IMPACT OF WOOD ON HUMAN THERMAL PERCEPTION OF TRANSIENT AND STEADY-STATE INDOOR ENVIRONMENTS

by

DENISE BLANKENBERGER

A THESIS

Presented to the Department of Architecture
and the Graduate School of the University of Oregon
in partial fulfillment of the requirements
for the degree of
Master of Science

June 2019

THESIS APPROVAL PAGE

Student: Denise Blankenberger

Title: Impact of Wood on Human Thermal Perception of Transient and Steady-State Indoor Environments

This thesis has been accepted and approved in partial fulfillment of the requirements for the Master of Science degree in the Department of Architecture by:

Kevin Van Den Wymelenberg	Chairperson
Alison Kwok	Member
Christopher Minson	Member
Siobhan Rockcastle	Member

and

Janet Woodruff-Borden	Vice Provost and Dean of the Graduate School

Original approval signatures are on file with the University of Oregon Graduate School.

Degree awarded June 2019

© 2019 Denise Blankenberger

THESIS ABSTRACT

Denise Blankenberger

Master of Science

Department of Architecture

June 2019

Title: Impact of Wood on Human Thermal Perception of Transient and Steady-State Indoor Environments

Humans thermally adapt and respond to the thermal environment in a number of ways, including psychologically. Preliminary evidence suggests that wood can lead to a perceived sensation of warmth while thermal history has been shown to affect the perception of thermal comfort. This thesis investigates two questions: (1) does wood material improve thermal comfort? (2) does thermal history impact present thermal comfort?

To explore these questions, two thermal comfort studies were conducted in a controlled laboratory setting. In the first, participants evaluated their thermal comfort with wood and white wall treatments while the thermal environment changed dynamically between warm and cool. The second tested the same wall treatments in a steady-state thermal environment. The first study indicates that recent thermal history impacts thermal perception, and no effect of wall treatment on thermal perception was found. The second study suggests that wood had a cooling effect.

CURRICULUM VITAE

NAME OF AUTHOR: Denise Blankenberger

GRADUATE AND UNDERGRADUATE SCHOOLS ATTENDED:

University of Oregon, Eugene, Oregon
Ball State University, Muncie, Indiana

DEGREES AWARDED:

Master of Science in Architecture, 2019, University of Oregon
Master of Architecture, 2019, University of Oregon
Bachelor of Architecture, 2016, Ball State University

AREAS OF SPECIAL INTEREST:

Perception
Thermal comfort
Wood
Biophilia

PROFESSIONAL EXPERIENCE:

Graduate Research Fellow, University of Oregon, Eugene, Oregon, 2017-2019

Intern Architect, Valeant Architecture, Portland, Oregon, 2016

Intern Architect, HAFER, Evansville, Indiana, 2015-2017

Design Specialist, Digital Corps, Muncie, Indiana, 2015-2016

GRANTS, AWARDS, AND HONORS:

Graduate Research Fellow, Energy Studies in Buildings Laboratory, University of Oregon, Eugene, 2017

Udall Scholarship, Udall Foundation, Tucson, Arizona, 2014

Cultural Vistas Fellowship, Cultural Vistas, New York, New York, 2014

PUBLICATIONS:

Blankenberger, D., Van Den Wymelenberg, K., and Stenson, J. (2019). *Subjective analysis of transient indoor thermal environments.* Submitted for publication.

Blankenberger, D., Van Den Wymelenberg, K., and Stenson, J. (2019). *Visual Effects of Wood on Thermal Perception of Interior Environments*, Architectural Research Centers Consortium Annual Conference, Toronto, Ontario, 2019.

Blankenberger, D. (2017, August). *Expanding the Daylighting Pattern Guide Using Annual Metrics*. Presented at the International Radiance Workshop, Portland, OR.

Blankenberger, D., Rachel Bergseteren Strange, R. Ramaswamy, A., Mahic, A., Van Den Wymelenberg, K. (2017, August). *Improving Lifeguard Visibility in Aquatics Facilities by Minimizing Glare*. Poster and paper presented at the Illuminating Engineering Society Annual Conference Proceedings, Portland, OR.

ACKNOWLEDGMENTS

I thank the Energy Studies in Buildings Laboratory at the University of Oregon for providing me with this opportunity, especially director Kevin Van Den Wymelenberg, my thesis advisor. Included among this incredible collaboration of minds, I would like to sincerely thank the following: Jason Stenson, Mark Fretz, Alen Màhic, Charlie Brown, Paul Ward, Serena Lim, Andrew Loia, and Alejandro Manzo. I would also like to thank the members of my committee, Professors Alison Kwok, Christopher Minson, and Siobhan Rockcastle, for their thoughtful contributions and inspiration both in and beyond the classroom.

The research was supported by a grant from the Agricultural Research Station, #290280, in partnership with TallWood Design Institute. I would like to acknowledge the consultation and assistance from Dr. Stefano Schiavon and colleagues at The Center for the Built Environment at University of California, Berkeley and Dr. Pat Lombardi from the University of Oregon Department of Biology. I would also like to thank Amy Laird and Alicia Johnson at the OHSU Biostatistics & Design Program for aid in analysis and interpretation of study physiological data.

Finally, I express deep gratitude to my family and friends without whose support I would have not taken this opportunity, much less been met with such success.

Dedicated to Brian and Delia.

TABLE OF CONTENTS

Chapter Page

LIST OF FIGURES

Figure Page

LIST OF TABLES

CHAPTER I

INTRODUCTION

1.1. Research Problem

Thermal comfort is a challenging topic to address because satisfaction with the thermal environment is inherently subjective, but it has measurable effects, including the design of buildings, the temperature setpoint to which these buildings are designed to maintain, the amount of energy required to deliver comfortable interior conditions, and the health and productivity of building occupants. According to a 2001 EPA study, the average American spends 87% of time indoors (Klepeis et al., 2002). It is no surprise, then, that the built environment is responsible for nearly 40% of total U.S. energy consumption and 75% of greenhouse gas emissions (EIA, 2017). On an annual basis, air conditioning accounts for 10% of annual energy consumption in commercial and 9% in residential buildings while heating accounts for greater than 25% in commercial and 44% in residential buildings in the U.S. (EIA, 2012). Combined, heating and cooling account for approximately one-third of energy consumption by buildings. Any steps made toward reducing these numbers can impact energy demands and overall energy consumption by buildings at a massive scale that would help address some of the most pressing challenges facing the built environment today.

Thermal comfort is particularly important because it can impact productivity, satisfaction, and mood (Gagge, 1969). While the physical inputs of thermal comfort (air temperature, mean radiant temperature, air speed, humidity, metabolic rate, and clothing) are relatively easy to measure and have been studied rigorously since the creation of the thermal comfort model (Fanger, 1970), the personal and perceptual inputs are more nuanced and challenging to quantify. People adapt to thermal environments in a number of ways, including behaviorally, physiologically, and psychologically (de Dear & Brager, 1997). Psychophysiology, the interaction between physiology and psychology, is important because the mind and the body are inextricably linked. This means that individual perception of the thermal environment can impact thermal comfort in addition to the physical inputs. Thermal perception varies widely across a population for any given thermal environment and are strongly impacted by one's thermal experience and expectation (de Dear & Brager, 1997). This thesis explores these perceptual and psychophysiological effects in relation to thermal comfort in two focused topics: thermal history and effect of visual materials.

Thermal history is the concept that the thermal environment which one experienced previously impacts perception of the current thermal conditions. There is an existing gap of knowledge of human perception of thermal comfort with regard to past thermal experience, specifically with regard to transient conditions.

The second topic explored in this thesis is the idea that wood can impact thermal comfort from a primarily visual standpoint. Visual materials have been thought to have thermal associations, such as red being a "warm" color, but little research exists supporting any realized thermal comfort effects. Similarly, because wood is often considered a "warm" material, it is thought that it can lead people to perceive the thermal environment as warmer than it truly is.

Understanding the psychophysiological effects of adaptation to thermal comfort is essential because it impacts human perception of the indoor environment, a topic with preliminary support through research and is not wholly understood yet what occurs in response to the built environment. By understanding the immediate and long-term effect of human perception on thermal comfort, designers and engineers can make more informed decisions to optimize both the design and operation of buildings to leverage thermal comfort with overall building energy consumption.

1.2. Research Questions

This thesis explores two questions: (1) Does thermal history in a transient thermal environment impact thermal perception? (2) Does wood material in an indoor environment impact thermal perception?

With respect to the first topic, thermal history has been studied in changing thermal conditions by step-change experiments (de Dear, 1993; Ji, 2017; Wu, 2014). These studies reveal that as participants move from one thermal condition to another, the conditions of the first space tend to affect occupant thermal comfort in the second space. This thermal “lag” applies to transition spaces and as building occupants move between zones. However, these studies do not illustrate the perception of a transient thermal environment: a single space that changes gradually over time. Few studies have examined transient thermal environments (Gagge et al., 1969; Zhang 2004), and fewer still utilize radiant systems (Griffiths & McIntyre, 1974). To the author’s knowledge, no transient thermal comfort studies exist that utilize radiant systems to study whole-body thermal sensation. Transient thermal environments more realistically illustrate the interior environment in buildings which have setpoints which are allowed to “float” rather than remain static. These types of environments have been shown to be both more comfortable and energy-efficient than steady-state buildings (Nicol & Humphreys, 2002; Arens, 2010).

To address the second question, previous research supports that wood is perceived to have a “warm” quality, but this effect has yet to be supported by quantifiable evidence for thermal comfort properties. Previous studies have investigated the thermal perception of warm-colored lights or colored materials (Fanger, 1977; Wastiels, 2012; Chinazzo; 2018), but not wood materials in isolation. Wood has been studied for its potential stress-reducing qualities (Sakuragawa, 2005; Tsunetsugu, 2007; Fell, 2010) and also for its perceptual visual qualities, such as association with words such as “warm” and “calming” (Rice, 2004; Wastiels, 2012) but not for perception of thermal comfort.

This thesis investigates the thermal perception of wood materials in both steady-state and transient interior thermal environments to address the gaps of knowledge in these two topics.

1.3. Thesis Organization

This thesis is structured in two main chapters (III and IV) which document two complementary human factors studies of thermal comfort in a laboratory setting. Chapter III encompasses the design and results of the first study which occurred in the winter season and explores both thermal history and effect of wood material on thermal comfort. The first study, titled “Subjective analysis of transient indoor thermal environments”, has been submitted to Building and Environment journal and is co-authored by Professor Kevin Van Den Wymelenberg and Research Assistant Jason Stenson. A rationale for the study redesign precedes Chapter IV, which encompasses the design and results of the second study, which explores the effect of wood material on thermal comfort. The second study, titled “Visual effects of wood on thermal perception of interior environments”, was published at the Architectural Research Centers Consortium 2019 Conference (May 2019) and is also co-authored by Van Den Wymelenberg and Stenson.

1.4. Definitions

Alliesthesia: thermal pleasure (Cabanac, 1981)

Biophilia: the urge to affiliate with other forms of life (Wilson 1984)

IEQ: Indoor environmental quality

MAP: Mean Arterial Pressure: the average of arterial pressure over one cardiac cycle

PMV: Predicted Mean Vote

PPD: Percentage of People Dissatisfied

TA: Thermal acceptability

Thermal direction: based on the past thermal environment, this describes the absolute direction the current thermal environment has been trending toward: in this paper, this is defined as either moving toward thermally neutral ($|\Delta T_1| - |\Delta T_2| < 0$) or moving away from thermally neutral ($|\Delta T_1| - |\Delta T_2| > 0$)

TSV: Whole-body thermal sensation vote

CHAPTER II

LITERATURE REVIEW

Chapter I introduced the importance of thermal comfort and the psychophysiological responses to indoor thermal environments. In Section 2.1 of this chapter, the topic of thermal comfort in the built environment is introduced. Following is an introduction to thermal adaptation and the three main ways in which people adapt to the thermal environment: 2.1.1. Behavioral Adaptation, 2.1.2. Physiological Adjustments, and 2.1.3. Psychological Adaptation. Two main topics relevant to psychological adaptation are covered in a thorough literature review: 2.1.3.1 Thermal History and 2.1.3.2. Hue-Heat Hypothesis. Section 2.2 is a literature review of the interaction effects of various indoor environmental qualities. Finally, Section 2.3 explains the energy implications of the discussed thermal comfort standards and defined thermal setpoints.

2.1. Overview of Thermal Comfort and Thermal Adaptation

Thermal comfort is defined by ASHRAE Standard 55-13 as “the condition of mind that expresses satisfaction with the thermal environment”. The standard method to measure thermal comfort is Predicted Mean Vote (PMV), developed by Fanger in 1970 through climate chamber studies. PMV is the index that represents the mean thermal sensation vote (TSV) on a standard 7-point scale of a large group of people in a given space, based upon six weighted parameters: air temperature, mean radiant temperature, air speed, humidity, metabolic rate, and clothing. PMV is a steady-state model of thermal comfort, which only applies to thermally acclimated, healthy adult people in a steady-state environment, typically regulated by heating and cooling equipment (Van Hoof, 2008). Predicted Percentage of Dissatisfied (PPD) predicts the percentage of people in a given population that might be dissatisfied in a given thermal environment.

Thermal *sensation* is the perceived level of satisfaction with the thermal environment. Thermal *comfort* is defined as neutral, or lack of discomfort (Humphreys and Hancock 2007). An important distinction between the two is that thermal sensation is measurable whereas thermal comfort implies satisfaction. Previous research supports that people do not always equate thermal neutrality with thermal comfort. In a study asking participants to identify their thermal sensation and thermal preference, it was found that many would respond identifying their thermal environment as "neutral" but that they preferred it to be warmer or cooler. Participants also responded stating that they found the thermal environment to be slightly warm or slightly cool but that they preferred no change (Humphreys and Hancock 2007). Ultimately, thermal comfort is a subjective metric for determining occupant satisfaction of the thermal environment, and because it is so heavily weighted by individual perception, establishing indoor environment conditions to meet the needs of large groups poses a large challenge for building designers and engineers.

Furthermore, perception of the thermal environment is also affected by adaptation, which is defined as a "diminished response to environmental stimuli over time" (de Dear & Brager, 1997). Adaptation can be anything beyond the physical parameters of the PMV model, including but not limited to: demographics, context, and cognition. Humans adaption to the thermal environment can be categorized in three ways: behavioral adjustment, physiological response, and psychological response. These adaptations to thermal comfort should complement the static heat-balance model rather than contrast it (de Dear & Brager, 1997).

In response to these adaptive modes of thermal comfort, de Dear and Brager created the adaptive thermal comfort model, which amended the ASHRAE Standard 55 in 1997 (ASHRAE 1997). This standard applies to naturally ventilated buildings that have no heating systems in operation. This model takes into account the outdoor prevailing temperature, which to some degree accounts for thermal history, but it does not include other methods of thermal adaptation, discussed in the following sections.

2.1.1. Behavioral Adaptation

Behavioral adaptation, or adjustments, are any changes that a person takes to alter the body's thermal balance with respect to the environment to which they are exposed, whether that be mechanical or not, such as putting on or taking off a layer of clothing, adjusting HVAC controls, opening or closing a window, or drinking a warm or cold beverage. In the static PMV model, metabolism (met) and clothing (clo) levels contribute the most weight to the PMV calculation, and therefore have the most powerful effect on individual thermal comfort of any adaptive responses.

2.1.2. Physiological Adaptation

Physiological adaptation is the response to physiological responses to the thermal environment that can gradually reduce the effect that a particular stimulus has on the body. Adaptation is an immediate physical response to a stressor in an effort to maintain homeostasis. Acclimatization is the alteration of body physiology over weeks or longer in response to repeated exposure to a given thermal condition, with lasting effects. Acclimation is an adaptation that occurs in a controlled setting, such as in a laboratory or climate chamber. Genetic acclimatization spans over the course of generations, resulting in similar body morphologies in entire populations (de Dear & Brager, 1997).

Humans are homeotherms, but human bodies are far from thermostatic (de Dear & Brager, 1997). This means that the body defends a core temperature, but skin temperature and blood flow vary to balance the heat exchange with the surrounding environment to maintain that setpoint. Adaptation to heat includes sweating and increased skin blood flow. Adaptation to cold includes shivering and reduced skin blood flow. Previous thermal comfort research measures the activation of skin thermoreceptors to understand the instantaneous physical response to the thermal environment (de Dear et al., 1993; Chen, 2011).

Because skin temperature is reliant on the body's thermoregulatory system, blood pressure fluctuates to maintain stasis, and therefore is an important biomarker to understand thermal comfort in response to indoor environmental conditions. Choi (2010) found that mean arterial pressure (MAP; the average pressure exerted on the arteries in one cardiac cycle) varied with occupant satisfaction with perceived indoor environmental quality. Gilani et al. (2016) found that by using MAP rather than activity (met) level, thermal sensation could be more accurately predicted than by the physical environment conditions. Gilani et. al speculate that this method may be beneficial as a biomarker because blood pressure is dependent on one's age, ethnicity, sex, body mass index, among other personal factors that are not accounted for in the PMV model.

In addition to physical stimuli, the body responds psychological stimulus by way of parasympathetic activation. The parasympathetic response is a branch of the autonomic nervous system, responsible for relaxing and calming the body. This is in contrast to the sympathetic nervous system, commonly understood as the "fight or flight' response to stressful events. The psychophysiological response to visual materials will be discussed further in Section 4.1.1.

2.1.3. Psychological Adaptation

Psychological adaptation is a change in perception and the subsequent reaction to thermal stimuli, which can be based on past experience or expectation. Here, it is worth revisiting the definition of thermal comfort: "a condition *of the mind* that expresses satisfaction with the thermal environment". From this statement, it is clear that thermal comfort is primarily psychological in nature. Humans do not accurately estimate temperature and rely heavily on contrasts to understand our current thermal environment (Parkinson & de Dear, 2017). This can be understood in the same sense that sensible heat is felt as a difference in temperature from the surrounding environment to body temperature. There are many examples of psychological adaptation to the thermal environment, but this thesis addresses two: physically by thermal history and visually by means of the Hue-Heat Hypothesis. These will be discussed in the following sections.

2.1.3.1. Thermal History

Thermal history, or thermal experience, refers to the influence of the thermal environment to which one was previously exposed on one’s current thermal expectation (Brager & de Dear, 1998). Thermal history can be long-term or short-term. Long-term, for example, refers to the thermal conditions to which a person is accustomed: for example, a person who lives in a building without air conditioning might find an air-conditioned office too cold for their thermal preference. Short-term refers to changing thermal conditions: for example, as a person moves from a warm outdoor space to an air-conditioned space indoors, they might find the indoor space cooler than someone who has been in the indoor space for some time and has thermally adapted.

Responses to changes in the thermal environment have been studied in various thermal transition experiments, most typically in step-changes. De Dear et al. (1993) tested subjects in up-steps and down-steps both toward and away from neutrality. Participants’ immediate thermal sensation after an up-step transition were similar to the thermal sensation after acclimation occurred. In contrast, the down-steps were twice the magnitude of change of the warm transitions (de Dear et al., 1993). This illustrates that cold thermoreceptors are located in the higher layers of cutaneous tissue and are therefore more sensitive to sudden thermal transitions than the warm receptors. Wu (2014) determined that as participants moved between a warm room (27°C) and a cool room (17°C), changes in thermal comfort vote are most consistent with a measure of the effective temperature difference between two rooms, rather than the temperature of either room. Zhao (2007) reports that upon returning to a neutral room (25°C) from a warm room

(30, 35°C or higher), participants were subject to an “overshooting” effect, in which they found the space to be cooler than what they had previously felt. Zhang and Zhao (2009) studied dynamic and non-uniform environment transitions using personal ventilation, finding that the larger the thermal sensation change over time, a corresponding change in comfort or discomfort was reported by participants, emphasized by the existing core body temperature.

Similar step-change studies consider the physical responses to thermal transitions by measuring skin temperature and its relationship to thermal comfort. Nakano (2003) analyzed participants’ skin temperature and thermal sensation votes in response to transitions between an indoor space, a semi-outdoor space, and an outdoor space, finding that transitions toward thermal neutrality in large temperature intervals corresponded with immediate and large improvements in thermal comfort but small changes in skin temperature. Chen et al. (2011) found that in response to temperature steps: both down-steps (from 32/28°C to 24°C) and up-steps (from 20°C to 24°C), a cold overshooting effect occurred not only in thermal sensation vote, but in skin temperature and skin capillary blood flow. Ji et al. (2017) found that as participants transitioned from non-neutrality (26°C) to neutrality (24°C) in step changes, skin temperature varied with the different conditions, but even when the thermal environment improved even slightly, thermal satisfaction increased significantly.

Sudden changes in ambient temperature can either be very displeasing or they can induce *alliesthesia*, meaning thermal pleasure or satisfaction with the thermal environment (Cabanac, 1971). Alliesthesia occurs when internal physiological signals modify the sensations that arise from peripheral receptors. For instance, when the core temperature is slightly above the desired setpoint, a light breeze on the skin elicits thermal pleasure. The effect is reversed if the core temperature is slightly below its setpoint and the same light breeze across the skin occurs (Candido, 2012). This effect depends on the magnitude of change and thermal history (Parkinson et al., 2017). In summation, a changing thermal environment can either positively or negatively impact thermal comfort but should be carefully considered to apply these concepts in the design and control (or lack thereof) in buildings.

2.1.3.2. Hue-Heat Hypothesis

Another instance of psychological adaptation is response to visual stimuli. One example is the notion that color can impact human temperature perception. This theory is referred to as the hue-heat hypothesis (HHH) and suggests that the subjective feeling of the temperature of an object can be altered by the object's color (Mogensen, 1926). Due to the typical association that people have with colors higher on the color spectrum as "warm" and those lower on the color spectrum as "cool", the visual environment a person experiences can be perceived as thermally warmer if it is colored red or orange. This may be due to the proximity of yellow-red hues to the end of the visible spectrum of light that is closest to infrared wavelengths which are associated with radiant heat (Masuda, 1992).

In architectural research, the HHH is typically tested in the form of investigating colored light on temperature perception. A preliminary study on colored light in which participants were instructed to adjust the ambient air temperature to their individual preferences (Fanger, 1977) found that participants preferred a slightly lower ambient air temperature (0.4°C) when exposed to red-colored light while no effect of blue light on thermal sensation was found. Chinazzo (2017) reported that colored glazing was found to have an effect on perception of thermal warmth at three temperature levels: 19°C, 22°C and 26°C. When exposed to orange tinted glazing, subjects reported higher estimated temperatures than neutral (clear) and blue in the slightly warm (26°C) environment. Independent of room temperature, a significant effect of the blue light was found: when viewing blue glazing, people felt cooler and less comfortable than with the clear glazing when exposed to the same thermal environmental conditions. Additional research supporting HHH with respect to materials rather than colored light is covered in Section 4.1.

2.2. Interaction Effects

A 2011 study showed that of 15 parameters for satisfaction with the interior environment, the most important were satisfaction with the amount of space, noise level, and visual privacy, followed by colors and textures (Frontczak et al., 2011). This revealed that colors and textures were more important to building occupants than temperature, amount of light, and air quality. A similar survey determined the relationship of indoor environmental quality (IEQ) factors, finding that colors and textures are a basic factor of overall satisfaction with indoor environment, meaning that they have a negative impact on overall satisfaction with the building when they do not satisfy occupant expectations (Kim & de Dear, 2012). This finding is not consistent across all studies. Frontczak and Wargocki (2011) found that thermal comfort was the most important quality among all measured IEQ factors, including thermal comfort, acoustic quality, air quality, and visual comfort. Furthermore, improving a single IEQ factory cannot linearly improve overall satisfaction (Humphreys, 2005). In any case, thermal comfort and visual performance are found to be important factors of overall satisfaction with the built environment.

2.3. Energy Implications

Typically, HVAC systems provide narrowly defined thermal comfort to indoor environments and often contribute to the largest amount of energy loads on the built environment. Corgnati et al. (2008) found that by changing a single temperature setpoint to a dual setpoint inclusive of the range of -0.5 PMV to +0.5 PMV to three climate zones in Italy (Turin, Rome, and Palermo), up to 50% reduced energy demand can be realized. In this study, occupants were not substantially less comfortable in the widened temperature range, with the same percentage of dissatisfied people realized in both the single and dual setpoints. The authors attribute this result to the varying of expectations regarding thermal comfort. Arens (2010) also reports that narrowly defined setpoints do not improve thermal comfort. Cai et al. (2012) suggests that by increasing the neutral setpoint temperature and widening the acceptable temperature range, it is possible to reduce the energy consumption in hot and humid climates by 6% for each 1°C increase in the setpoint when also incorporating increased local air velocity (because fans contribute to significantly less energy consumption as compared to HVAC systems).

To best realize sustainable and energy-efficient buildings, Nicol & Humphreys (2002) propose the application of sustainable comfort standards paired with some ability for occupants to control their thermal environment. (Stoops et al., 2000) estimates a potential 18% annual energy savings by implementing variable indoor temperature in all air-conditioned buildings in the UK. Other simulated energy analyses estimate 10% cooling load energy savings in the UK if adaptive comfort standards were implemented (Wilkins, 1995; Nicol et al., 1995). It is important, though, to maintain occupant comfort when selecting a wider setpoint range, as occupants are prone to using energy-consuming methods, such as personal desk heaters, to improve their comfort when in a state of discomfort.

To conclude, there are currently gaps in knowledge supporting adaptations to human thermal comfort. Physiological and psychological adaptations and their interactions impact individuals' perception of the thermal environment. By providing knowledge to fill these gaps, buildings can be better designed to provide thermally comfortable and energy efficient spaces for occupants.

CHAPTER III

SUBJECTIVE ANALYSIS OF TRANSIENT INDOOR THERMAL ENVIRONMENTS

3.1. Introduction

Heating and cooling systems have dramatically changed the way people experience the indoor built environment. In most buildings, a narrow setpoint dictates the operative temperature which a building is designed to maintain, and thus, the interior environment fluctuates within a small range over the course of a day, season, or even an entire year. Building occupants become accustomed to these narrow thermal environment ranges both physically and psychologically, which determines their perception of thermal comfort.

In contrast to static comfort models, variable temperature standards, such as the adaptive model of thermal comfort (de Dear & Brager, 1997), consider other factors for thermal comfort, especially when building occupants can alter their thermal environment in some way. Thermal adaptation consists of three additional categories by which persons might adapt to the thermal environment: behavioral, physiological, and psychological (de Dear & Brager, 1997). Behavioral is any action that a person takes to modify their thermal experience: opening a window, putting on a sweater, turning down the thermostat. Physiological is an involuntary adaptation to the thermal environment: such as short-term responses like sweating and shivering. Psychological is a change in perception of the thermal environment based on expectation and experience: for example, a person who sets the thermostat at home to 75°F will likely find a 68°F office to be quite cool. Psychological adaptation is challenging to address because it encompasses all the personal responses to the thermal environment, both physical and nonphysical.

Due to these adaptations to the thermal environment, people are not accurate judges of temperature. While humans are homeotherms, meaning we maintain a constant internal body temperature, we are not thermostatic in our temperature preferences, and human cold and warm receptors are subject to fluctuations. Like the proverbial frog in boiling water, humans are tolerant of small or nearly indiscernible temperature fluctuations over time, but sudden changes of larger magnitude are quickly detected.

Steady-state operative temperatures are challenging to maintain and require high energy consumption to achieve. Arens (2008) states that the narrower the range of acceptable temperatures, the more energy it takes to maintain, without equivalent increases in thermal comfort. Rather, if the building setpoint is allowed to “float” to wider ranges, energy demands can be reduced without sacrificing thermal comfort. Furthermore, building occupants may not even desire to feel thermally neutral. Humphreys and Hancock (2007) found that participants often did not respond with the same sensation for the same thermal conditions. Respondents’ thermal sensation was neutral, but their thermal preference was to feel warmer or cooler. This illustrates that people desire different thermal conditions in different scenarios, suggesting that thermally neutral is not always favorable.

It is possible that living within a narrow range of temperatures can reduce thermal acceptability over time. Yu et al. (2012) found that people who are acclimated to naturally ventilated environments did not feel as hot and uncomfortable as people who have been accustomed to air conditioning when exposed to warm indoor environments. For this reason, the benefit of deviating from the comfort zone can actually be beneficial. A study of indoor climate experience found that people who live in non-neutral thermal environments determine similar thermal comfort perception as those in thermally comfortable conditions (Luo et al., 2018). This reveals that an individual’s understanding of thermal comfort changes with indoor thermal experience. Departing from the comfort zone does not necessarily mean that people will be uncomfortable. Prolonged exposure to temperatures outside the comfort zone can lead to improved acclimatization and increased comfort ratings (van Marken Lichtenbelt et al., 2017).

Few studies investigate transient thermal environments. Gagge et al. (1969) found that participants were more likely to be uncomfortable when exposed to transient changes from comfortable to uncomfortable: either neutral to cold or neutral to warm. When reversed, such as going from cold to neutral, the perception of comfort and temperature were determined before the body temperature regulated, in anticipation of the change. Griffiths & McIntyre (1974) studied responses to thermal transients using overhead radiation, finding that raising the air temperature did not affect sensitivity to overhead radiation. Zhang (2004) studied responses to local transient thermal transient conditions using air sleeves attached to participants. It was found that when overall thermal sensation was cooler, warm local sensation became increasingly comfortable, and when overall sensation was warmer, warm local sensation became increasingly uncomfortable.

Many studies evaluating changes in the thermal environment utilize step-changes rather than transient conditions, likely because transient environments are challenging to control with a high degree of precision. Transient thermal conditions should be studied to understand their linkage to health, comfort, and energy consumption (van Marken Lichtenbelt et al., 2017). Because of this existing gap in the literature of thermal comfort research, this study analyses the effect that thermal history has on participants when exposed to a transient thermal environment.

3.1.1. Hypotheses

Based upon existing literature studying thermal history, we hypothesize that, for any given thermal environment, more people will perceive their comfort to be “neutral” (TSV = 0) as the thermal environment transitions toward thermally neutral than away from thermally neutral. The following hypotheses were tested:

$H_{1.1}$: Thermal sensation for subjects who were previously too warm or too cool will be closer to neutral than subjects who were previously neutral.

$H_{1.2}$: Blood pressure for subjects who were previously too warm or too cool will be lower than that of subjects who were previously neutral.

This study was originally designed to investigate impact of wood as a visual material on perception of thermal comfort. For these reasons, the following hypotheses were also tested:

$H_{2.1}$: Thermal sensation for subjects who experienced wood walls will be closer to thermally neutral than subjects who experienced white walls.

$H_{2.2}$: Blood pressure for subjects who experienced wood walls will be lower than that of subjects who experienced white walls.

3.2. Methodology

3.2.1. Research Setting

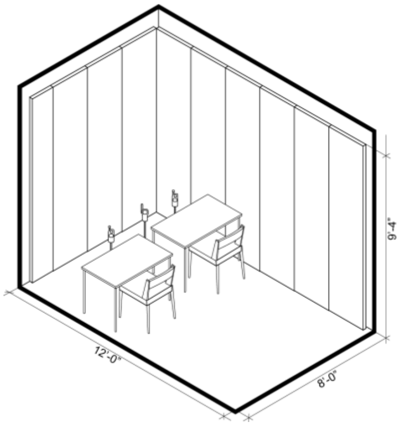

Figure 3.1: Climate chamber layout

The human subjects testing occurred weekdays February – March 2018 at the Energy Studies in Buildings climate chamber located at the University of Oregon's White Stag Building in Portland, Oregon. The climate chamber is an 8' W x 12' L x 9' H enclosed room with capability to control radiant temperature, air temperature, humidity, and airflow. The floor is gray laminate tile, and the ceiling is white-painted aluminum panels. Participants were situated with their backs to the sliding glass door entrance to the chamber, with the two workstations centered in the climate chamber, to minimize impact from the outside environment and daylight variability (Figure 3.1). Participants experienced two different visual wall conditions: floor-to-ceiling reversible panels with unfinished laminated wood on one side and painted off-white gypsum board on the reverse, which allowed both wall treatments to be physically present in the chamber for all participants, but only one treatment was visible in an individual session. The wooden wall panels were unfinished laminated Douglas fir (Light reflectance value [LRV] ~52). The white wall panels were standard drywall coated with an off-white matte finish (Benjamin Moore #2022-70, LRV 89.27). Electric lighting was used in all conditions (Phillips, F32T8/TL835/ALTO, 3500 Kelvin).

3.2.2. Participants

Participants were recruited from University of Oregon in Portland and Portland State University. Twenty-nine participants (16 female and 13 male) completed the experiment (summarized in Table 3.1), none of which reported significant sight impairment, suffered from any heart condition, or were ill at the time of the study.

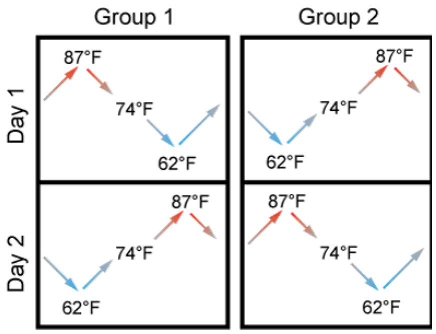

Figure 3.2: 2 x 2 factorial design groups

Table 3.1:
Participant demographic summary

	n	*Male*	*Female*	*Age*	*BMI*
Overall	29	13	16	27 ±6	24.2 ±4.8
Group 1	15	9	6	27 ±6	23.7 ±3.4
Group 2	14	5	9	28 ±5	22.6 ±4.6

3.2.3. Equipment

An ambulatory blood pressure monitor was used to record participant blood pressure readings at 20-minute intervals (Oscar 2, SunTechMedical, accuracy ±5 mmHg). Internal body temperature was recorded at the start and end of each testing phase with a tympanic thermometer (Braun ThermoScan Ear thermometer, accuracy ±0.4°F) to screen for high temperatures that might indicate illness.

A data logger (Kestrel 5400 Heat Stress Tracker, accuracy ±0.9°F ambient temperature and ±2% RH) was positioned at desk height (0.75m) at the front of the participants' desks, with continuous monitoring of environmental conditions, logged every minute.

3.2.4. Research Design and Procedure

The study used a 2 x 2 full factorial design to study effect of thermal history on thermal sensation in a transient environment. Each participant experienced two days of testing: both in either the morning or afternoon, and each experienced both heating-first and cooling-first treatments as well as both wall treatments: white and wood. The order of exposure was randomized (Figure 3.2). Each study lasted approximately 4 hours and followed the same protocol (Figure 3.3). Two participants sharing the same time block arrived at the facility for their scheduled session in the requested attire for the test: a long-sleeved cotton shirt, a light jacket or sweater, long denim pants, and closed-toe shoes (standard indoor winter season attire, 1.0 clo). In the introductory phase, the researcher explained the study to the participants who then read and signed the informed consent form. Participants were then instructed to complete a demographic/background questionnaire and were connected to the monitoring equipment.

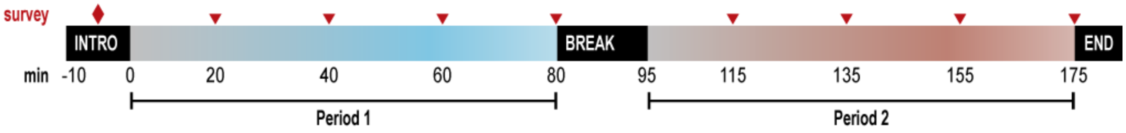

Figure 3.3: Typical study design for a single 4-hour session, broken into 2 periods. Pictured is a cooling-first treatment. The red markers indicate when questionnaires were administered.

The participants then entered the climate chamber, marking the beginning of the first 80-minute monitoring period. After 20 minutes had passed and at subsequent 20-minute intervals, participants completed a 5-item questionnaire (Table 3.2) on the provided tablets at their workstations, corresponding with blood pressure measurements. During this time, participants were instructed to remain seated at their desks and were permitted to work on their own provided material, with the limitation that it could only be low-level cognitive work or otherwise not stressful tasks. At the end of this period, participants exited the climate chamber for a 15-minute break during which no strenuous activity, food, or drink other than water was permitted. The participants then reentered the chamber for the second 80-minute collection period. In the same manner, participants answered the 5-item questionnaire at 20-minute intervals. At the conclusion of the second period, participants exited the chamber and completed a post-test questionnaire. 11 participants were asked to return for an additional session because data from their first experiment were not properly stored. In their return visit, they experienced the same conditions as their first experiment.

For all scenarios, relative humidity (RH) was 25% ±3%, an average indoor humidity value for the winter season. Clothing (1.0 clo), activity (1.0 met), and air speed (20 fpm) remained constant, with some exceptions in which 1 participant removed a sweatshirt and others changed their activity between sitting quietly and typing/writing.

Clo was determined by the researcher's visual analysis and the participant's written description of their attire. Only air temperature was changed to modify the thermal environment. For heating, the operative temperature (T_o) of the climate chamber was established at thermally neutral (T_o = 74.9°F±1.4°F, PMV ~ 0), then the temperature steadily increased to "warm" at 45 min (T_o = 87.5°F±1.5°F, PMV ~ +2), then returned to thermally neutral at 90 min. For cooling, the environment also began at thermally neutral, then the temperature was steadily decreased to thermally too cool (after 45 min) (T_o = 62.5°F±1.2°F, PMV ~ -2), then increased again to approach thermal neutrality (roughly around 110 min). For all sessions, the starting temperature was the same as ambient temperature in the laboratory as participants entered the climate chamber. Control switching was driven by runtime in each direction rather than temperature reached (Figure 3.4).

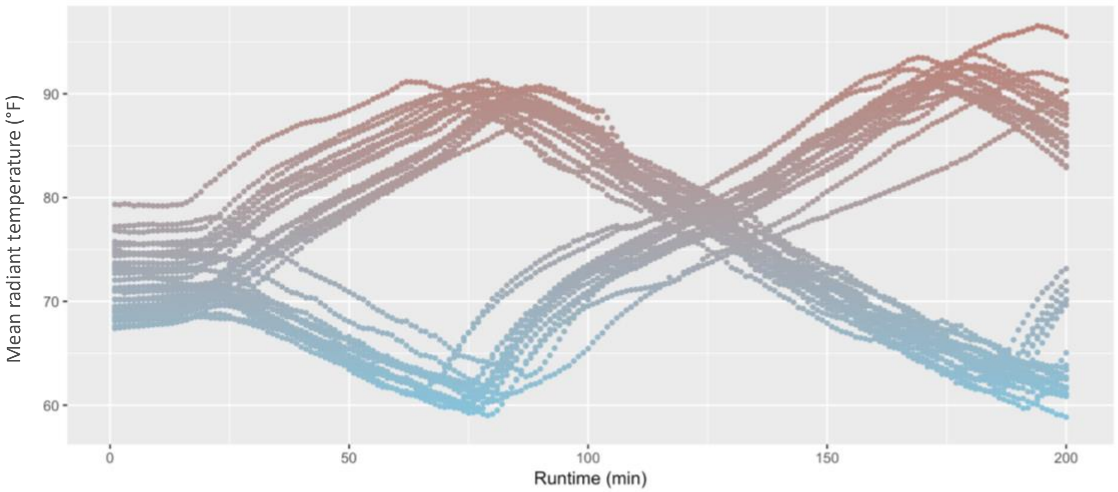

Figure 3.4: Mean radiant temperature by runtime for all experiments

3.2.5. Questionnaires

All questionnaires were completed on laboratory-provided tablets via the online survey tool Qualtrics, with the exception of one participant who completed the questionnaire on paper due to technical complications. Participants began the experiment with a demographic/background questionnaire and ended each session with a post-test evaluation. Subjective thermal comfort questionnaires occurred at 20 min intervals. The 5-item thermal comfort questionnaire consisted of two 7-point Likert scale questions (thermal sensation and thermal preference), a 5-point thermal acceptability question, one 1-100 selection, and one temperature estimation. Thermal sensation vote (TSV) was the ASHRAE 55-13 seven-point scale ranging from cold to hot, with neutral as the middle

Table 3.2: Repeated subjective thermal comfort questionnaire items

Thermal sensation (TS)	At this precise moment, how are you feeling? (7-point scale)						
	Cold (-3)	Cool (-2)	Slightly cool (-1)	Neutral (0)	Slightly warm (+1)	Warm (+2)	Hot (+3)
Thermal acceptability (TA)	How acceptable is your thermal environment? (5-point scale)						
	Clearly unacceptable (1)	(2)	(3)	(4)	Clearly acceptable (5)		
Thermal preference (TP)	How would you prefer to feel now? (7-point scale)						
	Much warmer (-3)	Warmer (-2)	Slightly warmer (-1)	No change (0)	Slightly cooler (+1)	Cooler (+2)	Much cooler (+3)
Temperature estimation (TE)	Open-ended (°F or °C)						

value (Table 3.2). The perceived qualities of the visual environment were assessed by a semantic-differential questionnaire of sixteen word pairs judged on a 7-point bipolar scale, which occurred at the beginning and end of each experiment.

3.3. Results

3.3.1. Analysis Methods

Fifteen datasets were not marked with time stamps to connect the participants' responses with environmental data and therefore were excluded from the analyses. A non-paired, two-tailed t-test was used to determine statistical significance when $p<0.05$. For physiological data, the first reading was excluded to remove potential white coat syndrome confounding data, and any false readings or data points with major artifacts were excluded from the analysis. All statistical calculations were calculated using RStudio software version 1.1.447. A Shapiro-Wilk normality test resulted in normal distribution of all TSV data ($W=0.93$, $p<0.001$).

Environmental data were calculated using the ASHRAE 55-13 standard for PMV, including mean radiant temperature, air temperature, air speed, and RH of the climate chamber, controlling for clo (1.0) and met (1.0). The established comfort range is -0.5 to +0.5 PMV, the standard comfort zone for steady-state conditions. Thermal history is defined as the temperature at the time at which a survey response occurred (T_2) compared with that of 15 minutes prior (T_1), calculated as follows: previously cooler ($T_2 – T_1 > 0$) and previously warmer ($T_2 – T_1 < 0$). Thermal direction compares the temperature at the time at which a survey response occurred (T_2) with that of 15 minutes prior (T_1), calculated as follows: toward neutral ($|\Delta T_1| - |\Delta T_2| < 0$), and away from neutral ($|\Delta T_1| - |\Delta T_2| > 0$).

Physiological data were calculated for each systolic blood pressure (SBP), diastolic blood pressure (DBP), and mean arterial pressure (MAP). MAP is the average pressure in an individual's arteries during one cardiac cycle and is calculated as follows:

$$MAP = \frac{SBP + 2(DBP)}{3}$$

MAP was significantly different for morning sessions (M = 88mmHg) compared with afternoon sessions (M = 94mmHg, $p < 0.01$). For this reason, MAP results are analyzed independently for both morning and afternoon groups.

3.3.2. Wall Condition Results

Wall type was not significant for TSV. For this reason, both wall conditions were included in the thermal direction data analysis. Wall condition was found to correlate most strongly with the semantic-differential word pair natural-artificial, r(56) = 0.82, (M_{white} = 2.94, M_{wood} = 4.00, $p < 0.001$). Also significant were the word pairs pleasant-unpleasant (M_{white} = 4.39, M_{wood} = 4.87, $p = 0.04$), interesting-uninteresting (M_{white} = 3.56, M_{wood} = 4.28, $p = 0.01$), like-dislike (M_{white} = 4.21, M_{wood} = 4.73, $p = 0.04$), heavy-light (M_{white} = 3.42, M_{wood} = 3.91, $p = 0.03$), and bright-dark (M_{white} = 5.65, M_{wood} = 5.25, $p = 0.03$) (Figure 3.5).

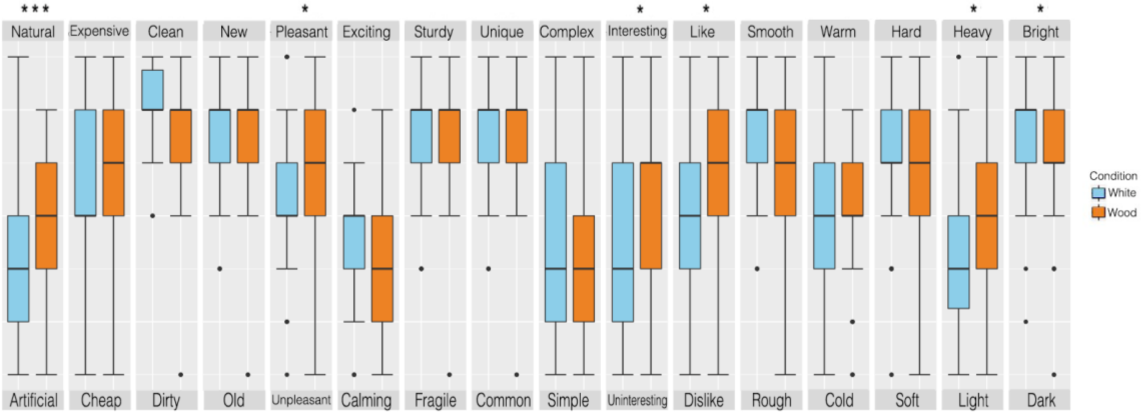

Figure 3.5: Semantic-differential word results by wall treatment. Significance is indicated at the top of each word pair; "*" $p < 0.05$, "**" $p < 0.01$, "***" $p < 0.001$

3.3.2.1. Physiological Results

MAP difference between wall type groups was found to be significant when controlling for time of day. MAP was lower for participants in the morning session experiencing the wood wall condition (M = 88 mmHg) than white (M = 90 mmHg, $p < 0.5$). The opposite was found for the afternoon sessions; MAP was higher for participants experiencing the wood wall condition (M = 95 mmHg) than white (M = 92 mmHg, $p < 0.01$) (Figure 3.6). In both cases, the effect size is small (AM: $d = 0.2$; PM: $d = 0.3$).

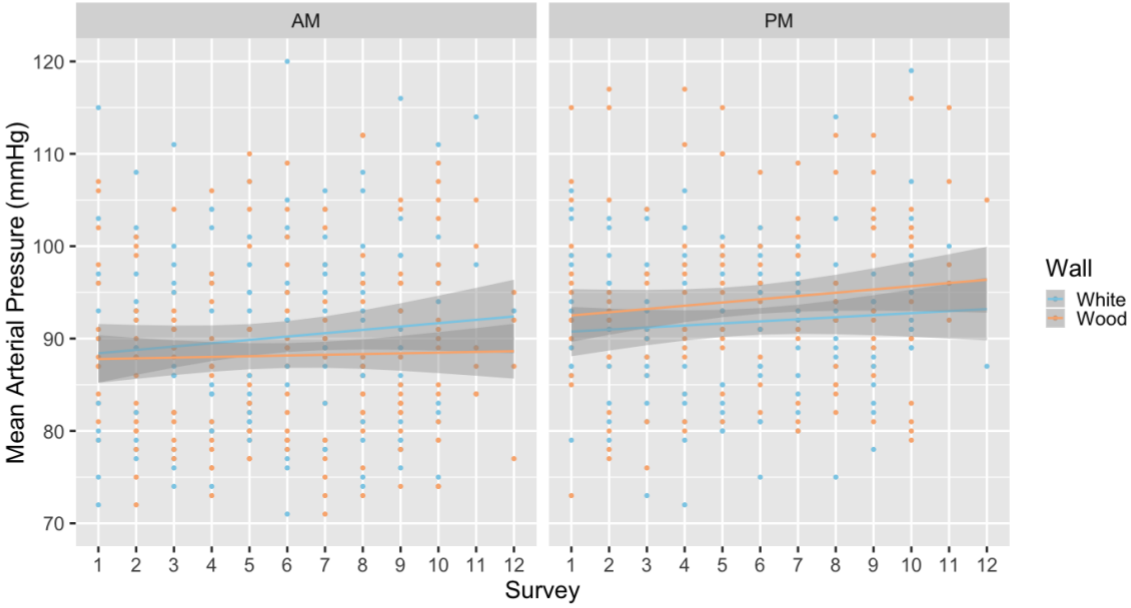

Figure 3.6: Mean arterial pressure over time for morning sessions (left) and afternoon sessions (right) as grouped by wall condition

3.3.3. Thermal History Results

Thermal direction for all environment ranges was significant ($M_{toward} = +0.15$, $M_{away} = -0.2$, $p < 0.01$). Thermal sensation results for all data are summarized in Table 3.2, which groups the data into three calculated thermal groups: cool zone (-2 to -0.5 PMV), mid-range - the standard comfort zone (-0.5 to +0.5 PMV), and warm zone (+0.5 to +2 PMV). All groups were significant, but the difference between the TSV means was more pronounced for the cool and warm zones (0.97 and 0.77, respectively) than for the neutral zone (0.36).

The air temperature at the time at which participants responded for TSV with "neutral" was significantly different depending on whether they had been previously warmer (M = 79.2°F) or previously cooler (M = 73.3°F, $p < 0.01$). There was no order effect on the temperature at which participants determined thermal neutrality between subjects' first day of the study (M = 75.8°F) compared with the second or third experience (M = 75.9°F, $p = 0.9$).

Table 3.3: Summary of results for calculated PMV thermal range groups at the time of TSV, as grouped by thermal direction: either *toward* neutral or moving *away* from neutral

	-2 to -0.5 (Away)	-2 to -0.5 (Toward)	-0.5 to +0.5 (Away)	-0.5 to +0.5 (Toward)	+0.5 to +2 (Away)	+0.5 to +2 (Toward)
Mean (PMV)	-1.19	-1.08	0.02	-0.06	1.21	1.39
Mean (TSV)	-1.57	-0.60	-0.07	0.29	1.45	0.68
Median	-2	0	0	0	2	0
Var	0.96	1.41	1.27	0.66	0.70	0.78
SD	0.98	1.19	1.13	0.81	0.84	0.88
p	<0.001		0.05		<0.001	

Figure 3.7 illustrates the temperature at which participants determined the thermal environment to be neutral for all conditions, when the environment was previously warmer, and when the environment was previously cooler. Figures 3.8, 3.9, and 3.10 are histograms of each of the groups represented in Figure 3.7. The y-axis represents

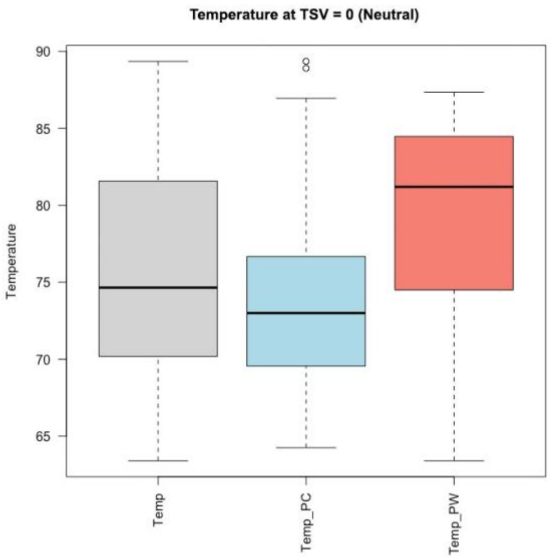

Figure 3.7: Temperature (°F) at which participants responded to TSV with "neutral" for all conditions (left, gray), when they were in a cooler condition 15 minutes prior (center, blue), and in a warmer condition 15 minutes prior (right, red).

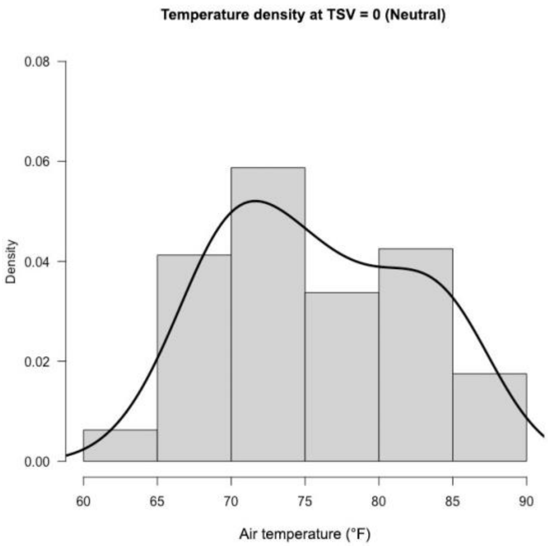

Figure 3.8: Histogram showing the frequency of temperatures (°F) at which participants responded to TSV with "neutral" for all thermal conditions

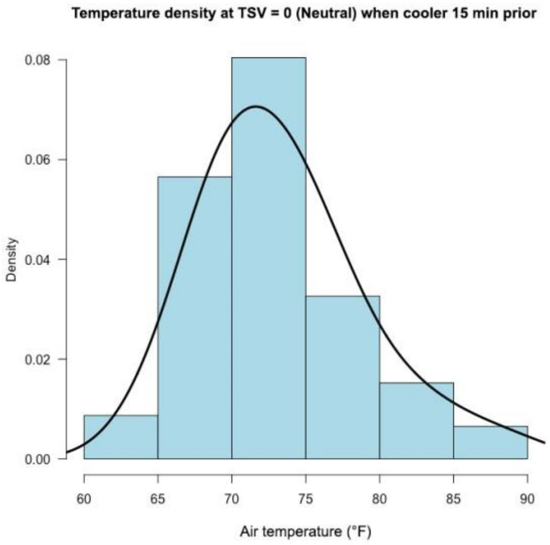

Figure 3.9: Histogram representing the temperature (°F) at which participants responded to TSV with "neutral" when they were in a cooler condition 15

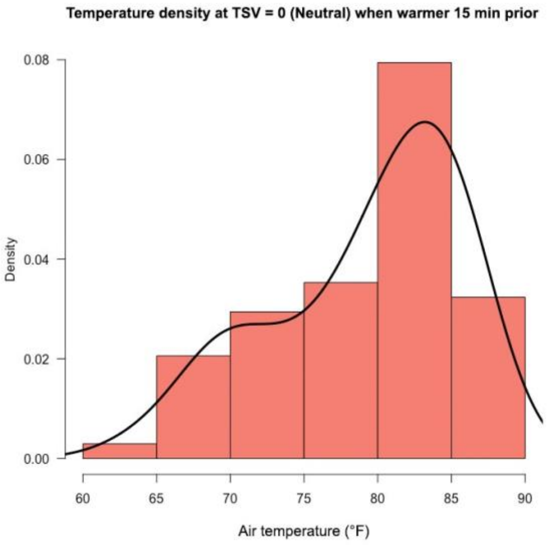

Figure 3.10: Histogram representing the temperature (°F) at which participants responded to TSV with "neutral" when they were in a warmer condition 15 minutes prior

frequency density, a standard statistical visualization in which the normalized value of the area of all the bins totaled to 1. In this case, the area is the y-value multiplied by the 5°F bins illustrated. The density curve uses kernel smoothing to show a smooth distribution of the data overlaid on the bars of the plot.

Figure 3.9 represents the air temperature at the time a TS question occurred and the response for TSV = 0 (neutral) when participants were cooler 15 minutes prior, and Figure 3.10 illustrates the same relationship for when participants were warmer 15 minutes prior. Figure 3.11 illustrates this data as a scatterplot of the temperature for all TSV responses for "neutral" and the temperature 15 minutes prior, as colored by whether participants were previously cooler (blue) or previously warmer (red). Blood pressure was not significantly different for thermal direction or thermal history.

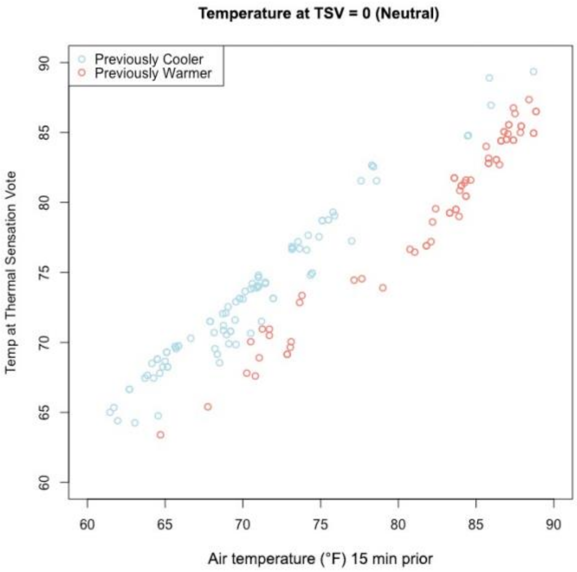

Figure 3.11: Temperature (°F) at which participants responded to a TS question with "neutral" and the temperature of the environment 15 minutes prior

3.4. Discussion

These results indicate that past experience strongly impacts current thermal comfort perception, particularly for thermal environments outside the comfort zone. The results show that it is possible to feel neutral when the temperature is around mid-60°F if previously it was in the low 60°F range, and to feel neutral when the temperature is in the high 80°F range if it exceeded that temperature 15 minutes prior. Figure 3.9 shows that perceived thermal neutrality is skewed toward cooler temperatures while Figure 3.10 is skewed toward warmer temperatures. The mean temperature at which participants felt thermally neutral when previously warmer was 79°F, which is high compared to the temperature which building occupants often establish the thermostat setpoints.

This shift toward warmer temperatures when previously warmer is greater than the shift toward cooler temperatures when previously cooler, the mean of which was 73°F. This is possibly due to two reasons: first, the study occurred during the winter (warming) season, and the warmth was welcomed. Though participants experienced both cool and warm thermal extremes, the longer-term thermal history and knowledge that it is cooler outdoors might drive participants' contentedness with higher indoor air temperatures. If this is the case, we would expect a similar shift of TSV for thermally neutral at cooler temperatures to occur if the same study design was run again in the summer (cooling) season. Second, this result may also be due to the distribution of thermoreceptors in human skin, which consists of 3.5 times as many thermoreceptors for cold as for heat. The data supports previous research that finds that humans are typically more sensitive to cold than warm. Because people are more sensitive to cold than warm, they are more likely to find warmer temperatures to be comfortable than cooler.

The time at which the thermal environment changed direction also impacted thermal sensation. Figure 3.11 illustrates that the greater the temperature 15 minutes prior, the higher the temperature that participants found to be thermally neutral, evident in the cluster of data points indicating that participants were exposed to temperatures greater than 85°F 15 minutes prior who also responded with TSV = neutral for temperatures greater than 80°F, even near 85°F. This suggests that the moment of relief from a thermal extreme triggers an immediate and marked shift toward feeling thermally comfortable, which supports the concept of alliesthesia.

The transient nature of this study, as compared to previous step-change experiments, found the temperature at which participants perceived thermal comfort in a changing environment. This allowed for investigation of the time and magnitude of responses to the thermal environment rather than gauging participants' reactions to immediate changes. The critical data that was captured in this study as compared to step-change experiments is the temperature and time at which people determined the thermal environment had become thermally neutral. As mentioned in the introduction, humans rely on contrasts to gauge thermal sensation. Step-change experiments utilize instantaneous transitions, which are relatively easy comparisons to make, by asking oneself, "Do I feel more or less comfortable than the previous condition?" The transient environment in this study becomes more challenging to perceive: "At what time did I last feel comfortable, and how does that compare to how I feel currently?"

This study did not collect skin temperature or constant core body temperature, so it is impossible to determine causality, but it is possible that this adaptive comfort effect is due to thermal lag of core body temperature to the environment. It is also likely that this is due largely to psychological adaptation: meaning that people remember the discomfort that was experienced previously and are thus more accepting of the current thermal state.

MAP did not vary significantly by a factor of thermal direction. This is likely due to the transient thermal environment. Because participants experienced both thermal extremes, too warm and too cool, small fluctuations in heart rate and blood pressure might have occurred to account for thermoregulatory responses to the slight heat and cold stress.

MAP varied as a factor of wall treatment, but the results were not consistent across time of day. MAP was lower for participants viewing wood walls in the morning sessions but higher in the afternoon sessions. This could be interpreted that the wood material had an excitatory effect in the afternoon sessions when there can often be an afternoon decrease in energy and attentiveness. The opposite could be interpreted in the morning sessions: the wood walls might have contributed to a calming sensation as energy levels rise in the morning hours. In any case, the effect size was small, and the difference in the means was only 2 to 3 mmHg, so the effect of visual materials on blood pressure, in this case, was minimal.

The strong response to the semantic-differential responses indicate that people associate visual materials by personal preference. Interestingly, though thermal sensation did not vary by function of wall treatment, participants correlated wood material with the word “warm”. This should be studied further to investigate if there is indeed a physiological response to subjectively “warm” materials in a more controlled thermal environment.

These findings can be applied to buildings with daily temperature fluctuations. If the temperature varies over time, for example, due to natural ventilation and passive heating strategies, these results suggest that building occupants will feel comfortable. For example, if a passively heated space implementing night flush ventilation of thermal mass has a slow release of heat, the space might feel too cool in the early hours of the morning ($PMV < -0.5$). As the space approaches thermally neutral, occupants will tend toward feeling more comfortable than they might feel otherwise at the same temperature. The opposite can be applied for a space that is occupied by people that were previously in a warmer condition. For instance, during the lunch hour in summer months, a space could be designed to drift higher than the typical comfort zone ($PMV > +0.5$) because occupants returning from warmer outdoor conditions might prefer a slightly warmer temperature as they return indoors.

PMV is intended to apply only to thermally adapted people in a steady-state environment. The comparison of these data suggests that steady-state thermal comfort models cannot reliably predict thermal comfort in a transient thermal environment. These findings contribute to the current understanding of adaptive thermal comfort and support that further adaptive thermal comfort models should take into account thermal history as a strong mechanism for determining individualized comfort.

3.5. Conclusion

This study found that participants were more likely to perceive their thermal comfort to be neutral as the thermal environment moved toward thermal neutrality than at the same environmental conditions when the thermal environment moved away from thermal neutrality. These findings suggest that thermal history impacts current thermal comfort in a transient environment. These results are consistent with step-change thermal comfort research which supports that as people transition from spaces outside the comfort zone to spaces within the comfort zone, their thermal sensation improves.

Participants who were previously in a warmer condition found higher temperatures to be thermally neutral. Similarly, participants who were previously in a cooler condition found lower temperatures to be thermally neutral. These findings are relevant because they support that occupants might find an indoor environment to be more comfortable if the building setpoint is allowed to change over time rather than remain static.

Thermal history should be considered when predicting thermal comfort, particularly because steady-state thermal comfort models do not account for changes over time or transitions from space to space. Transient thermal environments should continue to be studied to understand the longer-term thermal comfort, human health, energy-saving benefits, and other effects that are currently not established.

3.6. Limitations

As noted in the methodology, the original intent of this study was to investigate visual effect of wood materials on perceived thermal comfort, and there is some potential for a small influence of visual effect of the two wall treatments. The authors also recognize that this study lacked precise control of the transient thermal environment and that participants were not given sufficient time to fully acclimate to the environmental conditions in the climate chamber prior to the start of thermal transient manipulation.

The use of PMV to determine the driving temperatures is a confounding limitation. PMV only applies to steady-state conditions, so it is not the most effective metric to use to establish the transient thermal environment ranges or to analyze thermal sensation responses.

Collecting skin and core body temperatures would give a clearer image of what was occurring for each participant than repeated blood pressure measurements.

3.7. Rationale for Redesign

The winter study did not succeed in answering the original question for which it was designed. The intent of modifying the climate to reach both warm and cool temperature extremes was to explore if there is a point at which visual materials no longer impact thermal comfort and if so, at what temperature that occurs. However, there were too few responses for any given temperature range to be able to confidently conclude that materials have any effect on thermal comfort.

This also suggests that the range of temperatures was too wide to determine if there was any effect of visual material on thermal comfort. Based on these results, it was concluded that any visual effect of wood on thermal comfort is likely much smaller than the physical or behavioral responses to any given thermal environment.

The lack of data that supports the hypotheses suggests that either (1) there is no visual effect of wood on perception of thermal comfort or (2) the physiological responses to the transient thermal environment were more powerful than any response to the thermal environment. To further explore the possible psychological effect, it is necessary to conduct a study with fewer variables to hone in on the visual environment.

For this reason, the study was redesigned and ran in the summer season to explore the impact of wood materials on thermal comfort at the edge of the predicted comfort zone. The redesigned study, though similar, included distinct changes: a steady-state thermal environment, a single participant at a time, one hour-long experiment, independent measures design, controlled activity in the climate chamber, and a control period prior to treatment condition. Each of these changes will be rationalized in the following sections.

Steady-state thermal environment: The transient nature of the winter thermal comfort study, though beneficial for the thermal transient analysis, proved to be difficult to analyze thermal comfort with respect to wall treatment. Because the temperature was constantly changing, it is yet another variable to confound the data with which we had interest in studying. The summer study was set at a level at the edge of the acceptable thermal comfort zone: +0.5 PMV. This value was chosen because the study occurred in the summer, and we wanted to determine if wood has a cooling effect because buildings are more likely to be too warm during the summer months (in the northern hemisphere). If the study were to be repeated in the winter season, then the -0.5 PMV level would be selected to compare the two seasons. We selected +0.5 PMV because it is halfway between 0 "neutral" and +1 "slightly too warm", which essentially put participants "on the fence", and because participants are only presented with whole number options, rather than a sliding scale, they would have to make a decision as to how they perceive the thermal environment.

Single participant: During the transient study, two participants shared a single time block. This was designed for the sake of time constraints in order to reduce the extent of the experiment by half. However, some complications occurred. We observed that some participants interacted with each other and might have exchanged comments regarding the thermal environment. It is also possible that having two bodies in the small space impacted the thermal environment. There were some experimental sessions during which only one participant was present due to last-minute drop-outs or requests to reschedule. These are additional confounding variables that further complicate the data. It is for this reason that the redesigned study tested a single participant at a time.

Duration: The transient study required a longer period of time to be able to achieve both the warm and cool temperature conditions. This was also limiting because participants were given a break in the middle of the session, during which they left the climate chamber to uncontrolled conditions of the surrounding building. A lengthy experiment also means that participants might be subject to survey fatigue, meaning that they are less likely to respond accurately or honestly when they have repeated the same questions multiple times. The summer redesign, instead, utilized a single hour of testing during which participants responded to questionnaires in 5-minute intervals, rather than 20-minute.

Independent measures: One of the strengths of the winter study is its repeated measures design. Each participant saw both wall treatments: white and wood, as well as both thermal direction orders: heating-first and cooling-first. For the sake of timeliness, cost of compensation, and participant recruitment, the study was modified so that each participant only experienced a single session with one of the two wall treatments.

Activity: Because of the long duration of the winter study, we allowed participants to work on their provided laptops, phones, etc., so long as it was low-level cognitive work and non-stressful. However, some participants sat silently whereas others were typing, or some others who worked on hand drawings. These activities, though similar, have different met levels, which confounds the PMV calculations. In the summer redesign, we required participants to leave their belongings outside the climate chamber and only read the provided magazines for activity during the experiment session. This allowed us to more confidently analyze the data with control for all variables other than wall treatment.

Control period: One last major change that allowed the study to be conducted with independent measures design was the inclusion of a control condition: a neutral space that all participants experienced prior to the wall condition. During the winter study, participants walked into the climate chamber with the wall treatment visible. Participants did not fully acclimate to the starting conditions of the climate chamber before the temperature was modified. In the summer study modification, a floor-to-ceiling black curtain was drawn over the wall treatment to hide the wall during the acclimation phase of the experiment. This allowed for comparison of the difference from control to treatment for both wall treatments rather than a direct white to wood comparison. This also allowed us to capture data regarding visual response to wall treatment at the moment it was revealed to participants.

CHAPTER IV

VISUAL EFFECTS OF WOOD ON THERMAL PERCEPTION OF INTERIOR ENVIRONMENTS

4.1. Introduction

Thermal comfort is calculated as a product of six parameters: air temperature, mean radiant temperature, air speed, humidity, metabolic rate, and clothing level (ASHRAE Standard 55-2013). The adaptive model of thermal comfort has expanded on these parameters, including other non-thermal factors that contribute to thermal comfort: namely, the interaction effects among an individual's physiology, psychology, and behavioral processes (de Dear and Brager, 1997; ASHRAE RP-884). Most research focuses on physiological (primarily temperature acclimation) and behavioral processes (modifying one's thermal environment), but there is much to be learned about the relationship between psychological and physiological thermal perception, particularly related to visual perception interaction effects. This study is focused primarily on the psychological factor in the adaptive model and the interaction effects between psychology and physiology.

Wood is commonly referred to as a "warm" material, but it is unclear precisely why this association persists. This may be due to associations with its color, application, or comparison to other building materials. Humans perceive wood in yellow and red hues (Masuda, 1992), so wood materials are thought to be subject to the Hue-Heat-Hypothesis, which is the theory that warm-colored objects are actually perceived to be warmer than their cool-colored counterparts. Rohles and Wells (1977) designed an early experiment of material impact on thermal comfort. Two groups of participants (n=48) were exposed to the same thermal environment: one group (n=24) in a climate chamber with white enamel walls and the other (n=24) in the same space but with the addition of embellishments, including wood paneling, red carpeting, furniture, and décor. No significant differences were found between the two groups.

Wood might be perceived as warm because it is considered a *natural* material: that is, one that was once living as compared to its manufactured counterparts, such as concrete, glass, and steel, that, though technically also made from elements in nature, tend to be regarded as *cold* and *sterile*. Wastiels (2012) found that wood was regarded as visually warmer than plaster, steel, or stone. Rice (2004) investigated the visual impacts of wood finishes using a series of image cards with different images of interior finishes and furnishings, finding that wood was commonly determined as "warm" and "calming" as compared to other interior materials.

4.1.1. Biophilia

Biophilia is defined as the attraction of humans to nature and other forms of life (Wilson, 1984). This idea suggests that natural materials have a soothing or comforting effect on people. Wood, therefore, boasts biophilic properties and is thought to both improve productivity and well-being as well as reduce stress and fatigue levels, among other psychological and physiological benefits.

The autonomic nervous system response to stress leads to increased epinephrine, norepinephrine, increased blood pressure, heart rate, sweating, and vasoconstriction. (Burnard & Kitnar, 2015). Because wood is thought to impact the stress response, many studies have examined wood for its healthful qualities. Results from Sakuragawa et al. (2005) show that wood wall panels reduced depression scores and reduced systolic blood pressure in respondents as compared to white steel wall panels. Fell (2010) reports psychophysiological impacts of wooden materials, finding that furniture with wood finishes reduced stress levels in an interior environment by measure of skin conductance level. The effect of wood was even greater than the inclusion of plants in the same environment. Tsunetsugu et al. (2007) found that certain ratios of wood to other materials could lead to more comfortable and restful qualities in an interior space. Participants (n=15) exposed to a room clad in 90% wooden materials had lower diastolic and systolic blood pressure at the beginning of the test but an increase in pulse rate at the end. The same room with 45% wood coverage resulted in an increase in pulse rate, a significant decrease in diastolic blood pressure, and was subjectively determined to be the most favorable. This suggests that there might be a preferable ratio of wood with other finishes, and in this study, that ratio is certainly less than 100%. In response, Dématte et al. (2018) assessed individuals' degree of biophilia when exposed to a room with a medium amount of wood. Wood induced more positive emotions overall than white plaster. Additionally, it was found that those that responded as more strongly associated with nature had more powerful responses than those who responded as less attuned to nature.

Colored light and colored walls have been studied for thermal perception, and wood has been studied for psychophysical properties, but, to the authors' knowledge, wood has not yet been studied in isolation for visual perception of thermal comfort. This study is unique in its goal of investigating the visual impacts of wood on thermal comfort. The goals of this study are (1) to explore the impact of wood materials on perceived thermal comfort in the cooling season (2) to explore the perceived subjective qualities of wood materials and (3) to assess physiological associations of wood materials as indicators of stress response.

4.1.2. Hypotheses:

$H_{1.1}$: Thermal sensation for subjects will be closer to neutral for subjects who experienced wood walls than those who experienced white walls.

$H_{1.2}$: Blood pressure will be lower for subjects who experienced wood walls than those who experienced white walls.

4.2. Methodology

4.2.1. Research Setting

The human subjects testing occurred weekdays in July-August 2018 at the Energy Studies in Buildings Laboratory climate chamber located at the University of Oregon’s White Stag Building in Portland, Oregon. The climate chamber is an 8’ x 12’ x 9’ enclosed room with capability to control radiant temperature, air temperature, humidity, and airflow. The floor is gray laminate tile, and the ceiling is white-painted aluminum panels. Participants were situated with their backs to the entrance to the chamber (a sliding glass door), centered in the climate chamber, to minimize impact from the outside environment and daylight variability. The wall treatments were floor-to-ceiling reversible panels with unfinished laminated wood on one side and painted off-white gypsum board (hereby referred to as “white”) on the reverse (Figure 4.1B, 4.1C). This allowed for both wall treatments to be physically present in the chamber for all participants, but only one treatment was visible to each participant. A floor-to-ceiling black fabric curtain covered the wall treatments for the acclimation portion of the experiment (Figure 4.1A). The wooden wall panels were intended to mimic that of cross-laminated timber: laminated Douglas fir (Light reflectance value ~52). The white wall assembly was standard drywall coated with an off-white matte finish (Benjamin Moore #2022-70, Light reflectance value 89.27). Electric lighting was utilized in all conditions (Phillips, F32T8/TL835/ALTO, 3500 Kelvin).

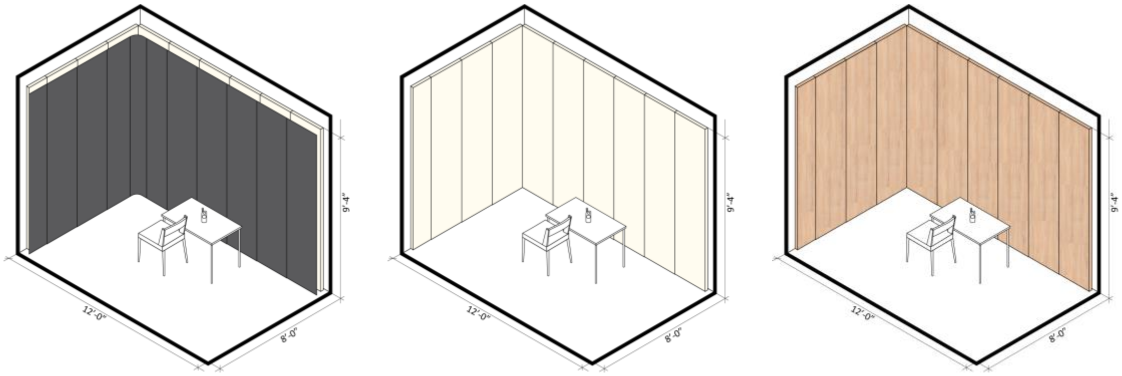

Figure 4.1: Wall conditions: (A) Black curtain (left), (B) White painted drywall (center), and (C) Wood (right)

4.2.2. Participants

The University of Oregon Internal Review Board approved that this study was in compliance with all Human Subject guidelines (Protocol #12012017.001). Participants were recruited from University of Oregon in Portland and Portland State University. Fifty-six participants (20 female, 36 male) completed the experiment (Table 4.1). No participants reported significant vision impairment, suffered from any heart condition, or were ill at the time of the study.

Table 4.1: Participant demographic summary

	n	*Male*	*Female*	*Age*	*BMI*	*Time (in hours) since last meal*
Wood	28	20	8	29 +/-11.5	24.2 +/-4.8	3.5 +/-2.7
Gypsum	28	16	12	33 +/-10.8	22.5 +/-3.8	3.3 +/-2.9

Participants were instructed to arrive 15 minutes before the beginning of the session. Participants were permitted to use any mode of transportation so long as they did not arrive “sweaty or out of breath”. Of the 56 participants, 29% arrived by car, 32% by public transportation, 25% by foot, and 11% by bicycle. Participants were instructed to arrive wearing or bring typical summer indoor clothing: a short-sleeved cotton T-shirt, long denim pants, and closed-toe shoes (0.5 clo). Participants were not informed of the purpose of the study, but they were briefed on the procedure via email before the start of their scheduled session.

4.2.3. Equipment

The thermal environment was maintained at +0.5 Predicted Mean Vote (PMV), the value halfway between “neutral” and “slightly warm” on the thermal sensation scale. Air temperature and mean radiant temperature maintained (81.5°F±1°F). Relative humidity was 40% RH (±5%), the seasonal average outdoor RH for the Portland TMY3 file. A data logger (Kestrel 5400 Heat Stress Tracker, accuracy ±0.9°F ambient temperature and ±2%RH) was positioned at desk height (0.75m) to the participant’s right-hand side, with continuous monitoring of environmental conditions, logged every minute. Clothing (0.5 clo), activity (1.0 met), and air speed (20 fpm) remained constant.

An ambulatory blood pressure monitor (ABPM) was used to record participant blood pressure readings at 5-minute intervals (Oscar 2, SunTechMedical, accuracy ±5 mmHg). Internal body temperature was recorded at the start and end of each testing phase with an in-ear clinical thermometer (Braun ThermoScan Ear thermometer, accuracy ±0.4°F) to check for high temperatures that might indicate illness.

4.2.4. Research Design and Procedure

In the first 15 minutes, participants' temperature, height, and weight were collected. A member of the research team would then apply the ABPM cuff. Participants were instructed to leave their arm down to their side, relaxed, for each blood pressure reading. The first reading was taken before entering the climate chamber to minimize the effects of white coat syndrome. Participants then entered the climate chamber at minute zero for the control condition. The first questionnaire included demographic information, the semantic-differential word pairs, and the first thermal comfort items (Q1). After 20 minutes and at subsequent 5-minute intervals, participants were prompted to complete the thermal comfort questionnaire. The participants again completed the semantic-differential word pairs assessment after the wall treatment was revealed (Q6). At the end of the session, a final questionnaire assessing daily personal thermal comfort was issued (Q9).

Figure 4.2: Standard experiment session timeline. The times at which questionnaires were completed are indicated by the letter Q. The acclimation period is the time during which a black curtain covered the wall treatment. At the 40-minute mark, the curtain was pulled away and participants then experienced either wood or white-painted walls for the treatment period.

4.2.5. Questionnaires

Questionnaires were conducted at 5-minute intervals with the exception of the first 20 minutes of the study during which participants acclimated to their environment. Questionnaires were completed on a laboratory-provided iPad via Qualtrics, an online survey tool. Thermal sensation (TS) was the standard ASHRAE seven-point scale ranging from cold to hot, with neutral as the middle value. A 5-point scale was used for thermal acceptability (TA), ranging from “clearly unacceptable” to “clearly acceptable”, with three unlabeled options between the two. The three-point McIntyre scale (McIntyre, 1978) was used for thermal preference (TP) to determine how subjects would prefer to feel without magnitude: warmer, cooler, or no change. The fourth and final question was temperature estimation (TE), which asked that participants give their best guess for the actual (dry bulb air) temperature of the room, with whichever scale (in °F or °C) participants had previously indicated they felt more familiar. The final question in the thermal comfort questionnaire was open-ended and asked participants to “describe any other issues related to comfort in your space.” (Table 4.2).

Table 4.2: Repeated subjective thermal comfort questionnaire items

Thermal sensation (TS)	At this precise moment, how are you feeling? (7-point scale)						
	Cold (-3)	Cool (-2)	Slightly cool (-1)	Neutral (0)	Slightly warm (+1)	Warm (+2)	Hot (+3)
Thermal acceptability (TA)	How acceptable is your thermal environment? (5-point scale)						
	Clearly unacceptable (1)	(2)	(3)	(4)	Clearly acceptable (5)		
Thermal preference (TP)	How would you prefer to feel now? (3-point scale)						
	Warmer (-1)	No change (0)	Cooler (+1)				
Temperature estimation (TE)	Open-ended (°F or °C)						

The perceived qualities of the wall treatments were assessed by a semantic-differential questionnaire of sixteen word pairs judged on a 7-point bipolar scale. The word pairs were selected from existing literature investigating perception of wood materials

(Rice, 2007; Wastiels, 2012). These pairs assess visual qualities (dark-bright, dirty-clean), tactile and thermal qualities (rough-smooth, cold-warm, soft-hard, light-heavy), and affective and preferential qualities (artificial-natural, cheap-expensive, old-new, unpleasant-pleasant, fragile-sturdy, common-unique, dislike-like, calming-exciting, complex-simple, uninteresting-interesting).

4.3. Results

4.3.1. Analysis Methods

The statistical analysis was carried out using RStudio software version 1.1.447. A Shapiro-Wilk normality test resulted in non-normal distribution of all thermal comfort data ($W=0.44$-0.90, $p<0.001$). For all non-normal data, a non-parametric Spearman correlation regression was used to compare thermal sensation and study variables. A non-paired, two-tailed t-test was used to determine statistical significance when $p<0.05$. Hotelling's T-squared statistic was utilized as a multivariate hypothesis test for determining significance of proportional data; which was appropriate for this application because we were testing the difference between the mean responses from distinct populations.

The perceived thermal comfort responses were analyzed both independently and as a set. Q1 was regarded as training for the participants and was not included in the data analyses. Because the acclimation time was relatively short, all questionnaires other than Q5 completed in the control environment are subject to each participant's thermal adaptation and are therefore unreliable. Comparisons are made between the control and test environments to ensure consistent thermal conditions. The analysis focuses on the difference between the immediate thermal comfort response from control to treatment (Q5 to Q6) and the long-term thermal perception from control to the last questionnaire of either wall treatment (Q5 to Q9) as well as the first response to the treatment condition (Q6) (Table 4.3).

Physiological data were analyzed each for systolic blood pressure (SBP), diastolic blood pressure (DBP), and mean arterial pressure (MAP). MAP is the average pressure in an individual's arteries during one cardiac cycle and is calculated as follows:

$$MAP = \frac{SBP + 2(DBP)}{3}$$

4.3.2. Thermal Comfort Results

Thermal comfort results are summarized in Table 4.3. Thermal sensation responses were not found to be significant for wall treatment. Figure 4.3 illustrates thermal sensation responses for the last survey in the control treatment (Q5) with the last survey in the wall treatment (Q9) (M_{white} = +0.71, *SD* = ; M_{wood} = +0.54, *p* = 0.4).

Table 4.3: Mean TSV for Q6 and perceived thermal comfort results (Δ from control (Q5) to first treatment exposure (Q6)) and Δ from control to last treatment exposure (Q9). Significance is indicated by "*" when $p<0.05$

	Wood			White		
	Q6	Q5|Q6	Q5|Q9	Q6	Q5|Q6	Q5|Q9
TS	0.68	0.39*	0.39*	0.54	-0.03*	-0.36*
TA	2.46*	0.21*	0.14*	1.93*	-0.12*	-0.12*
TP	2.79*	0.11*	0.18	2.46*	-0.08*	0.10
TE (°F)	71.57	-0.36	0.79	74.96	-0.04	0.50

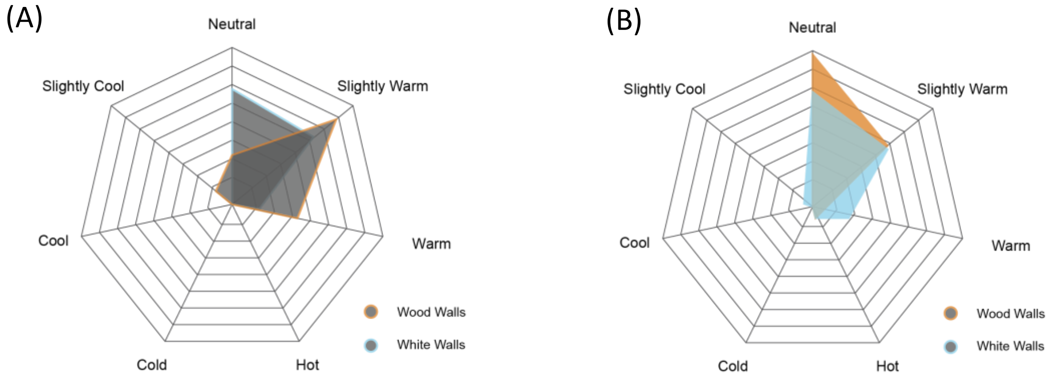

Figure 4.3: Radar chart of distribution of thermal sensation responses for (A) Q5: the last questionnaire in the treatment condition (black curtain) for both wood and white groups and (B) Q9: the last questionnaire of the wall treatment in which groups were exposed to their respective treatment condition (not significant)

On the 5-point thermal acceptability scale, with 1 being "clearly acceptable" and 5 being "clearly unacceptable", at the point at which the wall treatment was revealed (Q5|Q6), responses of participants who received the wood wall treatment at Q6 were significantly more accepting of the thermal environment (*M* = 1.93, *SD* = 0.88), than those of the white walls (*M* = 2.46, *SD* = 1.09), $p<0.05$.

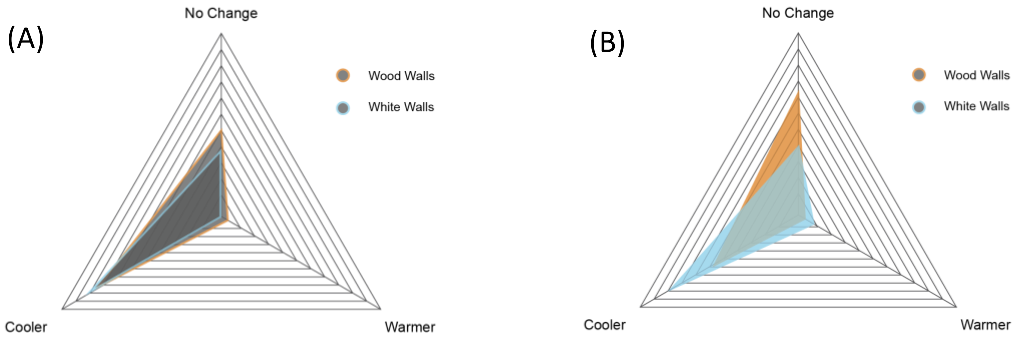

Figure 4.4: Radar chart of thermal preference responses for (A) Q5: the last questionnaire in the treatment condition (black curtain) for both wood and white groups (B) Q9: the last questionnaire of the wall treatment in which groups were exposed to their respective treatment condition

Wall treatment was also found to have a significant effect on perception of thermal preference. Mean participant response for white wall treatment revealed a desire for a cooler environment when compared to the control treatment prior ($\text{delta}_{\text{black|white}}$ = -0.08, *SD* = 0.39), with the mean decreasing from the control to the wood wall treatment ($\text{delta}_{\text{black|wood}}$ = 0.11, *SD* = 0.57, $p<0.05$).

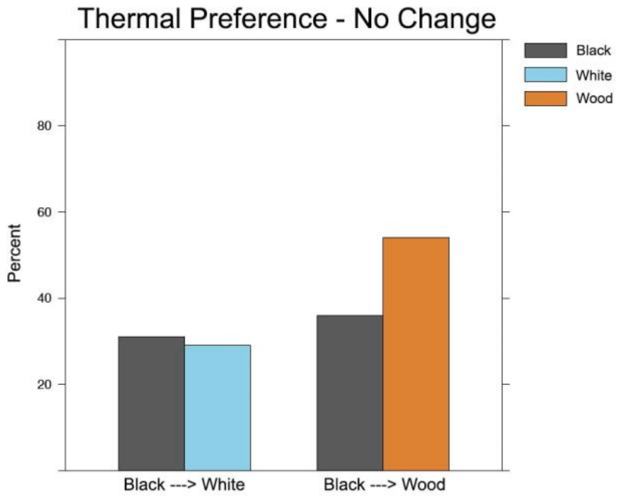

Figure 4.5: Percentage of TP responses indicating desire for ‘no change’ to the thermal environment. The blue (left) column indicates the last questionnaire in the control condition (Q5) compared with the last response of the two wall treatment conditions (Q9).

For the last survey in the treatment condition (Q9), perceived thermal preference of participants who received the wood wall treatment was cooler and closer to thermally neutral (*M* = 0.46, *SD* = 0.56), than those exposed to the white painted drywall wall treatment (*M* = 0.79, *SD* = 0.51, $p < 0.05$) (Figure 4.4). Because thermal preference is a directional scale without weight, the data are also represented in proportions. Proportioning the responses reveals that participants were more likely to respond with “no change” in the wood wall condition for the last survey before exiting the climate chamber (Q9, 54%) than the control condition prior (36%) and more than the white wall (29%) which decreased from the control condition prior (31%) (Figure 4.5).

4.3.3. Semantic-Differential Results

The strongest correlation of all data discovered was for the word pair natural-artificial to wall treatment, *r*(56) = 0.77, *p*<0.001. Wood was considered more “natural” than white walls or the control. Wood was also significantly more “liked” than “disliked” as compared to the white walls, *r*(56) = 0.58, *p*<0.01. Wood was also found to be significantly more “expensive”, “pleasant”, “sturdy”, “unique”, “interesting”, “new”, and “clean” than white.

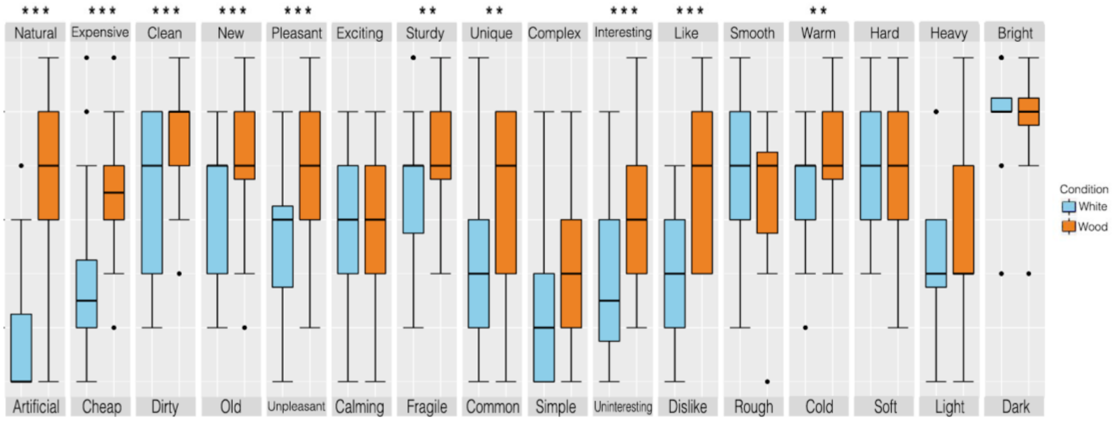

Figure 4.6: Semantic-differential word results by wall treatment. Significance is indicated at the top of each word pair; “*” $p < 0.05$, “**” $p < 0.01$, “***” $p < 0.001$

4.3.4. Physiological Results

Mean arterial pressure (MAP) was found to be significant for wall type: MAP for participants who viewed wood was lower (M = 84 mmHg) than participants who experienced the white (M = 87 mmHg, $p < 0.01$). The effect size was small ($d = 0.3$) (Figure 4.7). Both wood and white wall treatments found participants' MAP increasing slightly over the treatment condition.

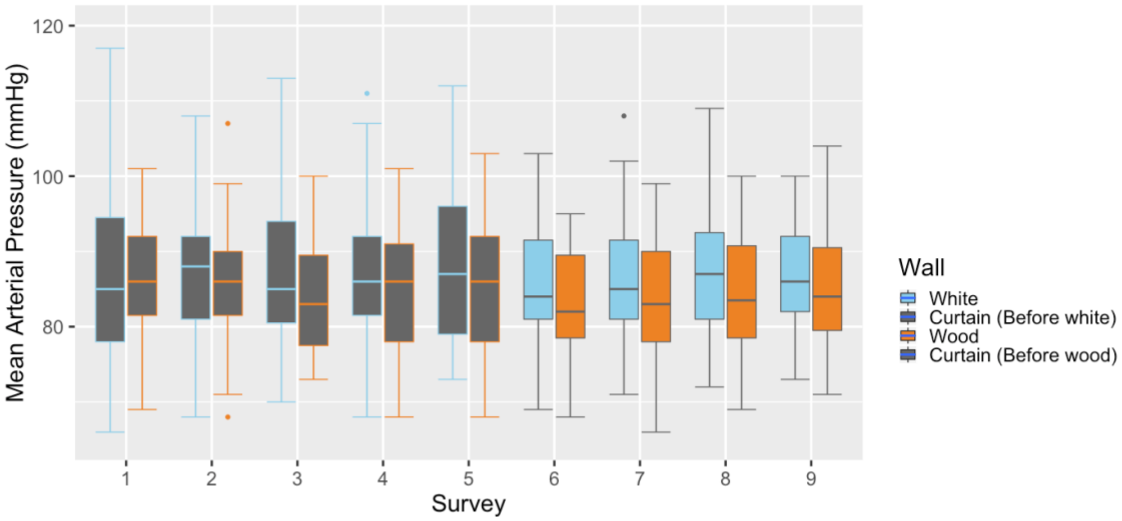

Figure 4.7: Mean arterial pressure over time, as grouped by wall condition, both pre- and post-control period.

4.4. Discussion

4.4.1. Thermal Comfort

The results for thermal preference alone, though minimal, are not negative. The HHH would reason that there may be some concern that exposed wood surfaces may lead to a perceived overheating is the potential for wood materials to lead to an overheating effect in the cooling season because of the HHH. This study supports the alternative. While the cause cannot be identified, we speculate that it is possibly due to a biophilic effect of wood materials. The perceived qualities of the wood walls might have led participants to feel more at ease, and therefore, more forgiving of the thermal environment.

We posit that we may be able to counteract slight increases in the temperature setpoint in the cooling season by leveraging the visual effects of wood materials on perception of thermal comfort. Based upon the perceived thermal comfort difference from white to wood (+0.14 PMV), with all other variables held constant (MRT, RH, air speed, met, clo), this translates to a potential air temperature difference of ~1°F. This effect will not go above and beyond the acceptable temperature range of the adaptive model but should be explored in future research. Importantly, even if further studies do not show persistence of this effect, this study lends some confidence that the HHH does not create a new obstacle when trying to reduce heating and cooling demands in exposed wood buildings.

According to Humphreys and Hancock (2007), the use of any particular thermal comfort scale can result in a vote bias. It is for this reason that the thermal comfort responses were treated as a set. This double-inquiry method compares thermal sensation with thermal preference. The data revealed that participants who rated their thermal comfort as “neutral” often selected their thermal preference to be “cooler”. The results are also inconsistent because the difference in the means for thermal sensation for wall treatment was not found to be significant whereas thermal preference was significant. The desired thermal change does not always reflect the responses for thermal sensation. The perceived thermal comfort for individual preferences is often different from what is desired. In this study, we were interested in determining not only how a person *feels*, but how they would *like* to feel. In perception research, this is critical. An individual might determine their environment to be thermally “neutral” but actually would *like* to feel either cooler or warmer, depending on the context. The thermal sensation and thermal preference scales led to inconsistent feedback from participants; for this reason, in this study, we define perceived thermal comfort as thermal contentedness. Participants were more likely to be thermally “content” in the wood environment than the white walls. The tendency to be more forgiving of the uncomfortable environment might be due to the biophilic properties of wood or its visual interest over that of white walls, but this study cannot articulate cause.

Of particular interest is the first thermal comfort response after the treatment condition was revealed. The instantaneous effect of wood on thermal sensation appears to be very strong. Over the remaining time in the treatment condition, this effect lessened. This begs the question: Could the effect of wooden materials become negligible over time as the subjects acclimate to their new surroundings? Future research should extend the study time period to determine if there is a duration at which wood no longer affects perceived thermal comfort or if it persists.

4.4.2. Physiological Results

MAP was higher for participants viewing white walls than participants viewing wood walls. This is the opposite effect of what was hypothesized. Based on previous research, blood pressure was expected to decrease in the wood wall treatment. Previous studies (Tsunetsugu, 2007; Fell, 2010) measured skin conductance, rather than blood pressure, which could account for some degree of variability. This may mean that wood triggers a parasympathetic response, but that it invokes either have a calming or an excitatory effect, depending on personal preference. In any case, the effect was quite small. These results could be due to any of the following: (1) there are no significant parasympathetic effects with respect to exposure to wood, (2) white coat syndrome led to increased blood pressure in any number of the participants and increased variability in HR, (3) the time spent acclimating to the space was not sufficient enough to trigger a parasympathetic response.

4.4.3. Material Preference

The semantic differential word pair results reveal that people found the wood walls to have favorable qualities all-around than the white. These findings are consistent with the literature and support that wood is perceived as a “natural” material. The greater effect size of the semantic results over the thermal comfort subjective results or physiological data suggests that the relationship between humans and biophilic materials such as wood are primarily psychological and rooted in personal preference. Interestingly, in the word pairs, the wood walls were found to be semantically “warmer” than the white, $r(56) = 0.31$, $p<0.05$. Additionally, for all word pairs, there was no significant change between the control condition for the white and the control condition for the wood. This reinforces that participants were in fact responding to the visual differences between the treatment walls as compared to other factors that might have affected their decisions, including other environmental factors such as smell, lighting, outdoor environment conditions, which seem to have had minimal effect on perceived qualities of the space.

Another discrepancy arose between semantic-differential responses and MAP results. Though the lower MAP for participants exposed to the wood walls suggests that they were more relaxed, there were no significant differences between the wall treatments for the exciting-calming word pair, meaning that participants, on average, did not consider the wood walls to be “calming”. This suggests that the response to wooden materials is an involuntary physical response that goes undetected by the viewer.

Finally, perception of thermal comfort is important because it can contribute to the adaptive model of thermal comfort. In combining the subjective results with the physiological results, as expected, physiology is the strongest factor for predicting thermal comfort. This study suggests that wood materials do not affect perception of thermal comfort greatly. Visual perception is influential in a person’s assessment of a space that is slightly uncomfortable, at least for the duration of an hour. We do not speculate that this cooling effect would also occur in a very warm environment (>±2 PMV). In this scenario, it is unlikely that the participants would perceive improved thermal comfort regardless of the visual field, but this should be tested in further investigations on perception of thermal comfort.

4.5. Conclusion

This study found that wood materials corresponded with thermal preference response indicating “no change” was desired, thus thermal preference was improved with exposure to wood walls over that of white. Participants associated wood walls with positive qualities for nearly all word pairs. Effect of wood was most strongly correlated with objective (semantic) responses, followed by perception of thermal comfort, then minimally with physiological responses. We conclude that the effect of material perception is highly subjective, and, in slightly uncomfortable thermal environments, visually “pleasant” or “warm” surroundings can improve perceived thermal comfort, even when the space may call for cooling.

4.6. Limitations

The authors recognize that the sample size was limited. A repeated-measures study might have more effectively illustrated the individual preference between the two wall treatments and increased the power of the study. In future work, we would like to also study neural activity at the time the wall treatment is revealed, given the strength of the initial responses. Studying participants’ brain activity in conjunction with the data collected in this study may add a critical perspective useful in interpreting the results.

CHAPTER V

CONCLUSION

5.1. Thermal Perception

This thesis considered adaptation to thermal comfort primarily in response to psychological effects of two factors: thermal history and visual wood. These studies were designed with intent to investigate the thermal perception of wood materials in an indoor environment in response to two thermal environments: transient and steady-state. It was determined that the transient environment changed too widely for any noticeable effect of visual material to impact thermal perception. The data collected allowed for analysis of the transient thermal environment, and it was found that thermal history strongly impacted thermal perception. The direction with which the thermal environment was changing, either toward or away from neutrality, impacted the temperature at which participants felt thermally neutral.

In the steady-state thermal environment, an effect of wood on thermal comfort was found. It was thought that wood, as a warm material, might lead to an overheating effect in the summer. However, the opposite effect was found, with participants in the wood wall treatment responded that they desired no change to the thermal environment more so than those in the white. It was hypothesized that this may be due in part to biophilia and satisfaction with the aesthetics of the wood treatment more than the white. This establishes a relationship between biophilia and thermal comfort.

5.2. Semantics

A difference between the semantic-differential word pairs was found between the two seasons. The lack of significant differences between wall conditions for most word pairs in the winter study is puzzling, because it was repeated-measures whereas the summer study was not. This may be due to the presence of the black curtain prior to exposed wall treatment in the summer study; the contrast at the point at which the curtain was removed likely heightened participant awareness of the visual environment. In both studies, the wood walls were found to be significantly more “natural”, “pleasant”, and “liked” than the white walls. Also, in both studies, the wood walls were found to be “warm” as compared to the white. In the case of the summer study, this does not align with the thermal responses, which indicate that participants perceived the wood environment to be cooler than the white. In this instance, it seems that subjective preference provides an overall sense of satisfaction with the visual environment, which may in turn lead to improved thermal perception of the space.

5.3. Energy Implications

As stated in Chapter III, the thermal transient results are best applied to naturally-ventilated buildings which experience timed during with the thermal environment goes beyond the thermal comfort zone (-0.5 < PMV < +0.5), as according to the ASHRAE Standard 55-2013 comfort zone limits.

In the summer study, participants were more accepting of their thermal environment than what would be typically expected by ASHRAE 55 standards by modifying the visual environment alone. The potential “forgiveness factor” of wood as a visual material likely does not go beyond this range, as indicated by the summer study. The translation of these findings into energy calculations makes another case for utilizing the adaptive model for thermal comfort in practice.

5.4. Application

As stated in Chapter III, the thermal transient results are best applied to naturally-ventilated buildings which experience timed during with the thermal environment goes beyond the thermal comfort zone.

Augustin and Fell (2015) suggest that wood can be employed in healthcare settings for its biophilic properties, based on blood pressure findings from previous studies. This study supports this notion, if not for physical properties but also improved satisfaction with the visual environment as far as it is perceived for qualities of “pleasantness” and “naturalness”. Other settings that might benefit from visual wood material include offices, education facilities, and multifamily residences. These findings best apply to spaces in which occupants are more prone to stress and overheating or overcooling.

5.5. Future Work

If afforded the time and ability, it would be ideal to run the steady-state study again in the winter (with a slightly cool thermal environment) to be able to compare the effect of wood materials in both seasons. A repeated-measures design and greater number of subjects would improve the validity of the findings.

The relationship between color of electric lighting paired with the hue of wall material should also be studied further. In both the winter and summer studies, the same electric lighting conditions (3500K) were used, but different combinations of material and light might result in differences in thermal sensation. For instance, a blue-tinted light on a white wall might have a stronger cooling effect than a blue-tinted light on a wood wall.

Other biomarkers than blood pressure might be beneficial in understanding the psychophysical response to wood materials. As stated in Chapter IV, studying brain activity in response to the wall treatments might reveal differences between the two. As is standard with rigorous thermal comfort research, it would be best to measure core body temperature and skin temperature in conjunction with subjective thermal sensation responses to better understand the effects of thermal history in a transient environment.

Thermal perception in response to psychological adaptation should be explored further. There are considerable research gaps and interaction effects between stimuli that should be considered. Of particular importance with regard to the transient study, it is critical to understand the connection between thermal transient environments and the rate of change at which building occupants are satisfied or dissatisfied. In addition, the relationship between biophilia and thermal comfort lacks significant support and should be studied further.

As with all thermal comfort research, both validation in a laboratory setting and field study are mandatory to integrate research into applicable codes and standards. A field study investigating thermal perception of visually “warm” materials should be considered. To the author’s knowledge, no existing studies exploring the HHH in architectural research has been conducted outside a controlled laboratory setting.

To conclude, the major findings from this thesis are twofold. First, thermal sensation in a transient environment is affected by past experience. A person who was previously in a cooler environment will be more comfortable in a cool environment. The same is true for a person who previously experienced a warmer environment, who will find higher temperatures to be comfortable. Second, the idea that wood can make a person feel warmer is not rejected. The steady-state study found that wood can actually make people feel cooler in a slightly warm environment.

REFERENCES CITED

Arens, E., Humphreys, M. A., de Dear, R., & Zhang, H. (2010). Are “class A” temperature requirements realistic or desirable? *Building and Environment*, *45*(1), 4–10.

ASHRAE. (2013). *ANSI/ASHRAE Standard 55*-2013*,* Thermal environmental conditions for human occupancy. Atlanta: ASHRAE.

Augustin, S., & Fell, D. (2015). Wood as a Restorative Material in Healthcare Environments, (February). Retrieved from FP Innovations.

Baniya, R. R., Tetri, E., Virtanen, J., & Halonen, L. (2018). The effect of correlated colour temperature of lighting on thermal sensation and thermal comfort in a simulated indoor workplace. *Indoor and Built Environment*, *27*(3), 308–316.

Burnard, M. D., & Kutnar, A. (2015). Wood and human stress in the built indoor environment: a review. *Wood Science and Technology*, *49*(5), 969–986.

Cabanac, M. (1971). Physiological role of pleasure. *Science*, *173*, 1103–1107.

Cai, K., Chen, Z., Yang, X., Zhang, Y., & Li, M. X. (2012). Effect of indoor thermal environment on building energy consumption. Applied Mechanics and Materials, 193–194, 137–141.

Candido, C., & de Dear, R. (2012). From thermal boredom to thermal pleasure: a brief literature review. *Ambiente Construído*, *12*(1), 81–90.

Chen, C., Hwang, R., Chang, S., & Lu, Y. (2011). Effects of temperature steps on human skin physiology and thermal sensation response. *Building and Environment*, *46*(11), 2387–2397.

Chinazzo, G., Wienold, J., & Andersen, M. (2018). Combined effects of daylight transmitted through coloured glazing and indoor temperature on thermal responses and overall comfort. *Building and Environment*, 144, 583–597.

Choi, C. Chen, C., Hwang, R., Chang, S., & Lu, Y. (2011). Effects of temperature steps on human skin physiology and thermal sensation response. Building and Environment, 46(11), 2387–2397.

Choi, J. H. (2010). CoBi: Bio-Sensing Building Mechanical Systems Controls for Sustainably Enhancing Individual Thermal Comfort (PhD Thesis). Carnegie Mellon University.

Corgnati, S. P., Fabrizio, E., & Filippi, M. (2008). The impact of indoor thermal conditions, system controls and building types on the building energy demand. *Energy and Buildings*, 40(4), 627–636.

Dalilah, N., & Yau, Y. (2016). Thermal sensations and comfort investigations in transient conditions in tropical office. *Applied Ergonomics*, *54*, 169–176.

de Dear, R., Brager, G., & Cooper, D. (1997). Developing an Adaptive Model of Thermal Comfort and Preference. *ASHRAE Trans*, *104*, 145-167.

de Dear, R.J. and Brager, G.S. (2002) Thermal comfort in naturally ventilated buildings: revisions to ASHRAE Standard 55, *Energy and Buildings*, 34, 549–561.

de Dear, R.J., Ring, J.W., & Fanger, P.O. (1993). Thermal sensation resulting from sudden ambient temperature changes. *Indoor Air*, 3:181–92.

Demattè, M. L., Zucco, G. M., Roncato, S., Gatto, P., Paulon, E., Cavalli, R., & Zanetti, M. (2018). New insights into the psychological dimension of wood–human interaction. *European Journal of Wood and Wood Products*, *76*(4), 1093–1100.

Fanger, P. O. (1970). *Thermal Comfort: Analysis and Applications in Environmental Engineering*. Copenhagen: Danish Technical Press.

Fanger, P.O. and Toftum, J. (2002) Extension of the PMV model to non-air-conditioned buildings in warm climates, *Energy and Buildings, 34*, 533–536.

Fanger, P.O., Breum, N.O., & Jerking, E. (1977) Can colour and noise influence Man's thermal comfort? *Ergonomics*, *20*(1), 11–18.

Fell, D. R. (2010). Wood in the Human Environment: Restorative Properties of Wood in the Built Indoor Environment (PhD Thesis). University of British Columbia. Retrieved from UBC Theses and Dissertations.

Frontczak M, & Wargocki P. (2011). Literature survey on how different factors influence human comfort in indoor environments. *Building and Environment, 46*(4): 922-937.

Frontczak, M., Schiavon, S., Goins, J., Arens, E., Zhang, H., & Wargocki, P. (2012). Quantitative relationships between occupant satisfaction and satisfaction aspects of indoor environmental quality and building design. *Indoor Air*, *22*(2), 119–131.

Gagge, A.P., Stolwijk, J.A., & Hardy, J.D. (1969). Comfort and thermal sensations and associated physiological responses at various ambient temperatures. *Environmental Research*, 2(3), 1-20.

Gilani, S.I., Khan, M.H., & Ali, M. (2016). Revisiting Fanger’s thermal comfort model using mean blood pressure as a bio-marker: An experimental investigation. *Applied Thermal Engineering 109*, 35-43.

Griffiths, I., & McIntyre, D. (1974). Subjective Response to Overhead Thermal Radiation. *Human Factors*, *16*(4), 415–422.

Humphreys, M. A. (2007). Quantifying occupant comfort: are combined indices of the indoor environment practicable? *Building Research and Information, 33*(4): 317-25.

Humphreys, M. A., & Hancock, M. (2007). Do People like to Feel ‘Neutral’?. Exploring the Variation of the Desired Thermal Sensation on the ASHRAE Scale. *Energy and Buildings,* 39(7): 867–74.

Humphreys, M.A. and Nicol, J.F. (2002) The validity of ISO-PMV for predicting comfort votes in everyday thermal environments, *Energy and Buildings, 34*, 667–684.

Ji, W., Cao, B., Geng, Y., Zhu, Y., & Lin, B. (2017). Study on human skin temperature and thermal evaluation in step change conditions: From non-neutrality to neutrality. *Energy and Buildings. 156,* 29–39.

Kim, J., & de Dear, R. (2012). Nonlinear relationships between individual IEQ factors and overall workspace satisfaction. *Building and Environment*, 49(1), 33–40.

Klepeis, N.E., Nelson, W.C., Ott, W.R., Robinson, J.P., Tsang, A.M., Switzer, P. … Hern. S.C., (2001). The National Human Activity Pattern Survey (NHAPS): A resource for assessing exposure to environmental pollutants. *Journal of Exposure Analysis and Environmental Epidemiology*, *11*(3), 231–252.

Luo, M., Wang, Z., Brager, G., Cao, B., & Zhu, Y. (2018). Indoor climate experience migration, and thermal comfort expectation in buildings. *Building and Environment*, *141*(2018), 262-272.

Masuda, M. (1992) Visual characteristics of wood and the psychological images. Mokuzai Gakkaishi, 38:1075–1081.

McIntyre, D.A. (1978). Three approaches to thermal comfort. *ASHRAE Transactions*. *84*(1), 101-109.

Mogensen, M., & English, H. (1926). The Apparent Warmth of Colors. *The American Journal of Psychology*, 37(3), 427-428.

Nakano, J. (2003). Evaluation of thermal comfort in semi-outdoor environment. (Masters Thesis). Waseda University. Retrieved from Waseda University Library.

Nicol, J.F., & Humphreys, M.A. (2002). Adaptive thermal comfort and sustainable thermal standards for buildings, *Energy and Buildings*, *34*, 563–572.

Nicol, J.F., & Humphreys, M.A. (2010). Derivation of the adaptive equations for thermal comfort in free-running buildings in European standard EN15251. *Building and Environment, 45*, 11–17.

J Nicol, J.F., Humphreys, M.A., Sykes, O, & Roaf, S. (Eds.). Standards for Thermal Comfort: Indoor Air Temperature Standards for the 21st Century. E and FN Spon, London, 1995.

Parkinson, T., & de Dear, R. (2017). Thermal pleasure in built environments: spatial alliesthesia from air movement, *3218*.

Rohles, F.H. & Wells, W.V. (1977). The role of environmental antecedents on subsequent thermal comfort. *ASHRAE Transactions*, *83*, 21–29.

Rice, J., Kozak, R. a, Meitner, M. J., & Cohen, D. H. (2006). Appearance Wood Products and Psychological Well-Being. Wood and Fiber Science, 38(4), 644–659.

Rupp, R. F., Vásquez, N. G., & Lamberts, R. (2015). A review of human thermal comfort in the built environment. *Energy and Buildings*, *105*, 178–205.

Sakuragawa, S., Miyazaki, Y., Kaneko, T., & Makita, T. (2005). Influence of wood wall panels on physiological and psychological responses. *Journal of Wood Science*, *51*(2), 136–140.

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(1), 11–16.

U.S. Energy Information Administration. 2012 Building Energy Consumption Survey.

U.S. Energy Information Administration. 2017 Building Energy Consumption Survey.

van Hoof, J. (2008). Forty years of Fanger's model of thermal comfort: Comfort for all? *Indoor Air, 18*(3), 182–201.

van Marken Lichtenbelt, W., Hanssen, M., Pallubinsky, H., Kingma, B., & Schellen, L. (2017). Healthy excursions outside the thermal comfort zone. *Building Research and Information*, *45*(7), 819–827.

Wastiels, L., Schifferstein, H. N. J., Heylighen, A., & Wouters, I. (2012). Relating material experience to technical parameters: A case study on visual and tactile warmth perception of indoor wall materials. *Building and Environment*, *49*(1), 359–367.

Wilkins, J. (1995). Adaptive comfort control for conditioned buildings, in: Proceedings of the CIBSE National Conference, Part 2, Eastbourne, Chartered Institute of Building Service Engineers, London, 9-16.

Wilson, Edward O. (1984). Biophilia. Cambridge: Harvard University Press.

Wu, Y., & Mahdavi, A. (2014). Assessment of thermal comfort under transitional conditions. *Building and Environment*, *76*, 30–36.

Yu, J., Ouyang, Q., Zhu, Y., Shen, H., Cao, G., & Cui, W. (2012). A comparison of the thermal adaptability of people accustomed to air-conditioned environments and naturally ventilated environments. *Indoor Air, 22*(2): 110-8.

Zhang, H., Huizenga, C., Arens, E., & Wang, D. (2004). Thermal sensation and comfort in transient non-uniform thermal environments. *Eur J Appl Physiol*. Sep;92(6):728-33.

Zhang, Y., & Zhao, R. (2009). Relationship between thermal sensation and comfort in non-uniform and dynamic environments. *Building and Environment*, *44*(7), 1386–1391.

Zhao, R. (2007). Investigation of transient thermal environments. *Building and Environment, 42*, 3926–3932.