Built Environment

Looking at wood through the skin: A multidisciplinary approach to explore the tactile quality of wood materials

Shiv Raj Bhatta

Aalto University

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Aalto University
School of Engineering
Built Environment

Supervising professor
Professor Marketta Kyttä, Aalto University, Finland

Thesis advisor
Professor Marketta Kyttä, Aalto University, Finland

Preliminary examiners
Professor Astrid M.L. Kappers, Eindhoven University of Technology, The Netherlands
Senior Research Scientist Lynette A. Jones, Massachusetts Institute of Technology (MIT), USA

Opponent
Senior Research Scientist Lynette A. Jones, Massachusetts Institute of Technology (MIT), USA

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Abstract

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Shiv Raj Bhatta

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Abstract

This thesis is focused on the developing knowledge base for exploiting the tactile quality of wood materials to improve the user perception of thermal comfort and satisfaction. Through the multidisciplinary approach, sensory, emotional, and thermal perception based on touch sense was studied using various wooden surfaces with various treatment and modification solutions. Psychophysical methods were utilized to collect the perceptual data and various tools were developed for experimentation.

Results showed that wood surfaces can elicit emotional component of touch during the tactile exploration of surfaces using finger-tips. Natural surfaces with smooth finishing were perceived positively while coated surfaces that felt a bit sticky-to-touch are evaluated negatively. It seems that preserving the naturalness of wood surface during product development is necessary for retaining the positive emotional component of touch in the wood-products. Perception of topographic attributes of wood surfaces was affected due to the surface treatment methods and modification solutions applied to them. Nevertheless, we still can preserve the naturalness of the surface and promote positive touch experiences, after (sometimes) unavoidable surface treatments or modification solutions, by creating desired sensory attributes of surfaces.

The good tactile warmth of wood, in comparison to other building materials, could be exploited to create a thermally comfortable living environment by influencing the perception of the surface temperature to its inhabitants. Results from psychophysical tests showed that subjects can reliably discriminate various natural and modified wood surfaces from each other based on the perception of tactile cold sensation. This is an important reason why we should take into account the thermal properties of wooden surfaces before the application of various treatment and modification solutions. Results offer important insights on how we can improve the tactile warmth of natural wood and other wood-based material surfaces, for example, floorings.

The next step taken in the present study was the quantification of temperature perception. The psychophysical parameters were applied to measure the perceptual similarities and differences in the temperature perception between paired surfaces from pine and oak, and pine and ceramic tile. Pine surface at 20 °, the oak surface at 20.9 °C, and ceramic tile surface kept at 22.66 °C felt equally cold to touch. The discrimination threshold between pine and oak was 2.01 °C, and those between pine and tile was 3.6 °C. The quantification of temperature perception can provide insight to develop a simulation for estimating the increased/decreased use of heating energy in the living spaces due to the use of certain building construction materials. Findings of the present study support the idea that by using more wood in living spaces it may be possible to achieve a thermally

Keywords Wood, Wood treatments, Tactile warmth, Psychophysical methods, Tactile perception, Sensory experiences

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Shiv Raj Bhatta
Helsinki, March 2020

Contents

List of Tables and Figures

List of Abbreviations and Symbols

2-AFC	Two-alternative forced choice task
AEF	Aalto energy Efficiency
ρ	Density
DT	The discrimination Threshold
JND	Just noticeable difference
MC	Moisture content
PSE	The point of subjective equality
λ	Thermal conductivity
α	Thermal diffusivity
e	Thermal effusivity
C_p	Specific heat

List of Publications

This doctoral dissertation consists of a summary of the following publications that are referred to in the text by their numerals

1. Bhatta, S.R., Tiippana, K., Vahtikari, K., Hughes, M., and Kyttä, M. (2017). Sensory and emotional perception of wooden surfaces through fingertip touch. *Front. Psychol. 8:367.* doi: 10.3389/fpsyg.2017.00367

2. Bhatta, S.R., Vahtikari, K., Hughes, M., and Kyttä, M. (2018). Investigating the tactile warmth of wood through measuring the cold sensitivity in paired-comparison test. Accepted for the publication to the *International Wood Product Journal* (March 2020).

3. Bhatta, S.R., Tiippana, K., Vahtikari, K., Hughes, M., Kivilouma, P. and Kyttä, M. (2019). Quantifying the sensation of temperature: A new method for evaluating the thermal behaviour of materials. *Energy & Buildings* 195 (2019) 26–32. doi: 10.1016/j.enbuild.2019.04.047

Author's Contribution

Publication 1: Sensory and emotional perception of wooden surfaces through fingertip touch.

Shiv Raj Bhatta was mainly responsible for the conception of the work, preparing the test setup, English-to-Finnish translation of the questionnaire, and running the experiment. SRB conducted the data analysis and result interpretation and prepared the manuscript as principle author under the supervision of Dr Kaisa Tiippana, Prof Mark Hughes and Prof Marketta Kyttä. M.Sc. Katja Vahtikari was responsible for preparing the test surfaces, supported for designing the experimental setup. KV was also involved in the manuscript writing and English-to-Finnish translation of questionnaire. KT also contributed to data analysis and interpretation of the results.

Publication 2: Investigating the tactile warmth of wood through measuring the cold sensitivity in paired-comparison test.

Shiv Raj Bhatta was responsible for the conception of the work, experimental design, data collection, data analysis and interpretation of the results. He also supervised the student project that aimed to develop the "Hand-skin Temperature Stabilizer" (Heater). M. Sc. Katja Vahtikari supported the preparation of the test-setup and test-specimen. SRB prepared the manuscript as a principal author under the supervision of Prof Mark Hughes and Prof Marketta Kyttä. KV also contributed to manuscript writing.

Publication 3: Quantifying the sensation of temperature: A new method for evaluating the thermal behaviour of materials.

Shiv Raj Bhatta was responsible for the Experimental design and planning of the work. Dr Panu Kiviluoma and SRB jointly supervised the student project that aimed to develop "TSYS01 Temperature Sensor Board" and "prototype of the test-boxes". SRB conducted the pilot tests and, M. Sc. Katja Vahtikari supported for the preparation of test surfaces and experimental setup. SRB conducted the pilot study and main experiments, collected data. SRB prepared the manuscript as principle author under the supervision of Dr Kaisa Tiippana, Prof Mark Hughes, and Prof Marketta Kyttä. KT also contributed to data analysis and the interpretation of results. PK and KV also contributed to Manuscript writing.

1. Introduction

1.1 General overview

Recently, there has been renewed interest at the EU level in the development of energy-efficient buildings to tackle the impact of climate change and the growing demand for energy (EEA Technical Report, 2013). The housing sector consumes 40% of total energy, of which 70% is used for space heating in Finland (Official Statistics Finland 2016). It has been of the utmost importance to stakeholders in the building sector to achieve (net) zero energy building, through innovative design solutions (Ascoine et al. 2016; Aeleina and Pereira, 2013) as well as the introduction of intervention programs to support the energy-friendly behaviour of inhabitants (Stern 2000, 2008).

There are two ways to influence the energy-friendly behaviour of humans in living spaces. The first is to directly influence inhabitants' behaviour by rules and regulations using incentives or deterrents to change or promote the attitudes, values and belief systems of individuals or society towards energy-friendly behaviour (Stern 2008; Iweka et al. 2019; EEA Technical Report 2013; Abrahamse et al. 2005; EU policy Brief 2018). The second is to take an indirect approach where instead of direct intervention in human behaviour, a change in environmental settings, which supports or promotes people's energy-friendly behaviour, is created (Ostende 2018), for example, introduction of separate waste bins in the household - to promote recycling behaviour. Among these indirect measures, improving the comfort and satisfaction of the inhabitants with the thermal environment of the buildings (Rupp et al. 2015) is a vital one, and needs to be addressed early in the design phase of the built environment in order to effectively promote energy-friendly behaviour (EEA Technical Report 2013; Ostende 2018).

The feeling of being comfortable and satisfied with the surrounding thermal environment is a subjective experience and such subjective experiences in living spaces can be influenced by creating or designing indoor living spaces that support this experience. Architects consider experiential aspects of materials in the selection process for designing the living spaces (Ashby and Johnson 2002;

Wastiels and Wouters 2012) and the quality of "warmness of the material" is clearly considered as relevant quality both by architects and users (Hall 2010; Wastiels 2010). Therefore, choice of building materials in indoor living spaces could be one way to influence the perception of comfort and satisfaction an inhabitant experiences with the thermal environment (Wastiels et al. 2012) and, wood, as a building material, has the potential to influence this experience.

Wood is considered to be one of the most fascinating construction materials and has been widely used throughout the history of humankind. Due to its abundance in nature and, environmentally-friendly and renewable characteristics, wood has been used in various ways to construct the living spaces. In addition, other indoor uses of wood materials include, but are not limited to, furniture, walls, flooring, kitchen utensils and bedding. The structural strength of wood materials, as well as its flexibility, are widely exploited for various purposes (Forest Product Laboratory 2010). Wood and wood-based materials have good insulating properties (Goss and Miller 1992; Kawaski and Kawai 2006) and this property has been exploited throughout the world, whether it is in extremely cold climates like in northern Europe or hot climates like in the Middle East or Africa (Shauerte 2010; Winter et al. 2012).

Wood is mostly perceived to be natural and warm by people (Hoibo and Nyrud 2010). There has been more research focusing on the perception of the warmness of wood materials, where the perception is assessed through the multisensory mode (Berger and Salvenmoser 2006; Hoibo and Nyrud 2010; Lindberg et al. 2013). Research evidences have shown that wood has better tactile warmth, where the perceived warmth is solely based on touch sense, then many other building construction materials (Obata et al. 2002, 2005, 2016, Ohkoshi et al. 2012) and, this topic has not been attracting much attention in the field of wood perception. Since the perception of tactile warmth is psychological, the measurement of perceptual experiences demands the use of psychophysical methods, where the relationship between physical quantity and perceptual experiences is defined in physical units (Macmillan and Creelman 2005). The use of psychophysical methods to measure the surface perception of materials requires an interdisciplinary approach and would be preferable to methods based on the intuitive judgement of sensory panellists or survey based on subjective ratings (Wastiels et al. 2012; Wongsriruksa et al. 2012). Therefore, the measurement of tactile warmth of wood material is one of the fields of knowledge where the present work aims to contribute. It would be of practical benefit in assessing the warmth of building materials, including wood, with greater objectivity and, perhaps, quantifying perceptual experiences in physical units.

The warmth of materials could be perceived in either the visual mode (Wright 1962; Wright and Rainwater 1962) or in the touch mode (Hollins et al. 1993; Souflet et al. 2004; Sonneveld 2007) or in a combined mode (Yosida 1968; Baumgartner et al. 2013; Lederman et al. 1986; Overvliet & Soto-Faraco, 2011; Fujisaki et al 2015). Visually warm materials exhibit colour spectra that lie within the range of "warm colours" (Wright 1962). Wood materials exhibit such quality (Fujisaki et al. 2015). Touching materials with the human skin evokes the sensation of thermal quality and this quality (cold or warm sensations) depends on the temperature state of the material (Bergmann Tiest 2010; Lederman and Klatzky 2009). The tactile coolness or warmth of heat conductive and semi-conductive materials are clearly distinguishable (Ho and Jones 2004, 2006, 2008), but within a group of semi-conductive materials, like a group of wood surfaces from different tree species, they may be difficult to distinguish. In such a scenario, the objective measurement of sensory phenomena could be achieved through the use of psychophysical methods.

The present work represents a multidisciplinary study, where the knowledge-base from neuroscience and psychophysics is utilized to assess the tactile perception of wood materials. Achieving greater objectivity in the measurement of subjective (perceptual) experiences is vital to understand the various aspects of consumer behaviour (Wastiels et al. 2012). On the other hand, studies regarding touching wood with the bare skin at normal room temperature could have practical significance: there are tremendous possibilities for touching wood surfaces in a building in a variety of settings, either for short or prolonged periods. These wood surfaces installed in buildings rarely remain untreated; different wood treatments and wood modification solutions are generally applied to achieve different functionality, such as strength, durability, aesthetics, flexibility etc. (Rautkari et al. 2010; Hayoz et al. 2003). Additionally, the surface characteristics of wood products are designed to influence consumer preferences and purchasing behaviours (Nyrud et al. 2008; 2009; Hobio and Nyrud 2010). The hedonic property is normally considered a defining factor behind product-touch experiences (Nyrud et al. 2008). Besides that, however, an emotional component of touch (Essick et al. 1999, 2010; Löken t al. 2009, 2011; Guest et al. 2011; Klöcker et al. 2012) is a relatively new research area in the field of psychology/neuroscience but is rarely applied to the field of touch-based product designing and marketing. Therefore, an investigation into the emotional touch of wooden surfaces seems to be very timely.

Therefore, the present work is an attempt to furthering the understanding that the tactile perception of wood can be exploited to improve the thermal comfort and satisfaction of users. Thermal touch-quantification using building materials could form a basis for understanding the indirect control over the use of space heating in the building by utilizing “warm materials”.

1.2 Aims of the Study

The overall aim of this study is to explore the touch experiences of wood and wood-based surfaces. First, I focus on understanding of how various surface treatment solutions affect the sensory and emotional aspects of touching wood. The aim is to improve the positive touch experiences of wood surfaces as well as suppress negative ones. The second aim is to assess the tactile warmth quality of wooden surfaces and, to compare these natural and modified wood surfaces based on touch sensation. The purpose of the study is also to explore ways of retaining or even improving the tactile warmth quality of wood materials. In addition, an aim is to measure, in numerical terms, the temperature perception of wood and non-wood surfaces, taking into account the psychophysical measure of perceived similarities and differences in cold sensitivity.

1.3 Outline

The main aspects of this study are summarized in three publications and illustrated in **table 1** given below

Table 1. Outline of the thesis

Publication I	Research questions of the article	-How is the sensory and emotional perception of wood surfaces related? -How do surface textures and surface treatment affect these perceptions?
	Theoretical/methodological context	-Research on the tactile perception of material surfaces through the fingertips from neurobehavioural perspective applied to wood touch -Highly controlled experiment -Validated/translated questionnaire
	Main findings	-Mild emotional touch was measured on wood surfaces

		-Natural and smooth wooden surfaces elicit positive affective touch evaluation -Surfaces textures influence emotional touch
	Significance for the dissertation	-The sensory and emotional dimension of the tactile perception of wooden surfaces
Publication II	Research questions of the article	-Does the tactile warmth of wood surfaces vary across tree species? -is the tactile warmth of wood surfaces influenced by surface coatings? -Is the change in the tactile warmth of wood surfaces perceptually detectable after a thermal modification and surface densification process?
	Theoretical/methodological context	-Cold sensitivity of wood surfaces should vary across specimens due to the differences in their thermal properties -The use of Thurstonian paired comparison method based on the low of comparative judgement to measure the tactile warmth -A measure of unimodal thermal perception
	Main findings	-Inter-species variation in tactile warmth of wood surfaces is noticed -Effects of modification solutions on tactile warmth were significant in some cases -The tactile warmth of wood surfaces can be retained or even improved after the surface treatment or modification solutions are applied to them
	Significance for the dissertation	-Discriminating surfaces based on tactile warmth

		-Surfaces discrimination based on tactile warmth is possible among natural and modified wood surfaces -Relative ranking of natural/modified wood surfaces based on tactile warmth
Publication III	Research questions of the article	-Can the similarities and differences in temperature perception coming from two different surfaces be measured numerically?
	Theoretical/methodological context	-Inspired by clinical practices on thermal detection/discrimination tests to explore the skin sensitivity towards the thermal stimulus -Test pieces of equipment were developed to overcome the problem with controlled heating of touch stimuli (i.e. wood) due to its semi-conductive nature -A customized 2-alternative forced choice (2-AFC) test procedure was developed in accordance with the application of stimulus intensity and test-setup
	Main findings	-At 20 °C room temperature, a pine surface maintained at 20 °C feels equally cold to the oak surface, which was kept at 20.9. The discrimination threshold (DT) for cold sensation between pine and oak was 2.01 °C. -At the point of subjective equality, the temperature of the pine and ceramic tiles were 20°C and 22.8°C. The DT between them was found to be 3.6 °C at 20 °C room temperature.
	Significance for the dissertation	-Quantification of thermal perception of the material surfaces.

			-Quantification of temperature sensation using building materials could form a basis for understanding the energy consumption potential for space heating related to the wood materials -Thermal touch quantification could provide insights for energy simulation to identify the amount of energy saved or consumed due to the use of specific building materials in living spaces.

2. Research background

2.1 Tactile perception

Tactual perception refers to every type of sensation related to the sense of touch, be it cutaneous (pressure, vibration, temperature), kinesthetic (limb movement) or proprioceptive (position of the body) (Loomis & Lederman, 1986; Bergmann Tiest 2010). The term haptic perception refers to the human ability to perceive the outer world through the cutaneous sense especially with the hand in an active exploratory way (Lederman and Klatzky 1987). These two terms: tactual and haptic are used interchangeably in the layman's perspective, though the latter is preferred by researchers in the fields of neuroscience and engineering. Tactile perception refers to all kinds of cutaneous perception of material surfaces (Okamoto et al 2013) including the contributions of kinesthetic information if the surface is actively explored.

Since the tactile perception of material surfaces is multidimensional in nature, and the most studied dimension is the discriminative aspect of surface touch: such as roughness, elasticity (Okamoto et al. 2013). Other tactile dimensions such as vibration, pain, itching, and thermal are also of interest both in the field of psychology and material science (Hollins et al. 1993; Picard et al. 2003, 2004; Okamoto et al. 2013), but this work is limited to the tactile exploration of the topography of material surfaces (discriminative properties) and thermal perception of materials which is also an aspect of the bulk property (i.e. thermal perception of materials is influenced by thickness of the tested materials). An additional tactile dimension which has recently gained attention in the field of material perception is called affective touch (Fujisaki et al 2015), which relates to the emotional aspect of the perception that is believed to be mediated through distinct neural pathways from the discriminative touch (Vallbo et al. 1999; McGlone et al. 2007, 2012, 2014; Olausson et al. 2010). The dimensionality exploration of a material's touch-quality or/and touch-properties depend on the objectives of the study, types/numbers of the material tested, types of exploratory touch, and the skin site used to touch (Lederman and Klatzky 2009; Okamoto et al. 2013). The skin sensitivity across the human body varies for these tactile perceptions (Stevens 1991). Regarding the ability of the hand to perceive cutaneous information, research has shown that the hand is excellent for these purposes (Mountcastle 2005; Klöcker et al. 2012) due to the intensive neural density and evolutionary dispositions (Mountcastle 2005).

Wood and wood-based materials have been tested as tactile stimuli in psychological/neuroscientific studies, the aim of which was to explore the breadth of human skin sensitivity and the neural processes behind such sensations (Guest et al 2011; Klöcker et al. 2012). In the field of material science, wood materials have been compared to relatively a large number of other materials (Fleming et al 2013; Overvliet & Soto-Faraco 2011; Obata et al 2002; Fujisaki et al 2015; Ino et al. 1993; Ding et al. 2017). These studies from materials science are focused on understanding perceptible material properties through the sense of touch (Overvliet & Soto-Faraco 2011), relating material properties to the specific types of sensation (Obata et al 2002; Fujisaki et al 2015) and the use of tactile cues for object recognition and object discrimination (Ino et al. 1993; Ding et al. 2017). In the abovementioned research area, whenever a wood material was chosen as the test object, the reason was that wood was considered to be a natural material that can be found everywhere. And, whenever wood is tested as a tactile stimulus, it stands alone because of its distinctive tactile attributes (Ino et al. 1993; Fujisaki et al 2015).

2.2 Tactile perception of wood surfaces

The main perceptual dimensions that have been found to be associated with the tactile perception of wood surfaces are rough-smooth, soft-hard, slippery-sticky, sparse-dense, and cold-warm (Bergmann Tiest 2010; Okamoto et al. 2013, 2016; Fujisaki et al. 2015). The soft-hard aspects of the perceptual experience may not be obvious if only wood stimuli are tested, due to the fact that wood cannot provide the breadth of soft-hard variation that is perceptible to the sense of touch. Efforts have been made to link the physical properties of wood and wood-based materials to the experiences of perception (Obata et al. 2002; Fujisaki et al. 2015), so that user satisfaction and preferences for wood products can be influenced in a positive way (Berger et al. 2006; Nyrud and Brinkslimark, 2009).

The main challenge of linking the physical properties of wood and its psychophysical attributes, relates to its surface heterogeneity: no two identical (physically) surfaces can be created for testing. In addition, surface topography varies between tree species (Thoma et al. 2015). The topographical variation of wood surfaces is also a result of the type of mechanical processing used (Sinn et al. 2004, 2009), machine parameters (Mitchell and Lemaster 2002), grain direction and wood density (Goli et al. 2004). Other wood specific parameters such as checks and knots as well as damage caused by mechanical or biological action, can also cause variation in the topographical characteristics of wood surfaces.

Measurement of the tactile experiences of wood materials and wood-based products have mostly been conducted using subjective ratings on category scales or the judgement of trained or untrained sensory panelists (Nyrud et al. 2008; Berger et al. 2006; Lindberg et al. 2013). These studies on the tactile experience of wood have in part failed to address the perceptual biases because of the methodology used (Poulton 1979, 1989), aspects of the physical attributes accessible to touch(Okamoto et al. 2013; Bergmann Tiest 2010), the need for specific touch procedures to access specific kinds of sensation (Lederman and Klatzky 1987) and consideration of contextual factors that could potentially influence the psychophysical data (Lawless and Heymann 1999). Therefore, implementing a multidisciplinary approach could certainly be justified in addressing the abovementioned shortcomings and in accessing the human sensory (tactile) experiences of touching wood.

2.3 Discriminative (sensory) and emotional touch perception

Discriminative touch refers to the topographical sensing of object properties through cutaneous mechanoreceptors (Olausson et al. 2010; McGlone et al. 2007, 2014; Gordon et al. 2013; McGlone and Reillly 2010). The discriminative (sometimes referred as sensory touch) aspects of material touch – rough-smooth, soft-hard, moist-dry and slippery-sticky – have been widely investigated (Yoshida 1968; Lyne et al. 1984; Hollins et al. 1993, 2000; Picard et al. 2003, 2004; Shirado and Maeno 2005; Bergmann Tiest and Kappers 2006). The dimension of roughness emerges quite strongly when people evaluate surface texture (Hollins et al. 1993, 2000; Shirado and Maeno 2005; Bergmann Tiest and Kappers 2006, 2007; Guest et al. 2011). Recent studies have shown that the sensory (discriminative) and affective aspects of touch go hand-in-hand in object touch as with social-touch situations (McGlone et al. 2007, 2012, 2014; Löken et al. 2011). Affective touch refers to the emotional aspect of material-touch in which a certain neural pathway is activated and which, in turn, activates the part of the brain that is responsible for the emotion (Vallbo et al. 1993, 1999; Mountcastle 2005).

While the affective aspect of touching material surfaces is a relatively new research topic, there remains ambiguity in the use of a touch lexicon to assess touch quality, and there is often confusion with the terms (words) such as “evaluative”, “emotional” and “preferences”. Guest et al. (2011) made it clear that “evaluating” an object using the touch mode refers to making judgement about the perception of discriminative properties, whereas “preference” is a hedonic term simply informing whether the properties of an object are liked or disliked. In addition, limited terminology has been used for affective touch measurement, such as pleasantness, comfort etc. (McGlone et al 2007). The cultural and linguistic issues are also associated with the affective aspect of touch because various languages and cultures differ with regards to the expressiveness of the emotion (Van Nes et al. 2010). Similarly, no two languages have parallel words that can express the same emotion in exactly same way (Fussel et al. 2002; de Gelder and ‘tVeld 2016). An intensive study was conducted by Guest and his colleagues in 2011, where they identified a number of affective (and discriminative) attributes in English (Known as Touch Perception Task, TPT, descriptors) and tested these using various types of materials with native English speakers (Guest et al. 2011). Later, this study was extended by Ackerley et al (2014a) in the Swedish language. An application of the aforementioned perceptual/linguistic knowledge in the field of wood science, using native Finnish participants, could be promising to explore the linguistic variation, if exist, in expressing the affective aspect of touching materials.

2.4 Thermal perception

Besides the abovementioned tactile dimensions, another immensely important tactile dimension is thermal perception: the cold-warm dimension. The biological bases of cold and warm sensations are found to be somewhat distinct in their neural origins and pathways in the human body (Scheper and Ringkamp, 2009; Vriens et al. 2014). Human skin temperature normally lies between 30 and 36 °C, and the surface temperature of an object above or below this temperature range gives rise to the sensation of warmth or cold respectively. An object maintained at normal room temperature (20-24 °C), therefore always feels colder to touch. In the field of material science, thermal sensibility is widely investigated and has applications in robotics, haptic simulation (Ino et al. 1993; Ho and Jones 2004, 2006; Yang et al. 2006), object discrimination/recognition (Dyck et al. 1974; Jones and Berris 2003; Ho and Jones 2008; Bergmann Tiest and Kappers 2009: Ho 2018), and subjective experiences of the thermal environment (Schlader et al. 2009, 2010, 2011, 2013, 2015). The thermodynamic basis of the cold/warm sensation can be explained in terms of the one-dimensional heat transfer phenomenon between two semi-conductive materials (i.e., human skin and object surface), where an object's thermophysical properties (such as its thermal conductivity, heat capacity) are the driving factors behind the heat exchange process between an object and the skin when the two surfaces come into contact (Ho 2018). Therefore, human thermal sensitivity across material surfaces varies to a great extent (Dyck et al. 1974; Ino et al. 1993; Jones and Berris 2003). Regarding the sensory discrimination/differentiation of the surface temperatures of materials at room temperature, various factors are found to influence the results, such as the mode of touch (Lederman and Klatzky 1987), touch duration (Bergmann Tiest 2010), the temperatures of the surfaces of the object and the skin, differences between the thermal properties of the objects (Ino et al 1993), the influence of other sensory modalities (Wright 1962; Wright and Rainwater 1962; Hollins et al. 1993) and the cognitive aspects of experimenter/respondent. Various methodological approaches are available in the field of psychophysics to address challenges in the objective measurement of thermal perception (Gescheider 2015).

2.5 Thermal perception of wood

In the wood field, studies about thermal perception are limited and focused on material discrimination based on thermal cues, comparing thermal data with other modality data (Obata 2002, 2005, 2016; Fujisaki et al. 2015), and linking thermal perception with subjective preferences (Obata 2002; Strobel et al. 2017). Although, the majority of the research has assessed thermal perception with intuitive methods, such as the judgement of coldness or warmth with trained or untrained sensory panelists (Obata et al. 2002). As mentioned earlier, wood materials are highly heterogeneous in nature. The thermal properties of wood vary across tree species (Glass and Zelinka 2010). The geographical distribution and climatic variation (Goss and Miller 1992; Forest Product Laboratory 2010) may indirectly influence the wood properties (and in turn the thermal properties). Certain wood-specific properties such as density, grain direction, the presence or absence of checks and knots, and equilibrium moisture content make it more complex in thermal sensory testing because of their effects on the thermal behavior of wood (Pelit et al 2015; 2017).

Relationship derived between the magnitude of physical-thermal property of a material and its perceived intensity is assumed to follow Fechner's law, which says that the strength of sensation becomes greater as the logarithm of physical intensity increases (Fechner 1860). In Fechner's law, the just noticeable difference, or JND, (alternatively the 'discrimination threshold') provides the unit of measurement for perceived intensity. JND refers to the minimum change in stimulus intensity that is detectable under the human sensory system. The ratio of JND to the stimulus intensity ($\Delta I/I$) is termed as Weber Fraction, and it denotes that the difference threshold increases when the original stimulus intensity is increased (Fechner 1860). The value of Weber fraction is found to be 0.02 for cooling skin when the baseline skin temperature ranges from 29 to 42 °C (Jones and Berris, 2002), meaning that subjects can perceive the 2% changes in cooling skin temperature.

Fechner's law can be applied to establish the relationship between thermal properties of materials to its perceived thermal sensation, for instance, thermal conductivity is considered as a driving factor when a group of different material surfaces are used as stimuli in the following thermal sensitivity studies (e.g., Dyck et al 1974; Jones and Berris 2002, 2003). it is possible to consider the thermal conductivity as an underlying physical property due to large variations in the values across those materials. However, such large variations (found among the group of materials) in thermal conductivity do not exist among wood species. The thermal conductivity of an object is its ability to transfer heat energy and, in wood, it varies from 0,08 – 0,30 w/mK when measured in the longitudinal direction (Glass and Zelinka 2010) and this range of physical intensity would be insufficient to explain the perceptible intensity of thermal sensation across wood materials.

The thermal effusivity of wood, on the other hand, could be a better measure of physical intensity (Obata, 2002, 2005, 2016). The thermal effusivity of an object is its ability to exchange heat with its immediate surroundings (it is human skin when touched), and mathematically is defined as the square root of the product of the material's thermal conductivity and its volumetric heat capacity. It is evident that small variations in wood-specific properties could lead to wide variations in the thermal effusivity of wood. Therefore, it could be easier to explain the thermal perception of wood materials when thermal effusivity is considered as the thermal characteristic.

2.6 Wood Surface coatings and wood modifications

Surface coatings, thermal modifications, and surface densifications are essential wood processing methods to improve the aesthetics, durability, and strength (Hayoz et al. 2003). The types of surface coatings such as water-based or other solvent-based, depend on the tree species and end-use of the wood-products;

i.e., interior or exterior (Nejad and Cooper 2017). Coatings are, generally, made of four components: resign or binders, pigments, solvents and additives. Coatings of wood surfaces are usually performed when it reaches its average equilibrium moisture content level (i.e. 12-15% MC). The standard procedure for surface coatings is layer-by-layer deposition of coating chemicals over the wood surface, either manually with the brush or using a machine (Nejad and Cooper, 2017). Whether a coating forms the layer over the wood surface (film-forming such as varnish, wax) or it penetrates into the wood (non-film-forming such as oil), depends on the types of components (abovementioned four components) mixed during the preparation of coating (Williams et al. 1996; Nejad and Cooper 2017). To my knowledge, there are no studies on how these coatings affect the thermal properties of wood but it appears unlikely that they do so. Although a layer over the surface could affect the heat transfer between the wood surface and human skin upon touch.

Thermal modification, on the other hand, can change the thermal and physical properties of wood (Esteve and Perera 2009; Pelit et al. 2017). In thermal modification, wood is heated up to 200°C in an oxygen-free environment for a few hours (3-7 hrs.) using either steam or hot oil as a medium for continuous heat transfer (Rautkari et al. 2013). A significant decrease in thermal conductivity and moisture content has been reported (Pelit et al. 2015), where the decreases are higher with higher treatment temperatures. Changes in specific heat, density, and extractives have also been reported in some studies (Pelit et al. 2015; Zhang et al. 2012). Due to these findings, a significant change in thermal effusivity of wood after thermal modification is undeniable.

In surface densification, wood surfaces are heated and compressed in a mechanical press, and the degree of compression depends on the types of wood and desired utility value (Rautkari et al. 2010). Higher compression is achieved with softwood with higher temperatures and moisture content (Rautkari et al. 2010). It has been shown that the change in the physical properties of surface-densified wood correlates with the degree of compression. The mechanical changes include an increase in density, decrease in moisture content and reduced capability of water uptake when exposed to a humid environment (Rautkari et al. 2013). Of course, these changes depend also on the process parameters (press temperature, closing time, holding time, moisture content, and compression ratio) (Rautkari et al. 2011). Therefore, significant changes in thermal properties of wood after surface densification could affect the perceptible change in the tactile warmth of wood surfaces.

2.7 Measurement of tactile warmth using wood as stimulus

The underlying factor behind thermal touch sensation is the heat exchange process between the two contacting surfaces (i.e., the skin and the wood surface); therefore, it is of utmost importance when designing a thermal touch experiment that the thermal sensation measured should only reflect the governing material properties behind the heat transfer phenomenon that occurs between the contact surfaces. The perceived thermal behaviour of building materials is generally referred to as their tactile warmth quality (Ashby and Johnson 2002). For a broader group of material, including wood, the psychophysical dimension of warmness (cold/warm) is found to be one of the fundamental dimensions in tactile perception (Okamoto et al. 2013, 2016). This has been proved by using various analytical methods, such as Factor Analysis (Tanaka et al. 2006), and multidimension scaling (Hollins et al. 2000; Shirado and Maeno, 2005). The perceptual mechanism regarding the cold and warm perception of the materials is discussed in previous **section 2.4**, and it is evident that the degree of coldness and warmness is proportional to the amount and direction of heat flow between contact surfaces (i.e. the skin and material surface). The ambient temperature condition determines the temperature of the material and hand temperature normally remain close (31 – 35 °C) to the core body temperature (i.e., 37 °C) at normal room temperature.

Therefore, when a wooden surface, kept at normal room temperature, is touched with bare hand it always feels colder because wood surface extracts the heat away from skin. Therefore, the tactile warmth of building materials, including wood, at normal room temperature reflects its ability to evoke the cold sensation to the human skin from its surfaces. This explanation is used to assess the tactile warmth quality of wood and non-wood surfaces in the studies leading to publications II and III.

2.8 Quantification of temperature sensation

The point of subjective equality (PSE) and the discrimination threshold (DT) for thermal sensation have been widely studied in the field of psychophysics to measure human sensitivity (Jamal et al. 1985; Stevens, 1991; Dyck et al 1974; Hagander et al. 2000; Vallbo et al. 1993, 1999) as well as to detect any sensory loss (for example due to ageing (Stevens and Choo 1998) or abnormalities in human thermal sensitivity that originate from neurological disorders (Backonja et al. 2014)). The PSE in temperature sensation refers to the perception of two different surfaces being equally cold or warm, whereas, the DT refers to the smallest difference between two temperatures (of the material surfaces) that a person can detect. There are various methods available for conducting these measurements with a wide scope of reliability and validity (Jamal et al. 1985; Hagander et al, 2000; MacMillan and Creelman, 2005). The abovementioned thermal sensitivity studies were carried out by applying either a metal thermode or radiant heat or Peltier device as a heat source for thermal stimulation. Peltier devices, used extensively in thermal tests, work on the principle that "when a current flow through a circuit comprising dissimilar conductors, thermal energy is absorbed from one junction and discharged at the other, making the former cooler and the later hotter (Peltier effect). This effect is utilized to create the thermal stimulus in Peltier devices. Varieties of tailored Peltier devices have been on the use in thermal sensory testing (for review, see Bakkers et al. 2013).

On the other hand, the challenges associated with using wood and ceramic tiles as thermal stimuli in the present study are profound. There is a problem with controlling/regulating/calibrating) the stimulus intensity (i.e., how to regulate the rate of change of temperature of the stimulus if a single piece of wood or ceramic tile is used). This problem was already described by Bergmann Tiest and Kappers in 2009, where they noted that to measure the thermal thresholds of various materials, it is important to find a range of materials so that they could be placed on a scale with equal spacing between them in terms of their thermal properties, which is not possible with real materials. Therefore, they used a heat-extraction simulation technique to provide the calibration of the thermal property scale. This issue was tackled in the current study through developing a mechanism to precisely warm the wood surfaces to a predefined temperature and reported in publication III.

3. Methodology

3.1 Participants and materials

All the participants in this study were university students aged between 18 and 35 years (only native Finnish speakers were hired for the study leading to publication I) to form a homogenous age-group which limited age-related variability in tactile sensitivity (Stevens 1991, Hagander et al. 2000; Schlader et al. 2009, 2010, 2013). The number of male/female participants in the studies leading to the publications upon which this thesis is based, was equal or nearly equal. The small sample sizes are justified because of the highly controlled experimental setup employed in this work. Written consent was obtained from each participant before experimentation and the tests were conducted in accordance with the Declaration of Helsinki. All experiments were approved by the Aalto University research ethics committee and reimbursements to each participant were provided as agreed beforehand in order to provide an incentive, as this is generally required to motivate the participants (Jones and Tan 2013). Individual differences in sensory ability is widespread in humans (Stevens 1991, Green and Akirav 2007) and it is obvious that any neurological disorder could severely affect an individual's sensory ability (Hoitsma et al. 2002). Since the participants were not asked whether they had any medically diagnosed neurological disorders at the time of signing the consent form, individual data were carefully checked for any marked deviations – that might indicate some underlying medical disorder. No such incident was observed and the data from all the participants were included for further analysis.

Various Scots pine (*Pinus sylvestris* L.*)* and European oak (*Quercus robur* L.) surfaces were tested in experiments on the sensory and emotional aspects of touch in publication I. Wood surfaces can vary considerably and it is important to control any extraneous variability in the experimental design to achieve greater consistency in the responses of participants. Similar surface appearances were obtained by glueing three pieces of wood together and then machine sanding before the application of various surface treatments (**Figure 1**). All the test samples had equal dimensions (20 cm long × 20 cm wide × 1.7 cm thick). Four specimens from each wood species were produced by first manually sanding with 240 grit sandpaper, manually brushing with a metal-brush over the surface, coating with varnish, and then coating with wax. Varnishing was performed by manual coating the test-surfaces with double layers and a piece of cotton was used to coat the double layers of wax. The first, two applications were performed to create topographical variations on test-surfaces and the last two applications (i.e. varnishing and coating) were produced to see the effect of surface coatings on sensory and emotional touch. Since it is not possible to create a very rough or very smooth wood surface, 240 grit sandpaper and silk cloth were used as reference surfaces representing abovementioned surface qualities.

Figure 1. *Test specimens used in the sensory and emotional touch perception study. Left figure: Top row – pine surfaces (from left: sanded, brushed, varnished and waxed). Second row – oak surfaces (from left: sanded, brushed, varnished and waxed). Last row – from left: A4-size paper, 240 grit sandpaper and, silk cloth. Right figure: test setup side view.*

In publication II, twelve varieties of wood surfaces were created from four wood species: pine (*Pinus sylvestris L.*), birch (*Betula pubescens Ehrh.*), oak (*Quercus robur L.*), and larch (*Larix sibirica Ledeb.*), to test the tactile cold sensation at normal room temperature. All surfaces were of equal dimensions (10 cm long × 10 cm wide × 1.5 cm thick) and the surfaces were of similar visual appearance (**Figure 2)**. The thickness of the test sample was controlled as it could influence the cold/warm sensitivity (Bergmann Tiest 2010). Before the application of the coating or modification, the surface topography of the samples was controlled by applying the same sanding procedures using the same

Figure 2. *Test specimens used in the experiment to test the tactile warmth of wood surfaces.*

grading sandpaper as described in the previous section. The presence of sapwood and heartwood in the test-surfaces were also controlled by selecting the test samples having a similar amount of sapwood and heartwood. All surfaces were free from checks and knots. Oil treated surfaces were prepared by applying a double-layered coating with cloth and varnish coating was done with double-layered brushing over the surface. Thermal modifications of samples were carried out according to the method described by Rautkari et al. (2011) and comprised a single-phase treatment method at 180 °C for four hours in a saturated steam environment. Surface densification was achieved through an open mechanical compression system at 150 °C for 30 minutes (Rautkari et al. 2013). The 15 mm-thick test samples were compressed to 10 mm. Material related odour was controlled, by storing them under ambient room condition for about one month, to minimize its effect on thermal touch sensation, since inter-modality interaction/integration of sensory cues in the tactile perception of material surfaces is common (Fujisaki et al. 2015).

For publication III, ceramic tiles (*product ID: LC68, Trendgrey PEI 2 R9 harmaa. Shop:RTV-Yhtyma OY, Helsinki)*, scot pine (*Pinus sylvestris L.*), and European oak (*Quercus robur L.*) wood samples were prepared (**Figure 3**), all having equal dimensions (9.8 cm long × 9.3 cm wide × 6 mm thick). For the wood specimens, surface topography was controlled to make test-surfaces visually homogeneous by manually abrading the test-surfaces with 240 grit sandpaper. It was confirmed during pilot testing that all the test specimens, including ceramic tiles, were indistinguishable when subjects explored them in a static touch mode whilst blindfolded. For the ceramic tile surfaces, no such control was applied to retain the factory-made surface glaze, as any surface abrading could affect the heat transfer process between the skin and the tile surface.

Figure 3. *Test specimens used in the thermal touch quantification test. Left: pine surface, Middle: oak surface and right: ceramic tile surface. (Bhatta et al. 2019. Used under a Creative Commons CC-BY License.)*

3.2 Measurement of sensory and emotional touch

3.2.1 Tools: Touch questionnaire

A part of the emotional touch questionnaire (TPT descriptors) from Guest's study (2011) was adopted to measure the emotional touch of wood in publication I. The TPT-emotional descriptors were translated into the Finnish language using 3-backward and 3-forward translations. Language and culture influence how you express emotion (Fussel 2002; Van Nes et al. 2010) and this could be the reason why some of the English attributes were translated into a single Finnish word. Such as "enjoyable and pleasurable" were translated as "nautittava", "calming and soothing" were translated as "rauhoittava", and "exciting and thrilling" were translated as "jännittävä". Some emotional descriptors, such as sexy, arousing, and sensual were not seen as relevant to the perception of wood ("not attributable to wood surfaces") and, thus their Finnish counterparts (i.e., seksikäs, kiihottava, and aistikas respectively) were removed from the list. Out of 14 emotional attributes, only eight Finnish emotional attributes were used to assess the emotional touch of wood (**Table 2**).

Table 2. Results from the English-Finnish translation of emotional descriptors

<u>*Instructions*</u>

- *Emphasize conceptual rather than the literal meaning of word*
- *Consider the meaning that is used in the emotional expression during the informal conversation in daily life situation.*
- *Consider the meaning that is commonly used while a person is in an emotionally aroused situation*
- *Avoid meanings that may offend the young female student*
- *Consider the meaning into a single word*

ENGLISH words	**EXACT meaning in Finnish (if there)**	**similar words in Finnish (if any)**	**Selected word**
Irritating	Ärsyttävä (3)	Harmistuttava (1)	Ärsyttävä
Comfor-table	Mukava (1) Miellyttävä (2)	Miellyttävä (1); Mukava (1)	Miellyttävä
Discomfort	Epämukava (2) Epämukavuus (1)	Epämukavuus (1)	Epämukava
Relaxing	Rentouttava (3)	Rento (1)	Rentouttava
Calming	Rauhoittava (3)	Rentouttava (1) Viilentävä (1)	Rauhoittava
Soothing	Rauhoittava (2)		Rauhoittava

	Hoitava (1)		
Exciting	Jännittävä (3)	Innostava (2)	Jännittävä
Arousing	Kiihottava (2) Nouseva (1)	Herväävä (1)	Kiihottava
Thrilling	Jännittävä (3)	Kiehtova (1)	Jännittävä
Sensual	Aistikas (2) Sensuelli (2) *	Aistillinen (1)	Aistikas
Sexy	Seksikäs (3)		Seksikäs
Pleasurable	Viihdyttävä (1) Nautittava (1) Miellyttävä (1)		Nautittava
Desirable	Haluttava (2) Toivottava (1)		toivottava
Enjoyable	Nautittava (3)	Miellyttävä (1)	Nautittava

** One person suggested two "exact meanings of the English word"*
Numbers inside the brackets represent no. of times suggested

3.2.2 Experimental Design and procedure

A custom-built experimental setup was used for experimentation in publication I (**Figure 1**) so that participants could access the stimulus surface in a touch-only mode. Touching the stimuli was performed without vision, applying a uniform pressure with lateral exploration of the surfaces (Lederman and Klatzky 1987) with four fingertips from the dominant hand. The test set-up was designed in such a way that participants did the task in a quiet environment. Verbal communication between the participant and experimenter was minimized by using an audio signal that indicated to the participants when to make contact with the surface and when to provide the response. Sensory fatigue or tiredness is one of the sources of bias in psychophysical experimentation, where subjects no longer perceive the upcoming stimulus and, therefore, respond to the stimulus based on prior experiences or the response could be merely a guess. A typical example is "perceptual adaptation" (Cliff and Green 1994). To avoid this, breaks were provided during experimentation. Another source of disturbance in the measurement of tactile perception could come from auditory modality (e.g., Brisciani et al. 2005).

Auditory disturbances were controlled by using noise-cancelling headphones. Olfactory disturbances, that may arise either from the wood or from the coating chemicals (Bulian and Graystone 2009), were controlled by allowing volatile compounds to evaporate from the stimuli for a period of up to three months in the workshop before the experimentation. The pressure exerted by finger/palm skin when touching the test surface can alter the sensation (Bergmann Tiest 2010), therefore, this was controlled by asking the participants to practice exerting a light and uniform touch-pressure over test surfaces, prior to the experiments. There was sufficient practice in each experiment before the actual data collection began. In publication I, a lateral hand movement over the surface was adopted to touch the stimulus surface: participants had to move their fingertips 8 cm three times without lifting them (**Figure 4**). In publication I, participants were asked to evaluate one stimulus at a time with only eleven descriptors.

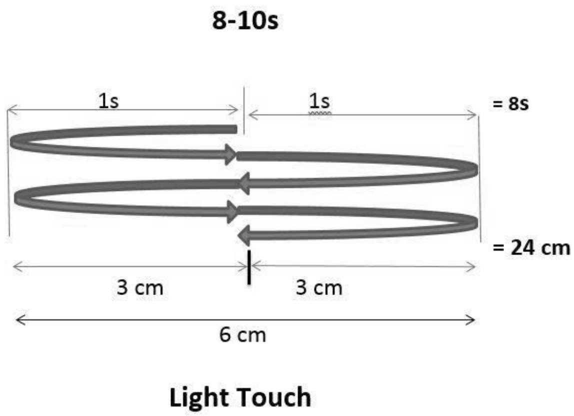


Figure 4: *Hand-movement instruction used during the experimentation of sensory and emotional touch perception.*

Instructions contained in the questionnaire and other related texts were also translated into Finnish. There was complete randomization of attributes in the questionnaire and the test samples were presented at random. Randomization of the position of the test surfaces could help eliminate the left-right response bias from the binary choices in psychophysical tests (Poulton 1989; Gescheider 2015). In addition, serial position effects (Poulton 1989) could come into play in the Touch questionnaire, because participants can better memorize the first few and last descriptors and this could affect the subsequent trial responses. Randomizing the placement of attributes in the list could help eliminate this effect.

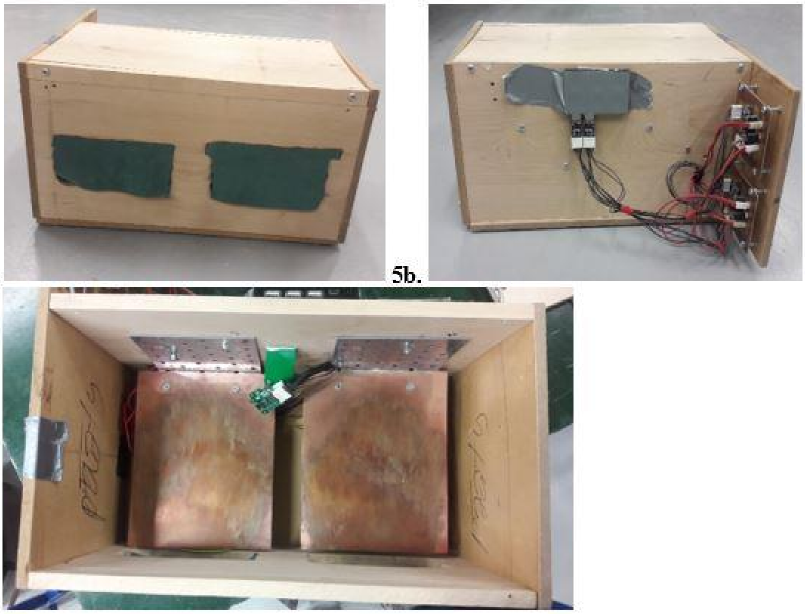
3.3 Measurement of tactile warmth

As mentioned earlier, the tactile warmth of building materials, including wood, at normal room temperature reflects its ability to evoke the cold sensation to the human skin from its surfaces. During measurement of tactile warmth of wood surfaces (publication II), the effects on cold sensation from sources other than the inherent thermal properties were controlled. These sources included, for example, surface geometry, texture, the visual properties of the surface and surface topography (these might be called stimulus noise), as well as psychological variables such as attention and spatial context. Simultaneous presentation of the test surfaces in a simple binary choice procedure was adopted due to its simplicity and having some methodological benefits over the sequential presentation of stimuli in the paired comparison experiment (Jogan and Stalker 2014). Test surfaces were presented as a pair to the participants, who were then asked them to detect the colder surface. This kind of simultaneous stimulus presentation with the controlled experimental conditions and with a number of repeated trials, should lead to reliable results.

The Thurstonian paired comparison scaling method, based on Weber's law of comparative judgement (Thurstone 1927), was applied to the data collection and analysis in the publication II. This method is simply a binary choice, where a respondent chooses one surface from the two that she/he feels higher for a given criterion (e.g. surface coldness). T is the number of test specimens provide "T (T-1)/2" number of total pairs, where each respondent has to provide the responses for all possible pairs. The total number of preferred responses an item or test specimen receives in the group can result in the relative rank position for that item in the group. A psychological continuum was calculated based on the preference scores for each item in the group. A psychological continuum can be calculated either for an individual or for a whole group of respondents (see for example, Brown and Peterson 2009).

3.3.1 Design of Heater

Controlling the initial temperature of the contact surfaces is crucial for measuring the differential thermal sensation. For this purpose, a heater or a hand-skin temperature stabilizer (**Figure 5**) was designed to keep the hand skin temperature at the desired level (i.e., 33 °C) and it was also borne in mind, during the design phase that the heater should be ergonomically fitted to the experimental setup. A controlled heating system, to heat a metal plate inside the wooden box, was developed (similar to the heating system used in thermal boxes, which is described later in **section 3.4.1** and the metal plate was wrapped with a copper sheet. A thermal sensor was attached to the copper plate that worked as a feedback loop for the control (Arduino software) program. It had an accuracy of ± 0.5 °C. The purpose of the copper sheet was to provide a uniform surface. The heater has two openings where participants can insert both hands easily, in each opening, during experimentation. Curtains were installed in the opening to avoid heat loss and to block the touch-area (of the copper plate) from the participant's view. The heater was used in publications II and III.



5a. 5b. 5c.

Figure 5. The heater **5a.** Front view **5b.** Back view **5c.** *Top view with cover removed.*

3.3.2 Experimental setup and Procedure

In publication II, the test setup used in the publication I was slightly modified (**Figure 6**) so that the respondent can touch two surfaces simultaneously and the heater was mounted just below the moving surface. Two openings were made so that each hand could be inserted to touch a pair of specimens simultaneously. Due to many specimen-pairs, three moving surfaces (each could accommodate 5-6 pairs of tests specimens) were used in the experiment. 12 variety of untreated/treated surfaces from pine, larch, birch and oak trees were prepared and divided into five group. The group consisted of: 1. Untreated group (pine, oak, larch, birch), 2. Mixed pine group (untreated, oiled, varnished, thermally modified, surface densified), 3. Mixed oak group (untreated, oiled, varnished), 4. Coated group (oiled and varnished pine, oiled and varnished oak), and 5. Mixed group (untreated, thermally modified surface densified surface from both pine and birch). These five group yield 33 pairs of test specimens.

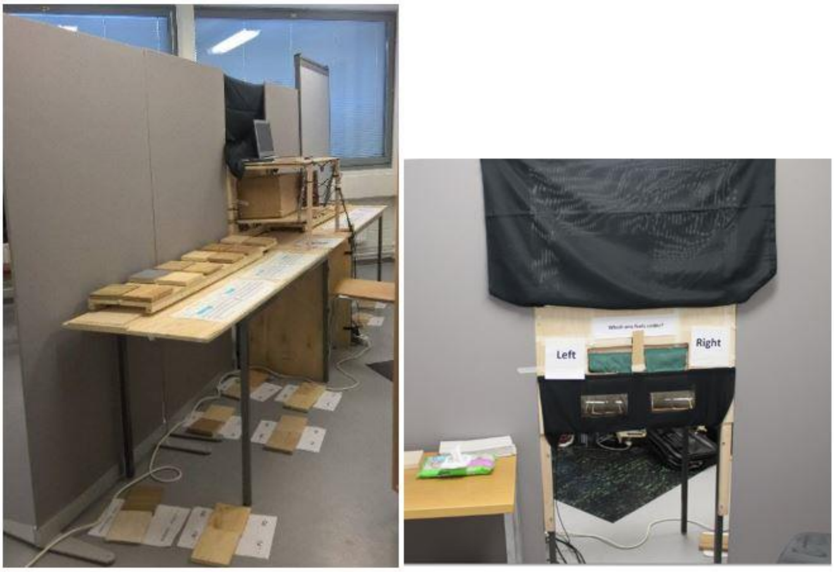


Figure 6. *Test setup used during the measurement of tactile warmth of wood surfaces. Left – Experimenters' side view showing the movable surfaces and test specimen. Right – participants' side view.*

The experiment was conducted in two sessions and seventeen participants took part in both sessions. During a trial, the participant was asked to warm up their hands inside the heater for 15 seconds and, then touch the specimen-pair simultaneously using four fingers of the hand for 5 seconds. At the end of the trial, participants had to say which side of the surface felt colder. Responses were paper-pencil recorded and each participant performed 198 trials (33 × 6 repetations). It took 50 minutes (20 minutes for practicing and 30 minutes for completing the task) to complete the first session for a participant and 42 minutes (6 minutes for practicing and 36 minutes for completing the task) to complete the second session. The whole procedure was guided by audio signals and short breaks were provided after completion of 36 trials. The experiment was conducted at a room temperature of 22 °C.

3.4 Quantification of thermal sensation

To quantify thermal sensation, eighteen thermal boxes (**Figure 7**) were constructed, so that the same number of wood surfaces could be simultaneously warmed-up to the desired level. Before that, an algorithm was developed for the precise heating of non-metal surfaces. Designing of the boxes and heating arrangements are elaborated later in **section 3.4.1**. These thermal boxes were arranged during the set up so that they all lay within the range of both hands of the participants and were easily accessible during the experimentation. This kind of arrangement demands various levels of insulation for each box to overcome challenges with overheating of the sample and the time required for the boxes to return to the pre-defined temperature state after the surface touch.

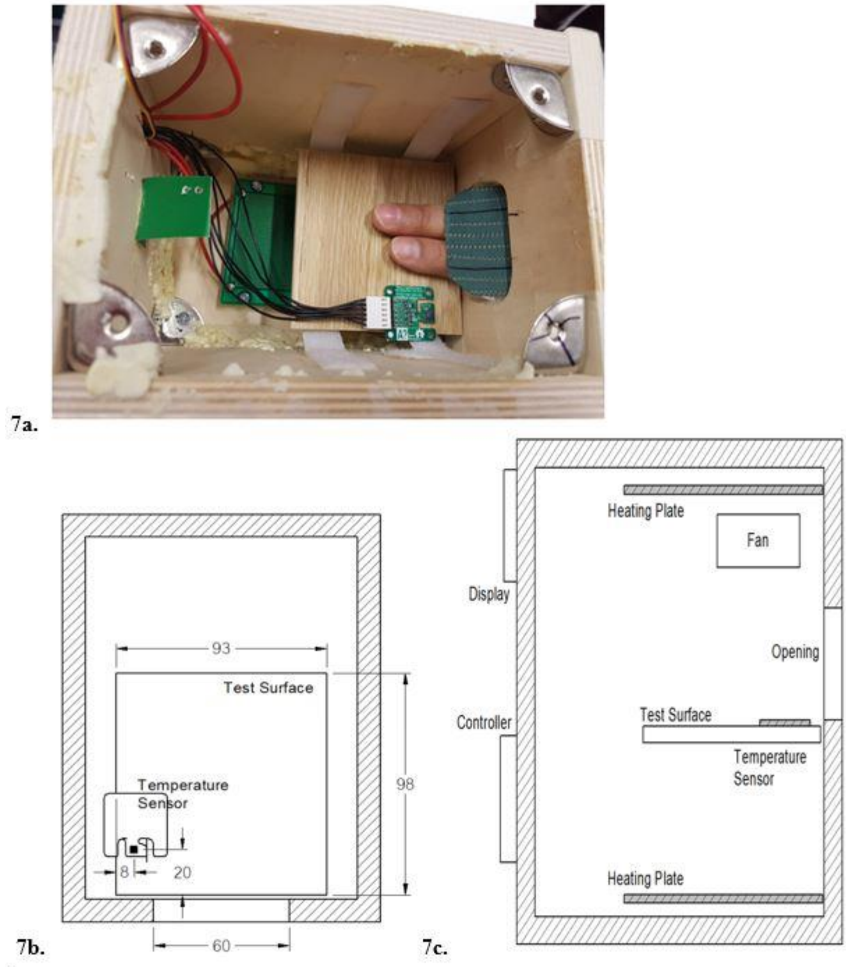


Figure 7. **7a**. *The test box with the cover removed* **7b**. *Schematic diagram of the box. The measurement unit is millimeter (mm)* **7c**. *Cross-sectional diagram of test box. (Bhatta et al. 2019. Used under a Creative commons CC-BY License.)*

There was 0.4 °C increment of the surface temperature after 3-4s when it was touched during the pre-test. The fully insulated boxes took too long time to return to the pre-defined temperature; this was, mainly due to the inner boxes in the setup (**Figure 8**). Therefore, the inner boxes were less well insulated than the outer boxes. An efficient test procedure was developed and validated in pre-tests with 10 participants. Pine surfaces were always heated to 20 °C and the oak and ceramic tile surfaces were heated to a range of temperatures, and the range included the upper and lower thresholds for discrimination (**Figure 8a**).

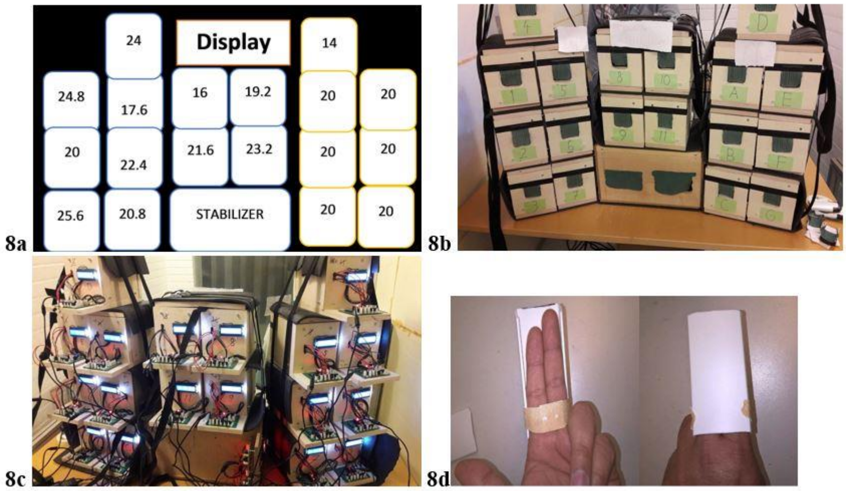


Figure 8. *Test setup for thermal touch quantification.* **8a**. *Temperature distribution of test surfaces in the pine-tile test,* **8b**. *Participants' view of the test setup,* **8c**. *Experimenters' view of the test setup,* **8d**. *Finger guard.*

3.4.1 Design of thermal boxes

For publication III, a unit wooden test box having the dimensions: 18 cm × 15 cm× 20 cm, was designed that allowed regulation and control of the test surface temperature (**Figure** 7). A test surface was fixed 3 cm above the heating-plate and another heating-plate was situated 5 cm above the test-surface. There was a 10 mm gap between the test sample and the wooden wall of the box to allow air circulation.

Heating of the stimulus surface was achieved through an optimal state estimator controller based on the actual temperature measurement and a physical model of the system. An Arduino Pro Mini 3V3 microcontroller board installed in each box ran the control program which controls the heating to two heating elements (**Figure 7c**). The stimulus surface achieved the desired temperature by absorbing the heat from the surrounding air inside the box. A custom-built TSY01 temperature sensor was used to measure the actual temperature of the stimulus surface. This sensor was attached to the test surface 1-2 cm near the touch area (**Figure 7a**). The control program assists in setting the target temperature of the test surface (i.e. control program operates on the basis of feedback received from the sensor attached on stimulus surface), which was connected to the digital display (**Figure 8c**). One fan was attached below the upper heating plate to aid air circulation. There was a 4 × 6 cm opening in the front side where the participant was able to insert two fingers to touch the test surfaces during experimentation. A curtain was placed in the front opening to block the vision and to control the airflow. The skin of the test fingers was covered with finger guards to avoid air blowing directly on the back of the finger (**Figure 8d**).

3.4.2 Experimental setup and procedure

In publication III, a test set up was developed in such a way that allowed the subjects to touch two test surfaces at a time with a minimum of physical effort. Any deviations in the test surface temperature after touching by the participant was closely evaluated. The testing procedure was developed so that an earlier trial would not interfere with the later trials. Separate pre-tests were conducted to find the temperature range for test surfaces to make sure that the differential threshold for cold sensation should lie within the tested range. The temperature range of 16 to 24 °C was found for pine/oak comparison test, and it was 17.6 to 25.6 °C for pine/ceramic tile comparison test. In both tests, all the boxes (placed right-side in the setup) containing pine surfaces were heated to 20 °C. The boxes containing oak were warmed to 16, 16.8, 17.6, 18.4, 19.2, 20, 20.8, 21.6, 22.4, 23.2, and 24 °C. Similarly, ceramic tile surfaces were heat to 17.6, 18.4, 19.2, 20, 20.8, 21.6, 22.4, 23.2, 24, 24.8 and 25.6 °C. The arrangement of the boxes and their temperatures in pine/tile comparision test is shown in **Figure 8a**.

An auditory signal was used to guide the stimulus touch, hand warming and the resting phase, as this reduced the need for any verbal communication during experimentation. A computer display, mounted in front of the participant's seat, was used to guide the trials. A complete randomization of trials was performed to minimize any temporal order effects. An efficient test procedure was developed where participants felt relaxed and performed the test in less than one hour with many resting phases to avoid fatigue. Eight repetitions (96 trials for each data points) yielded enough data to calculate the point of subjective equality (PSE) and the discrimination threshold (or just noticeable difference, JND) in the psychometric analysis. Each session (i.e. a session of 12 trials) was started with the boxes "4" and "D" (topmost boxes in the **Figure 8a**), where the stimulus inside box no "4" was always warmed to 24 °C and the stimulus inside box

“D” was always warmed to 14 °C (room temperature was 13 °C). This trial was for the thermal stimulation and if a participant failed to notice the difference correctly in these two boxes, he/she would be disqualified from further tests. No one was excluded from the experiment on this basis.

3.5 Data analysis

In publication I, participants had the opportunity to rate one stimulus for four times, and then these ratings were averaged for further analysis. Data from reference samples were separated and only a descriptive analysis was carried out. For the rest of the data (i.e., data from wood surfaces), multivariate analysis of variance (MANOVA) was utilized to explore any effects of following two conditions (i.e. wood type and surface treatment) on the sensory and affective touch evaluation of wooden surfaces. The wood type condition had two levels: pine and oak, and surface treatment condition had four levels: sanded, brushed, varnished and waxed.

To find the relative rank of the wood specimen based on its tactile warmth, the Thurstonian scaling technique was used in Publication II to convert the participant’s binary choices into ordinal values, which were further converted into a psychophysical scale (e.g., Brown and Peterson 2009). First, the proportion of responses received by each surface as colder (in the pair) was calculated, and each score received by the stimulus represent the ordinal position of that stimulus in the preference scale for tactile coolness. Second, these proportions were reversed to get the preference scale for tactile warmth (= 1 – score received on preference scale for perceived coolness). Expressing the results in terms of the tactile warmth quality, instead of perceived coolness, has the benefit of reflecting the aim of the thesis. The responses were checked for consistency in a “raw score matrix” (e.g., Brown and Peterson 2009). It was not possible to directly measure the consistency in response choices in the Thurstonian model (Brown and Peterson 2009: Brown 2016), but it could be easily observed in the raw data (for example, early-trial choices vs late-trial choices). In other words, most inconsistencies in choices were observed in those pairs where surfaces are similar in physical intensity. The lack of precision in binary choices in such cases is characterized by the law of comparative judgement which does not necessarily indicate a lack of reliability. Instead, the choice reflects stochastic (random) processes and transitivity (subject’s choice shift from one surface to the other) should be viewed as a stochastic concept (Brown and Peterson 2009).

In publication III, to find the psychometric parameters (i.e. the point of subjective equality and differential threshold) of thermal sensation between pine and oak (and ceramic tile), 2-alternative forced-choice (2-AFC) method was applied. The thermal intensity of the oak surface was calibrated from 16 to 24 °C with the step of 0.8 °C, which gave 11 data points for the comparison. Similarly, it was calibrated from 17.6 to 25.6 °C for the ceramic tile with the same step difference. A Gaussian function was fitted to the cumulative data using minimized squared errors to find the best model fit. The point of subjective equality lies where 50% of responses indicated in the response distribution. The lower and upper differential threshold lies at 25% and 75% of responses in the distribution, respectively.

4. Results and Discussion

4.1 Methodological findings

Results from the Finnish-translated TPT emotional descriptors suggest the existence of cultural differences in expression of emotional touch perception. As mentioned in the earlier section, the English language TPP questionnaire was originally developed with the aim of discovering a touch lexicon for the sensory and emotional perception of an object's surface and relate this to the underlying neural mechanisms and perceptual processes (Guest et al. 2011; Ackerley et al. 2014a). In the present study, the TPT was translated into the Finnish language and successfully tested with wood surfaces using native Finnish participants. After translation from English to Finnish (**Table 1**), some of the positive emotional descriptors in the English language were found to have similar meanings in the Finnish language, for instance, "soothing" and "calming" were translated as "Rauhoittava". Similarly, a few descriptors were found to be inappropriate for the evaluation of wood surfaces (such as "sexy" or "sensual") and were discarded from the questionnaire (**Table 2**). Hence few positive emotional descriptors (than in the original TPT lists) would be sufficient to express the touch quality of wood surfaces among Finnish participants.

Results from the reference samples (sandpaper and silk cloth) were comparable to previous studies (Guest et al. 2011; Ackerley et al. 2014a) which also validated the use of Finnish-translated TPT descriptors in the present study. These reference samples were also tested in the original TPP study (Guest et al. 2011) and some other follow-up studies (e.g., Ackerley et al. 2014a). In the present study, it was shown that the low score in roughness and a high score in smoothness was found in the evaluation of the silk surface using active fingertip-touch exploration. Additionally, silk was perceived to be higher in all positive emotional attributes and lower in all negative emotional attributes in the present study (**Figure 9**), which was also a finding in Guest's study (Guest 2011). In previous studies (Ackerley et al. 2014a, Verrillo et al. 1998, 1999) sandpaper has been perceived as high on roughness dimension and lower in pleasantness and associated perceptions, which is also true in the present study. Ackerley and her colleagues (2014a) had used the Swedish version of the TPT questionnaire for sensory and emotional touch perception with sandpaper, a piece of artificial fur and an artist's brush. Therefore, publication I also represents an extension of the study of the TPT questionnaire to a new culture and language, as well as its application in a new field: wood perception.

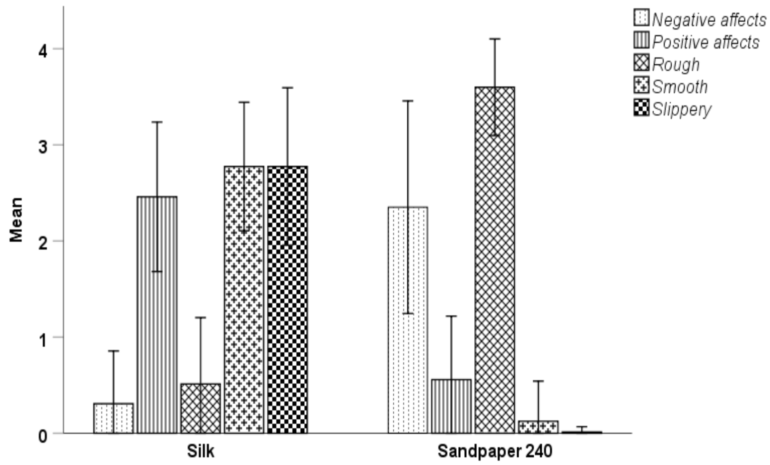


Figure 9. *Sensory and emotional perception of Silk cloth and sandpaper.*

The Thurstonain paired comparison method, applied in publication II, based on the law of comparative judgement (Thurstone 1927) could be useful when comparing a range of material surfaces based on thermal sensation. The Thurstonian paired comparison method can do well enough with a small number of participants and, compared with other psychophysical methods, many test surfaces can be accommodated at once (Brown and Peterson 2009). The procedure and analysis could easily be adopted by non-psychologists due to its simplicity, and the method provides the luxury of controlling possible bias in the measurement of perceptual phenomena. In the following section, I will explain how possible biases in binary choice setting were controlled in the present study using the Thurstonian method.

First, in the paired comparison, the carry-over effect (Rueckert et al. 2002) on the participant's responses may occur when the test surfaces are repeatedly exposed to participants, where a previous order of stimulus presentation can influence the participant's choices in the subsequent order of stimulus presentation. This effect is more likely when the experimental conditions (i.e., order of stimuli presentation) follow each other quickly. Second, the order effect: participants may warm-up or improve performance over time because of learning (Gescheider, 2015). These effects were controlled in publications I and II by randomizing the pairs during exposure (stimuli presentation), and by systematically varying the position of a stimulus (i.e., on the left side or on the right side) within the pair so that each stimulus is presented equally on both sides. Additionally, participants were divided into two groups in the study leading to publication II. One group started the experimentation with one order and the other followed the experimentation with the reverse order of the stimuli, which is known as "counterbalancing" (e.g., Pollatsek and Well 1995).

Third, the participants' performance may be different near the end of the session if the experiment is too long and repetitive because they were either tired or bored (fatigue effect). The fatigue effect was controlled by shortening the procedure and providing enough breaks during the experimentation. Fourth, the first position effect could occur in a paired comparison test (Gescheider, 2015): this kind of bias emerges when the same set of surfaces (i.e. test-pair) is presented at the beginning of every block of stimulus presentation (session). The first position effect, in publication II, was eliminated by starting every trial session with a different test-pair. Similarly, the blind labelling of test surfaces could help eliminate the contextual bias if a participant accidentally sees the test pair and if test surfaces are labelled by their true name (Jones and Tan, 2013). Therefore, test surfaces were labelled with either abstract names (in publication I and II) or were numbered (publication III). Although the cognitive biases that can affect the measurement of tactile perception are not limited to the abovementioned, one should be aware of other psychological and contextual factors that can affect psychophysical data, either from the experimenter's perspective or from the participant's perspective (Poulton 1979, 1989).

In the present study (publication III), the heating equipment was contrived to achieve precise, controlled warming of the materials with low thermal conductivity. Publication III sets a milestone for the quantification of temperature perception using materials with low thermal conductivity and this test protocol can easily be extended to other similar materials in the future. The test equipment and test procedure can be varied by altering the ambient temperature of the test setting (in this work it was set at 20 °C) and the nature of the stimuli (must be in solid physical-form). The immediate feedback system in the experiment provides researchers with an opportunity to control or correct the response errors during experimentation. This is important because these types of studies (psychophysical tests) take a lot of time for the test-setup development and test execution.

As stated earlier, the quantification of thermal sensitivity, such as finding the differential thresholds, is quite common and is undertaken especially in the psychophysics and medical fields for the diagnosis of small fibre neuropathy (Hagander et al. 2000). A complete experimental setup and procedure was developed in the present study, with a view to quantifying thermal sensation using non-metallic stimuli. Calibration of thermal intensity with real materials with low thermal conductivity is challenging (Bergmann Tiest and Kappers 2009), but now, with the help of these thermal boxes, calibration of thermal intensity using real materials is possible.

4.2 Wood surface textures and affective touch perception

The results from the publication I suggest that wood surfaces have the potential to evoke an emotional sensation in the glabrous skin of the fingertips and the desired affective responses could be achieved by manipulating the surface properties. The results show that uncoated surfaces with a smooth finish (sanded surfaces) can elicit a higher level of positive touch evaluation (**Figure 10**), for example, being "pleasant-to-touch", whilst a higher level of "stickiness" of a wooden surface diminishes it. Pleasantness and the associated positive feeling with the stimuli have previously been measured using tactile stimuli such as a soft brush or fur (Guest et al. 2011; Löken et al. 2011; McGlone et al. 2012; Ackerley et al. 2014b; Drewing et al. 2017). Such positive emotional attributes were also measured with hard materials as the stimuli, for instance, sandpaper or wood (Klöcker et al. 2012) but the intensity of feelings was not as high as they were with soft stimuli.

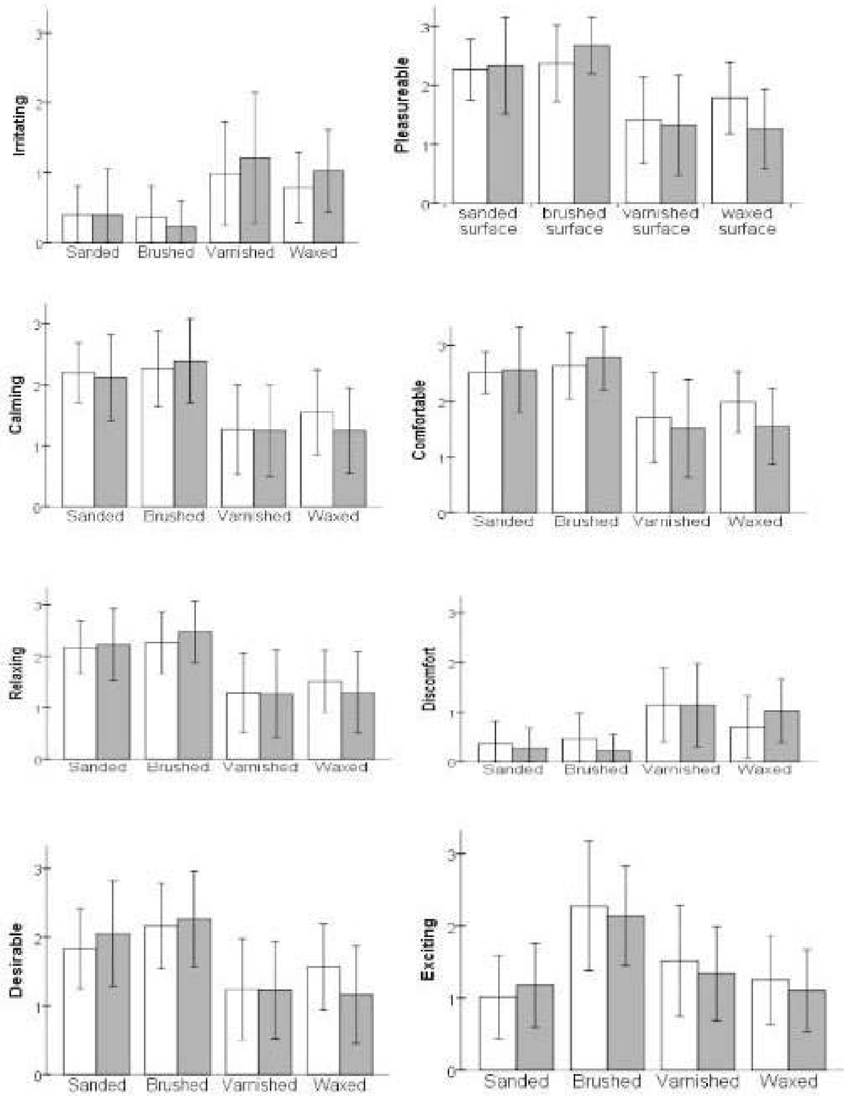


Figure 10. *The average scores of emotional descriptors. Each descriptor is displayed with the average scores for the wood type condition under four different surface treatment conditions. Error bar represents ± 1 SD. Scale 0 = "not descriptive", 4 = "very highly descriptive". White and grey bars represent pinewood and oakwood surfaces respectively. (Bhatta et al. 2017. Used under a Creative Commons CC-BY License.)*

The present study has confirmed that with wood as the tactile stimulus, pleasantness and associated feelings exist and these feelings could be enhanced by careful crafting of the surfaces. It is interesting that the coated wood surfaces were perceived to be distinct in terms of sensory attributes, but they were rated more-or-less similar in affective attributes. An increase in negative touch evaluation and a decrease in positive touch evaluation after surface coating suggests that care should be taken at the time of designing wood products. The surface coating of wood is unavoidable most of the times, however the results from publication I suggest that a negative evaluation could be mitigated by making surfaces smooth and slippery, by abrading the coated surfaces with sandpaper or by other means of surface preparation (Goli et al. 2004; Kilic et al. 2006). Unlike in previous research (Guest et al. 2011; Löken et al. 2011; McGlone et al. 2012; Ackerley et al. 2014a; Drewing et al. 2017; Klöcker et al. 2012) that showed that rougher surfaces are less pleasant to touch than smoother surfaces, the effect of roughness was not significant in the emotional evaluation in the present study. This is because of a narrow range of roughness among the wood stimuli tested in the present study. But the roughness-related results are still very important in relation to the design of wood products because the roughness range tested in the present study was similar to that found in commercial wood products.

The results showed that varnish and wax coatings can increase the smoothness and slipperiness of wood surfaces but can reduce the positive touch evaluation: a slight increase in the negative emotional touch ratings was observed after varnishing and waxing. However, these findings also hint at the possibility that the positive emotional-touch qualities of untreated surfaces could be retained after surface coating if suitable abrading procedures, or other techniques, for increasing surface smoothness or slipperiness (e.g., Goli et al. 2004) are applied.

4.3 The relationship between physical properties and tactile warmth of wood materials

Four types of tree species were tested for their tactile warmth quality in publication II. In this study, pine was found to have the highest tactile warmth and oak the lowest (**Figure 11**). Participants could readily discriminate the untreated surfaces of pine, larch, birch and oak from each other tactually. These differences in the tactile warmth across tree species are due to the perceived differences in the intensity of thermal cues felt on the surfaces. The intensity of the thermal cue depends on how fast heat is conducted between the contact surfaces (skin and wood) and, as mentioned earlier, this heat transfer process is governed by the thermal properties of the wood and skin of the finger (Obata 2016).

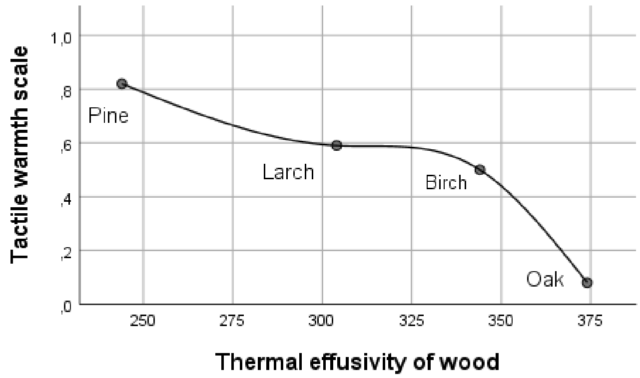


***Figure 11**. Tactile warmth and thermal effusivity of untreated wood surfaces.*

Literature-based analysis of the thermal properties of wood materials combined with data gathered from the thermal touch experiment (in publication II) shows a negative monotonic relationship between thermal effusivity and tactile warmth (**Figure 11**). It is evident that higher thermal conductivity could result in the surface being less warm to the touch since, at room temperature, heat energy is conducted away more quickly from the skin as compared to a material with lower thermal conductivity. Thermal conductivity (λ) alone cannot, however, explain variations found in the tactile warmth of wood species because of the fact that the λ can be influenced by many other wood-specific properties such as moisture content, the grain direction of the surface, the amount of extractives, the presence/absence of checks and knots (Glass and Zelinka, 2010).

In the present study, many of the possible factors, such as moisture content and surface grain orientation that could influence thermal conductivity were controlled by selecting check and knots free wood surfaces for testing, however, it was not possible to eliminate or control the influence of some other factors such as the amount of extractives due to the heterogeneity of wood. The results of the present study did agree with previous literature (Obata 2005, 2016), which claims that the thermal effusivity (e) of wood could be a better predictor of the tactile warmth of wood materials. This is because the thermal effusivity of wood surfaces is more variable than other thermal properties such as specific heat (C_p) and thermal conductivity. As mentioned earlier, thermal effusivity depends not only the thermal properties of the materials but also on the wood-specific properties.

The correlation found between physical properties and tactile warmth of wood in publication II is strong and positive. It is evident that to achieve a greater objectivity in determining the relationship between the physical properties of wood materials and subjective aspects of thermal perception, there needs to be precision in the measurement of subjective experiences. Therefore, results from these psychophysical experiments help establish the relation between the human perceptual experiences and the properties of the wood surfaces with higher accuracy.

Furthermore, the method of thermal touch quantification leading to the publication III showed that temperature perception of material-surfaces could be assessed quantitatively. This would further help in comparing the tactile warmth of wood materials numerically. Once we have the numbers for perceived tactile quality, assessing and comparing the thermal behaviours of materials could become easier and can be explained with greater precision. By continuing this line of multidisciplinary research, with wider varieties of test materials, it would help define the relationship with greater accuracy in the future.

4.4 Effects of surface coatings on the tactile warmth of wood surfaces

The types of wood-surface coatings tested in the present study were oil and varnish based on natural "drying oil". The results (in publication II) showed that after application of the varnish coatings there is a general decrease in the tactile warmth of the surface for same tree species, compared to the untreated surface (**Figure 12**). Such changes in tactile warmth in the hardwood (oak) seem to be more visible than in softwood (pine). However, the effect of oil coatings on the tactile warmth is not uniform across wood species: tactile warmth is found to decrease after oil coating over oakwood surface but increase on pinewood surfaces. Although it is known from previous studies (Forest Product Laboratory 2010; Nejad and Cooper 2017), that these coatings cannot alter the thermal properties of wood (thermal conductivity, specific heat) directly, coating may alter the thermal effusivity values by influencing the wood-specific properties, such as moisture content. Consequently, this might affect the heat transfer phenomenon between the skin and the material surfaces during touch.

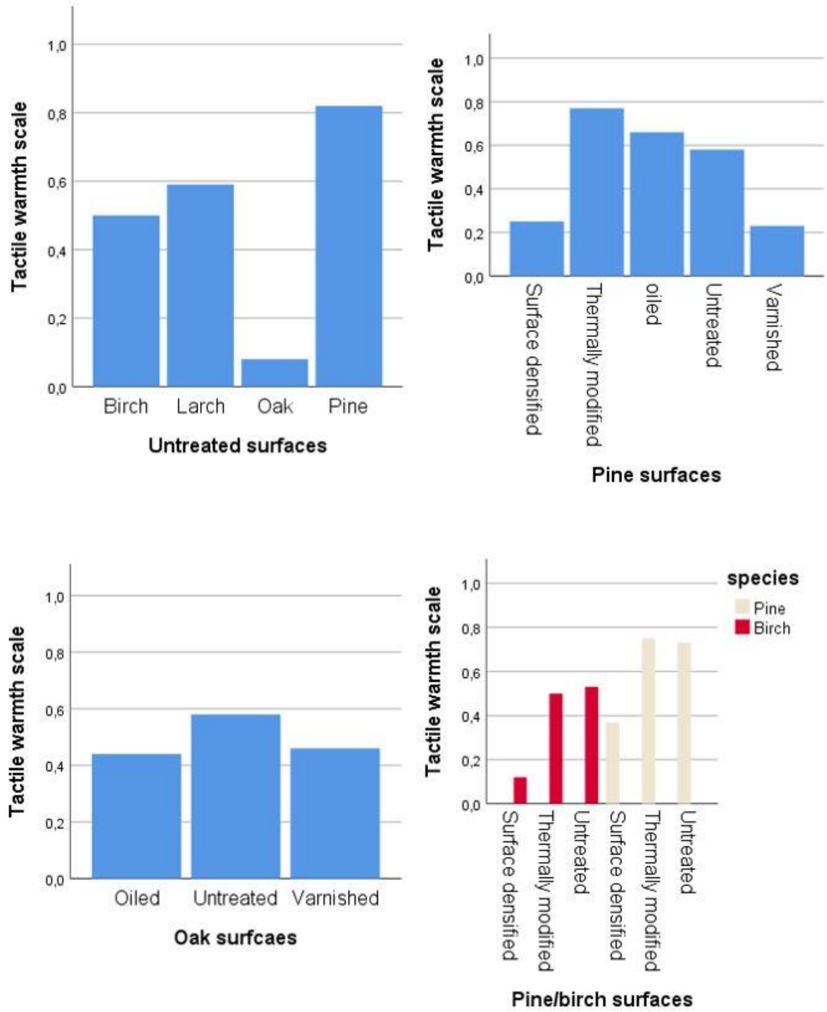


Figure 12. *Tactile warmth of various wood surfaces compared in the group. (Scale 0 = least warm, 1 = most warm).*

Another plausible explanation for the decrease in the tactile warmth of the wood surface after coating could be that the coatings can either penetrate the outermost wood layer or form a thin layer over the surfaces (Nejad and Cooper 2017). In the case of surface penetration by the coating chemicals, the thermal intensity felt by the hand skin might not be the same, since these chemicals would have filled the surface cracks and might influence the heat-transfer phenomenon during contact. On the other hand, a complete layer of coating chemicals formed over the test surface could obstruct the sensation originating from the wood, with the sensation arising from the coatings. In such cases, the thermal sensation of coated wood is governed by the thermal properties of the coatings.

The surface penetration of oil coatings has been found to be higher in pine than in oak (Nejad and Cooper 2017). With hardwood like oak, less surface penetration of coating chemicals means a larger deposition of coating over the surface. These explanations could support the results that a decrease in tactile warmth of the oil-coated oak surfaces but an increase in tactile warmth seen after the oil-coating of pine surface.

4.5 Effects of wood modifications on the tactile warmth of wood surfaces

Publication II deals with the effects of wood modifications, in particular the thermal modification and surface densification of wood, on tactile warmth at normal room temperature. Two species - pine and birch - were chosen as the test specimens for thermal modification and surface densification, representing a softwood and hardwood respectively (Rautkari et al. 2011). These modified surfaces were compared to their untreated counterparts. The results showed that the change in the tactile warmth of the wood surface after thermal treatment was not significant; both the modified pine and birch were quite close to their untreated counterparts on the scale of tactile warmth (**Figure 12**).

In the present study, the thermal modification could not influence the cold sensation of wood surfaces. Theoretically, the thermal properties of wood change after thermal modification (Suleiman et al. 1999; Pelit et al. 2017). In addition to reduced moisture content, many wood-related chemical extracts might vaporize during the thermal modification process whilst the thermal degradation of some of the cell wall polymers can lead to a loss in density and an alteration of wood properties (Hughes et al. 2015; Ulker et al. 2012). This could lead to a decrease in the heat transfer ability of wood and an increase in tactile warmth (should feel relatively less cold to touch). Similarly, a decrease in thermal conductivity after thermal modification (Pelit et al. 2017) should lead to increasing tactile warmth. However, the absence of a change in tactile warmth after thermal treatment in the present study (in publication II) could be attributed to an insignificant decrease in thermal effusivity after thermal modification, because the decreased conductivity might be counterbalanced by alteration of wood-specific properties. Regarding the ability of hand for thermal sensory threshold discrimination, it can detect the 2.5% change in cooling temperature if the background skin temperature is 34 °C (Johnson et al. 1973). In that sense, the changes in thermal properties of wood after thermal modification should be below the threshold level of cold sensitivity.

On the other hand, surface densification could influence the tactile warmth of wood materials in a negative way. This effect was readily observed both on pine and birch surfaces: the densified surfaces were significantly colder than their untreated counterparts at normal room temperature (**Figure 12**). The surface densification process can alter the thermos-physical properties of wood in an irreversible way (Ulker et al. 2012; Rautkari et al. 2010), resulting in an improvement in the structural and/or functional qualities of wood. These thermo-physical changes after surface densification include an increase in density, an increase in thermal conductivity, and a decrease in specific heat and porosity (Ulker et al. 2012; Rautkari et al. 2010), resulting in an increase in thermal effusivity. Therefore, the decrease in the tactile warmth of densified wood surfaces in the present study was in line with expectation.

4.6 Quantification of temperature perception using wood surfaces

The two psychophysical variables - "the point of subjective equality (PSE)" and "the differential threshold (DT)" - were used to measure any similarities or differences in the tactile perception of surface temperatures using the hand. The results showed that dissimilar materials could be perceived to be equally cold when they were at different temperatures. Three surfaces were tested where a pine surface, maintained at 20 °C used as the reference surface, was compared with oak and ceramic tile surfaces (separately). For both the PSE and the DT, the difference in the surface temperature between pine and ceramic tile was found to be higher than that between pine and oak surfaces (as shown in **Figure 13**). The results also showed that discriminating one wood surface from another wood surface (pine from oak) was more difficult than discriminating a wood surface from a non-wood surface (i.e., discriminating pine from ceramic tile was easier).

13a.

	Responses (8 repetitions)												
Pine Temperature	R1	R2	R3	R4	R5	R6	R7	R8	Total	Oak Temperature	total P(correct)	P(correct) model	Error	
20	0	0	0	0	0	0	0	0	0	16,0	0	0,000991205	9,82E-07	
20	0	0	0	0	0	0	0	0	0	16,8	0	0,00466717	2,18E-05	
20	1	0	0	0	0	0	0	0	1	17,6	0,125	0,017590676	0,011537	
20	0	0	0	0	0	0	0	0	0	18,4	0	0,05337553	0,002849	
20	0	0	0	1	0	0	0	0	1	19,2	0,125	0,131426177	4,13E-05	
20	0	1	0	0	0	0	0	1	2	20,0	0,25	0,265532921	0,000241	
20	1	1	0	0	1	1	1	0	5	20,8	0,625	0,447063153	0,031662	
20	0	0	1	1	1	0	0	0	3	21,6	0,375	0,640655025	0,070573	
20	1	1	1	1	0	1	1	1	7	22,4	0,875	0,803310399	0,005139	
20	1	1	1	1	1	1	1	1	8	23,2	1	0,910977707	0,007925	
20	1	1	1	1	1	1	1	1	8	24,0	1	0,967122871	0,001081	
													0,13107	Error sum

Which side of your hand feels colder?

Response option: Left (coded as 0) and Right (coded as 1)

(Room temperature = 13,6, Humidity = 53%)

Psychometric Function		
	Mean (PSE)	21,0
	Slope	1,621747605
0,75	JND (DT)	22,10968211

Participants																		
1	2	3	4	5	6	7	8	9	10	11	12	total	Pine Tem.	Ceramic Tem.	total p(correct)	p(correct) model	error	
0	0	0	0	0	0	0	0	0	0	0	0	0	20	17,6	0	0,0000	0,0000	
0	0	0	0	0	0	0	0	0	0	0	0	0	20	18,4	0	0,0005	0,0000	
0	1	0	0	0	1	0	0	0	1	1	0	4	20	19,2	0,041666667	0,0036	0,0014	
0	0	0	0	0	1	2	0	0	0	0	0	3	20	20	0,03125	0,0186	0,0002	
0	2	2	0	1	1	3	0	1	2	2	0	14	20	20,8	0,145833333	0,0698	0,0058	
3	0	0	0	1	1	2	0	0	2	1	1	11	20	21,6	0,114583333	0,1915	0,0059	
2	4	1	4	4	5	5	4	2	4	6	4	45	20	22,4	0,46875	0,3946	0,0055	
7	4	4	8	1	7	4	4	2	2	5	3	51	20	23,2	0,53125	0,6322	0,0102	
7	8	5	8	5	8	7	7	8	8	7	8	86	20	24	0,895833333	0,8271	0,0047	
7	8	7	8	8	8	8	7	6	8	8	8	91	20	24,8	0,947916667	0,9392	0,0001	
8	8	8	8	8	8	8	8	8	8	8	8	96	20	25,6	1	0,9843	0,0002	
																	0,0340	*Error sum*
																Psychometric function		
																Mean (PSE)	22,75361	
																Slope	1,322165	
															0,75	JND (DT)	23,64539	

13b.

Figure 13. *Screenshots of the data file showing thermal touch quantification data **13a.** showing responses from a participant, and the PSE and DT calculated from the data from single participant in pine/oak comparison test, **13b.** showing responses from 12 participants and analysis of the PSE and the DT from group data in pine/ceramic tile comparison test. Note: the highlighted terms "PSE and the DT" in the figure represent the actual temperature of the comparison surfaces at the PSE and the DT (i.e. temperatures of the oak surface in **Figure 13a,** and temperatures of the ceramic tile surface in **Figure 13b**).*

The results also provide some insights into why two materials maintained at normal room temperature feel the same (or different) when touched. Pine and oak when maintained at 20 °C, for instance, felt more-or-less similar in coldness (in another words it was not possible to thermally discriminate between the two by touch most of the time). When we decrease the temperature of the oak surface by only 0.3 °C, it begins to feel clearly colder than pine (lower discrimination threshold). When we gradually increase the temperature of the oak surface from 20 °C up by 0.9 °C, the oak surface felt equally cold to that of the pine surface at 20 °C (the PSE). By further increasing the oak surface temperature by 2.1°C, it now began to feel clearly warmer than pine (upper discrimination threshold). The region between the lower and upper thresholds (i.e., 19.7 °C - 22.1 °C: difference = 2.4 °C) is termed the "the window of equality" where an oak surface cannot be reliably discriminated from a pine surface maintained at a temperature of 20 °C. This window of equality for the ceramic tile surface, when pine was at 20 °C, was found to be 1.8 °C (21.9 - 23.7), which implies that when pine and tile are maintained at 20 °C, the tile always feels colder to the touch.

The DT measured in the present experiment also reflects the temperature sensitivity of the finger skin for the tested materials, but not the absolute thermal sensitivity of the skin. In the field of neuroscience, skin sensitivity to temperature has been measured using metals, radiant heat, or Peltier devices as a source of the thermal stimulus and the measured differential thresholds are very small (Stevens 1991). The larger value of DT indicates that thermal changes are more difficult to discriminate in comparison to a smaller DT, and this is due to the slower and smaller change in the thermal intensity of the stimulus (due to the comparatively poor heat conducting capacity of wood and ceramic tiles surfaces). Therefore, the measured DTs in the present study (in publication III) reflect the thermal properties of material surfaces and do not reflect the skin's ability to discriminate temperature.

The temperature of the tested material at the PSE reflects the relative thermal quality of the tested materials: the pine surface needed to be maintained at a lower temperature than the comparison surfaces for it to feel equality cold. This means that when all these surfaces are maintained at the same temperature, pine would be the warmest, followed by oak and then by the ceramic tile.

Therefore, it could be argued that that these quantified values of temperature perception of material surfaces could be taken as parameters of subjective thermal experiences. These quantified values, obtained from the psychophysical experiment, should better represent the subjective experience of the tactile warmth of materials, including wood. It is well known that psychophysical methods can provide less biased results when perception is measured and then related to physical properties. By combining the quantified values of thermal perception with the “hard” physical properties of materials, there is the possibility of developing innovative ways of designing the surface of a material to achieve the optimum tactile warmth for its users. Furthermore, continuing this line of research using a variety of building materials could offer a list in which a material’s tactile warmth quality could be compared with greater accuracy, and this could certainly benefit all stakeholders, including designers, manufacturers, architects and users.

5. Concluding Remarks

This study focused on an exploration of the tactile perception of wood surfaces through a multidisciplinary approach. The main aim was to find ways to improve the subjective experiences of touching wood so that product surfaces made of wood feel pleasant, comfortable and warm.

To improve consumer touch experiences, it is important to retain the naturalness and mild surface topography of wood surfaces. The positive emotional quality of touching wood surfaces is important for the hedonic preference of consumers. The good tactile warmth of wood materials at room temperature means that it feels warmer to the touch than some other materials do. This implies that by maintaining an even lower surface temperature (in wood), its better tactile warmth quality enables it to feel equally as warm as other less warm materials (like ceramic tile).

Reliable research evidence is not available to show that there is a straightforward connection between the tactile warmth of materials and human thermal comfort in living spaces. Human thermal comfort is a multidimensional issue and many things come into play, such as air humidity, body insulation levels, the body statistics (BMI, age, fat level, emotional state) of the inhabitants, spatial design, weather seasons, geographical location etc. However, leaving these things aside and, under ideal conditions, the tactile warmth of materials may be exploited for reducing energy use in the buildings.

By further researching the thermal quantification of material surfaces, we can have a list of materials with their quantified values. These values may provide the basis for energy modelling to explore how the use of certain building materials in the living space could influence energy use. This means the development of simulations to find out the amount of additional heating energy saved due to the use of wood floorings instead of using, for example, ceramic tiles. For example, if the PSE level of various materials at room temperature is known, we can estimate the quality of the thermal environment that has been constructed from certain building materials, and this makes it easier to quantify the energy consumption or conservation due to the use of such construction materials.

The results from the quantification study suggest that two materials at different temperatures can evoke the same level of cold sensation. This has some practical significance in relation to the thermal properties of construction materials: choosing a “warm” material at a lower temperature implies that there is a possibility to achieve a thermally comfortable environment even at lower temperatures. In other words, choosing a “cold” material with a warm temperature implies that we can save with air conditioning costs. This is exactly what has been done in traditional architecture in cold and warm climates. Hence, the material selection based on their touch quality for creating living spaces could be a way to lower the heating energy consumption of living spaces in a passive way without compromising the thermal comfort of its user. The present study supports the idea that thermally warm materials, like wood, can improve thermal comfort even in a lower temperature environment, which could be another good reason to use wood as interior elements from the viewpoint of energy-saving.

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People prefer to use wood in the built environment in many ways such as furniture, artefacts, and building-construction materials. People's experiences in the living environment are influenced by the types of materials used for creating that environment. Therefore, understanding the touch quality of wood materials could be beneficial to architecture, researchers, other stakeholders including the end-users to help improve the sensory experiences related to the comfort and satisfaction of living in the wood-built environment. The tactile sensory experience is one of the aspects of human perceptual experiences of the materials. This thesis explores tactile qualities of wooden materials and the ways to improve the tactile sensory experiences. According to the findings of this dissertation, wood material is perceived to be comfortable and warm through the touch modality. The good tactile qualities of wood material could be retained or even improved during the manufacture/design phase. The results from this dissertation are beneficial to all wood stakeholders to get the insights on user experiences of wood in the living spaces from the multidisciplinary point of view.

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