood is greater than carbon released by activities inclusive of harvest and disposal and all steps in between (e.g., production, transportation) (Hashimoto et al. 2002). Therefore, effective use of wood products can reduce the amount of carbon released to the atmosphere. Correspondingly, well-managed forests provide a continuous supply of sustainable materials offering a variety of potential uses in the built environment.

Wood is an excellent building material because of its excellent strength-to-weight ratio and the variety of forms in which it can be used (e.g., in log form, lumber form, in fibre form, and in combination with other materials) (Kretschmann 2010; Stark et al. 2010). In the USA, more than 90 % of residential buildings are wood-framed and Japan is not far behind (Sinha et al. 2013). However, wood used in housing is often a concealed structural component, thereby limiting occupant interaction with it. Furthermore, wood use in non-residential construction is considerably less common than in residential construction (O'Connor et al. 2004). Beyond structural uses, wood is also an excellent architectural material for furniture and in decorative applications and is used in many forms such as solid wood, wood-based composites such as plywood, particleboard, and medium density fibreboard (Architectural Woodwork Institute 1994). Though exposed wood is present to some degree in many indoor environments, there are opportunities for greater utilization, which may contribute positively to occupant health (Fell 2010; Nyrud and Bringlimark 2010; Rice et al. 2006). Increasing wood use indoors by, for example, using exposed massive timber (cross laminated timber) may also offer improved indoor thermal comfort by buffering indoor temperature variations (Hameury and

Lundström 2004). Some common interior uses of wood are tables, chairs, cabinetry, desks, flooring, and moulding.

Furthermore, wood is generally viewed positively and evokes feelings of warmth, comfort, relaxation, and is reminiscent of nature (Fleming et al. 2013; Nyrud and Bringlimark 2010; Rice et al. 2006). Aspects of wood connecting humans to nature include recognition as a natural product, pattern, and colour (Fell 2010; Nyrud and Bringlimark 2010; Rice et al. 2006; Masuda 2004).

Though wood is often available in a variety of natural colours and patterns, the yellow-red hue with relatively low contrast is common and provides a positive, agreeable, and pleasant image (Masuda 2004). Colour contrast in wood is due to naturally occurring colour differences between earlywood and latewood, knots, and other natural wood features. In addition to the colour contrast provided by these features, they also construe pattern to the viewer (Fig. 1). This aspect of wood also contributes to the positive and agreeable image of wood and fits well with the fascination principle of restorative environments (Masuda 2004). The presence of knots in wood products, however, demonstrates cultural differences in our perception of it as a pleasing material. In Japan, the presence of knots are considered to diminish its purity, while in North America knots are considered natural and rustic (Rice et al. 2006).

Though not specifically mentioned as a biophilic material in *Biophilic Design* (Kellert et al. 2008), Fell (2010) notes that of the 30 images used as examples of biophilic indoor environments, 25 images feature wood. Furthermore, wood can address each of the six biophilic design tenets discussed in the previous section:

1. Environmental features—wood provides a direct link to nature, as it is a recognizable natural element.
2. Natural shapes and forms—patterns in wood grain are naturally developed and wood can be used in forms representative of the material as a living organism

Fig. 1 Douglas fir (*Pseudotsuga menziesii*) grain patterns reveal colour contrast and natural patterns

Fig. 2 Reception area of Sibelius Hall in Lahti, Finland, designed by architects Kimmo Lintula and Hannu Tikka

(such as the tree-like columns in Fig. 2, which serve both structural and aesthetic purposes).

3. Natural patterns and processes—grain patterns, colour spectrum, and the presence of knots evoke natural patterns and process (Fig. 1).
4. Light and space—wood naturally has colour diversity and can be stained in a variety of colours without losing its familiarity as a natural product, and it can easily be deployed in products of various sizes to address space concerns.
5. Place-based relationships—using locally sourced wood products can evoke a regional connection to nature, and historical and regional building methods, which utilized wood, may also be imitated.
6. Evolved human relationships with nature—trees and wood have long been used as source for shelter, tools, transportation, and art.

Environments that may benefit from restorative environmental design

There are many indoor environments in which occupants would benefit from RED. Recent research has focused on offices, hospital recovery rooms, schools, and homes (Derr and Kellert 2013; Fell 2010; Nyrud et al. 2010; Tsunetsugu et al. 2007; Ulrich 1984).

Office environments are considered to have an effect on occupational health (Danna and Griffin 1999). Emphasizing employee health is not only important to the individual, but also directly related to productivity and efficacy; Danna and Griffin (1999) cite work setting as an antecedent of well-being and health in the workplace.

Though they do not specifically suggest restorative environments as a solution, the connection between healthy employees and productivity is made clear. RED, therefore, is a potential solution to help ensuring healthy and productive workers.

Hospital stays after cholecystectomy surgeries were studied in a Pennsylvania hospital between 1972 and 1981 to examine whether the view from the recovery room might influence recovery times as well as analgesic and anxiety medication use (Ulrich 1984). Ulrich (1984) found patients with a view of nature recovered more quickly and used less analgesic medication. No significant results were found regarding anxiety medication, except that analgesic dosages may have impacted the amount of anxiety medication taken.

A case study of four children's environments (three schools and one "learning environment") revealed the variety of ways RED was implemented in schools and school-like settings (Derr and Kellert 2013). In these environments, Derr and Kellert (2013) report finding many aspects of sustainable building such as energy reduction through passive and active solar systems, rooftop gardens, sustainable and local material use, use of recycled material, rainwater harvesting, and even composting toilets. Similarly, the authors identified many biophilic features including, natural materials in the building construction and curriculum, direct exposure to plants, animals and water, connections to ecological place, exhibits including natural materials, natural forms and motifs, nature-based colour palettes, and the transformability of indoor and outdoor spaces—meaning spaces where children can interact with, affect, and manipulate their environments (Derr and Kellert 2013). Children generally reported positive feelings about their schools. Furthermore, the restorative elements of the environments served as potential learning opportunities. That is, the natural elements in the schools were directly used to teach lessons, but also as part of the environmental construct connecting the children to nature. By connecting children to nature at an early age and reinforcing the human–nature connection sustainability principles may also be more readily embraced (Derr and Kellert 2013). The authors identified the need for more research to examine the impact restorative environmental design has on fostering enhanced understanding of the natural world and its processes. Identifying these benefits may provide children and students with increased learning capacity, reduced stress, and improved overall well-being. Additionally, promoting a stronger connection to nature may inspire and motivate individuals to care for their environment.

Discussion and conclusion

Whether at home, at work, or at school indoor environments affect buildings occupants. In workplaces healthier environments can reduce sick leave and increase productivity, which directly impacts profitability (Danna and Griffin 1999). Similarly, in addition to enhancing relationships with nature healthy school environments could reduce illness and improve student performance and learning.

Wood is a well-suited building material for sustainable design because it sequesters carbon throughout its life cycle and is derived from a renewable resource. Furthermore, because wood is a material that is well recognized as being natural, it is an excellent material for biophilic design and, consequently, RED. However, a more robust body of research must be developed in order to more tightly integrate wood use with RED. Although few studies directly examined the restorative properties of wood as a material for the built indoor environment, those that have suggest interior wood use provides restorative benefits and positive health impacts to occupants. Questions remain about the types of wood and the attributes (e.g., colour, pattern, solid, composite) expected to provide restorative benefits, and about the quantity of wood required to induce a benefit. While these questions remain specific, guidance on interior wood use in RED is premature. More studies with stronger designs are necessary to close this knowledge gap.

Recommendations for future experiments

To investigate wood use for RED future studies should emphasize studying different attributes of wood including colour, pattern, and type (e.g., solid wood, wood-based composites such as plywood, particleboard, medium density fibreboard). To gain a more complete understanding of the stress responses to wood, these studies should examine HPA axis responses to stress in indoor environments using salivary cortisol as an indicator of the response along with other indicators, when feasible. In future experiments, recovery from the stress events should be specifically examined by extending the period during which participants are monitored for stress responses to more fully understand how aspects of the interior environment affect recovery and restoration. Previous research from other fields examining stress can serve as a guide for studies examining wood and human stress in the built environment. For example, the work of Lucini et al. (2002) and Gaab et al. (2003) provides helpful frameworks for studying real-world stress and monitoring recovery from stress while using salivary free cortisol as an indicator of stress. Thoughtful experimental design can address concerns about both the circadian nature of cortisol levels and its pulsatory releases. For example, using within-subjects design can be effective in overcoming individual differences in pulsatory cortisol release, while simply testing subjects at similar times of day (for example, during the afternoon) is useful to address circadian cortisol levels. Finally, studying the relationship between interior wood use and human stress in diverse contexts will provide more robust results that are more readily applicable in real-world situations.

If future studies exploring the restorative effects of wood in the built indoor environment provide evidence of positive health impacts, more wood should be used as a material in restorative environmental design.

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