WARM SURFACES OF ELECTRONIC DEVICES AND HUMAN THERMAL RESPONSES

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Han Zhang
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Han Zhang, Ph. D.
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Heat dissipation is an essential consideration for the hardware design of the handheld electronic devices. For such devices the surface temperature needs to be maintained at a level that is comfortable and that will not create risks of skin burn or user thermal discomfort. As the packaging of handheld electronic devices becomes smaller and thinner, effectively dissipating the heat generated by components such as central processing unit, power supply and batteries, while maintaining a comfortable and safe surface temperature, is becoming more challenging. Current standards provide information on the maximum surface temperature to prevent skin burns, but not user thermal comfort. Many experimental studies have investigated the skin temperature thresholds for thermal sensation and heat pain. However, only limited research exists on how users' cutaneous thermal sensation and comfort is affected by prolonged duration in contact with electronic devices. Research is also lacking on the effects of heat distribution patterns and the characteristics of surface materials.

In the present work a comprehensive literature review was conducted on various aspects related to thermal sensation and comfort. A preliminary survey was completed to understand laptop users' thermal comfort and its relation with surface temperature. A novel tablet-size heating surface was developed. Afterwards, a series of experiments was completed to systematically investigate how finger and palm thermal sensation and comfort were affected by the following variables: the surface temperature, the ambient temperature, the rate of surface temperature change, the spatial distribution of the heat, and the roughness of texture. Results from these studies have practical implications for the future design of handheld electronic devices. Future research also may focus on extending the current work to study more varied user tasks and other body parts that may be in contact with future electronic devices.

BIOGRAPHICAL SKETCH

Han Zhang was born in Tangshan, China. He received his Bachelor of Engineering degree in Industrial Engineering at Chongqing University in 2007. Since then, he has been interested in understanding the needs, emotions and capabilities of human, and how to integrate the information into product and system designs. Afterwards, Han completed his master degree at Mississippi State University in 2010, where he learned more about human factors and industrial engineering. Han’s passion in human factors in product design continued to grow, and in 2011 he joined Cornell University to pursue a doctoral degree in the program of Human Behavior and Design, with the guidance of Professor Alan Hedge. During his PhD program, Han also conducted human factors and ergonomics research for the early developments of Google Glass at Google X, and a new wearable computer at Motorola Solutions (Zebra). Since January 2016, Han will join Amazon in California to continue his interest in human factors and product design. His goal is to apply human factors methodologies and principles to make future products to benefit people’s life.

To the years of my 20-30

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CHAPTER 1

INTRODUCTION

1.1 Overview of thermal issues

With the development of computing power and sensor technology, mobile and wearable computing devices have become ubiquitous. As the form factor decreases and the power of computing components increases, heat dissipation design and user related thermal issues have become more important. The ISO 13732-1 (2006) standard states that the burn threshold for 1-minute contact period for metal is 51 °C. Yet, cases have been reported on toasted skin syndrome or 2nd and 3rd degree skin burns, caused by prolonged use of laptop computers (Billic and Adams, 2004; Paulius et al., 2008; Bachmeyer, 2009; Arnold and Itin, 2010; Patel and Leon-Villapalos, 2011; Fernández-Portilla et al., 2012). The bottom surface of some laptop computers can reach 55.4 °C, and the temperature at some laptop's ventilation outlet can reach 65 °C if ventilation is blocked (Paprottka et al., 2011; Tsang et al., 2011). A survey of laptop use by college students found that about 20.8 percent of daily users report some types of thermal discomfort (Zhang and Hedge, 2014). It has also been shown that the surface temperature of a tablet computer can reach 47 °C with graphic intensive computing tasks (Chatterjee, 2014). The surface temperature of head-mounted computers in contact with a user's skin possibly can reach an even higher temperature of 51.9 °C when running video chat application (LiKamWa et al., 2014). The temperature is far above 48 °C, which is the burn threshold of skin for 10-minutecontact with plastic materials (ISO 13732-1, 2006). Therefore, it is necessary to understand more about how user thermal sensation and comfort are influenced by the heat from such electronic devices, and to develop innovative methods to improve heat dissipation, and thus to improve user comfort.

Up to now, among the different forms of personal computers such as laptops, tablets, and wearable computers, the tablet computer is predicted to be the most popular trend, at least through 2017 (Statista, 2015a). In 2014, 42% of American adults owned a tablet computer (Zickuhr and Rainie, 2014). In 2015, the global shipments of tablet computers is predicted to be 332 million (Statista, 2015b). Globally, as tablet computer sales have increased so laptop computer sales have slowed down, and the ownership of wearable computers is still very small compared to tablet computers, although such devices may have great potential in the future (Statista, 2015a; Statista, 2015c). Therefore, tablet computer related heat dissipation issues are a worthwhile area to study.

1.2 Thermal design standards and thermal sensation

Standards have defined the temperature limits to prevent skin burn (BS 4086, 1966; ISO 13732-1, 2006; ASTM C1055 – 03, 2014). However, no standard describes people's thermal sensation when their hands are in contact with a heat producing product for a prolonged time. Laboratory studies have investigated the skin temperatures responsible for the sensory continuum from warm sensation to heat pain (Dyck et al., 1993; Taylor et al., 1993; Meh and Denislic, 1994; Yarnitsky et al., 1995; Hagander et al., 2000; Harju, 2002; Kelly et al., 2005; Defrin et al., 2006). However, most of these studies were conducted in controlled laboratories with small probes up to 12.5 cm^2 and a short exposure duration of 15 seconds or less. Such heat stimuli are smaller and briefer than the typical user exposures to the heated surface of a tablet computer during normal use. Therefore, studies are needed to understand thermal sensation and comfort associated with using a tablet computer and to test possible design elements that may improve user thermal comfort. In addition, a tablet computer is in contact with a user's hands. The findings of studies of finger and hand thermal sensation and comfort when in contact with a tablet computer surface can also be applied to help design the surface temperatures of other types of hand-held electronic devices.

1.3 Focus of the dissertation

This dissertation consists of the following:

1. An extensive literature review of thermal sensation and thermal comfort associated with skin temperature. This literature review covers the physiology of thermal sensation, past laboratory tests on thermal sensation, current standards related to skin burns and cutaneous thermal comfort, recent development of the use of thermal feedback in human-computer interaction, and current research on the effect of laptop computers' heat on users.
2. A preliminary survey of user thermal comfort when using laptops. The preliminary survey explored how user thermal comfort relates to the design and normal use of laptops, and it identifies factors that affect user thermal comfort.
3. The development of a novel tablet-size heating surface. A heating surface was developed to control the surface temperature, the rate of temperature change, the area to be heated, and the change of surface materials.
4. Four experiments were conducted to test how these different aspects can affect the thermal sensation and comfort when participants' hands were in contact with the surface. According to the literature review and the results of the preliminary survey, the following variables were determined to be of interest for the subsequent experiments: the surface

temperature, the rate of temperature change, the effects of environmental conditions, and the effects of surface texture.

The findings in the dissertation can be applied in different electronic products. The cutaneous thermal sensation and comfort ratings can be used as guidelines to limit the surface temperatures of hand-held electronic devices or tools at different ambient temperatures. The findings on the effect of temperature change rate, heated areas and the roughness of surface texture can be used for the new designs of heat dissipation and selection of materials. For example, at the same surface temperature, user thermal comfort might be improved with a slower rate of temperature increase, and the use of rougher texture.

CHAPTER 2

A REVIEW OF HUMAN RESPONSES TO WARM SURFACES

2.1 Introduction

In this section, literature is reviewed on cutaneous thermoreceptors, human perception of thermal stimuli, guidelines on skin burn thresholds, and the application of thermal feedback in human computer interaction. The characteristics and functions of different types of fiber afferents and ion channels in cutaneous thermoreceptors are summarized. Cutaneous heat-pain thresholds and warmth thresholds, discomfort ratings with cutaneous thermal stimuli, and factors that affect perception on heat pain thresholds are described. The use of thermal feedback in human computer interaction are also discussed, including how the rate of thermal change can affect users' perception of thermal feedback, and how environmental factors affect the use of thermal feedback.

The human body has a delicate physiological system in the skin to perceive heat and register thermal sensations. Skin temperature typically ranges from 32 ℃ to 35 ℃, but can span from 20 ℃ to 40 ℃ due to different daily activities. Skin temperature is affected by heat absorption, heat conduction, radiation, heat convection, sweating, skin wetting, clothing and cutaneous blood flow (Jones and Berris, 2002; Parsons, 2014). The thermal sensation arising from the skin temperature results from the activation of some combination of cutaneous cold receptors and warm receptors. Cold receptors are much more abundant than warm receptors in a ratio up to 30:1 (Jones and Berris, 2002). These receptors transduce, encode and transmit thermal sensation along afferent nerve fibers (Schepers and Rinkamp, 2009).

2.1.1 Cutaneous thermal receptors

For sensations of warmth, heat and pain there are at least four types of fibers: A-alpha and A-beta fibers respond to mechanical stimuli, while A-delta fibers conduct an instant heat pain sensation, and C fibers conduct a slower heat pain sensation (Darian-Smith et al., 1979; Campbell and LaMotte, 1983; Treede et al., 1995, 1998). The A-beta fibers have the largest diameter of more than 10µm and fast conduction velocity (30-100m/s), and the A-delta fibers have a medium diameter of 2 to 6µm with a conduction velocity of 12-30m/s, while C fibers have much smaller diameters of 0.4 to 1.2µm, with a slower conduction velocity of 0.5-10m/s (Harper and Lawson, 1985; Millan, 1999; Zhu and Lu, 2010). These afferent fibers are distributed at different depths and density in the skin. The proportion of nociceptors is 70% C fibers, 20% A-beta fibers, and 10% A-delta fibers (Millan, 1999). Nociceptors are defined as the specialized peripheral sensory neurons that are activated with noxious physical or chemical stimuli (Dubin and Patapoutian, 2010). The mechanical nociceptors in cats' hairy skin are found at around 50µm depth, whereas nociceptors that mediate pain are at a depth of 200µm (Kruger et al., 1981; Stoll and Greene, 1959). The density of C fibers is 2-8 fibers per mm2, while A delta fibers are less dense with less than 1 fiber per mm2 (Lyn and Baranowski 1987; Zhu and Lu, 2010). C-fiber nociceptors in monkey skin are estimated to be at a depth from 20 to 570µm with an average of 201µm in response to ramped thermal stimuli, and the heat threshold for receptors to be active was 40.4 +/-2.2 ℃ (Tillman et al., 1995b). The conduction speed of heat-pain mediated fibers is estimated to be approximately 1.2m/s in the hairy skin and 1.4m/s in glabrous skin peripheral nerve fibers, both within the range of C fibers (Pertovaara et al., 1996).

2.1.2 Non-noxious heat (skin temperatures below the skin burn threshold)

When human skin is in contact with thermal stimuli of 30 ℃ and above, warm fibers are activated. Warm fibers (mainly C fibers) have a slower conduction velocity of around 1m/s than A-delta fibers (LaMotte and Campbell, 1978; Darien-Smith et al., 1979; and Schepers and Rinkamp, 2009). Warm fibers respond to thermal stimuli at temperatures between 30 ℃ and 50 ℃ (Lamotte and Campbell, 1978; Duclaux and Kenshalo, 1980). The static temperature discharge rate for warm fibers is an inverted U shape with the maximum rate at 40 to 43 ℃, and minimum at both 30 ℃ and 50 ℃ (Hensel and Iggo, 1971; Duclaux and Kenshalo, 1980). Eighty percent of warm fibers stop firing at 50 ℃ (Darian-Smith et al., 1979).

The transducer molecules active for sensations of warmth are transient receptor potential vanilloids (TRPV 3 and TRPV 4). TRPV families form ion channels in the receptors to generate action potentials which transmit thermal sensation information (Julius and Basbaun, 2001; Pedersen et al., 2005). When skin temperature reaches 33 ℃ TRPV3 is activated, and a warm sensation is experienced (Schepers and Rinkamp, 2009). Repetitive 37 ℃ heating pulses can sensitize TRPV3 in mice and thus cause an increase of the channel activity which may lead to increased thermal sensitivity to heat (Xu et al., 2002; Moqrich et al., 2005). Another ion channel for non-noxious warm temperatures is TRPV4 with active range above 24 ℃ (Guler et al., 2002; Nilius et al., 2003; Nilius et al., 2004), and this is responsible for non-noxious heat sensations (Watanabe et al., 2002).

Cutaneous thermal sensations can quickly adapt to innocuous temperature changes in the skin and the range of adaptation temperatures is relatively wide. As temperature increases to 45 ℃, thermal sensations can change from warm to hot and eventually pain (Schepers and Rinkamp, 2009). Warm fibers have steady-state activities below 30 ℃ and above 50 ℃, while the peak of discharge rate for most warm fibers are at 43 ℃ and 46-47 ℃ (Duclaux and Kenshalo, 1980). For stimuli between 40 ℃ and 45 ℃, after about 10 seconds contact, the discharge frequency decreases to a steady state close to the frequency before the application of the stimuli (Darien-Smith et al., 1979; Duclaux and Kenshalo, 1980). Above 50 ℃, 80% or all of the warm fibers stop responding to thermal stimuli (Darien-Smith et al., 1979; Duclaux and Kenshalo, 1980).

2.1.3 Noxious heat (skin temperatures near and above the skin burn threshold)

Two major groups of afferent fibers respond to noxious heat stimulation, A fibers and C fibers (Treede et al., 1995). A-delta fibers mediate thermal stimuli when the skin temperature is more than 43 ℃, and they produce a nociceptive response (Hensel and Boman, 1960; Koniezny and Hensel, 1975; Konietzny, 1984; Claus et al., 1987). A-beta fibers only respond to mild, innocuous mechanical stimuli while A-delta and C fibers are polymodal, producing corresponding sensations for thermal, mechanical and chemical stimuli (Treede et al., 1992; Millan, 1999; Julius and Basbaum, 2001).

All three types of fibers can deliver non-nociceptive information but only C and A-delta fibers can transmit nociceptive information (Millan, 1999). The A delta fibers can be classified to type I and type II fibers (Treede et al., 1995; 1998). Type I A fibers show an average response latency of 5s with a thermal stimulus of 53 ℃ and 30s duration presented every 60 seconds, and they have a high threshold of over 53 ℃ and an average conductivity velocity of 25.4m/s, whereas type II A fibers show a very short latency with an average of 0.22s and have a mean threshold of 47.2 ℃, with an average conductivity velocity of 14.2m/s (Treede et al., 1998). Type II A fibers display similar characteristics to C fibers in their response to heat stimuli, show rapid adaptation to heat stimuli and fatigue to repeated heat stimuli. The adaptation time for

Type II A fibers is 2.4s, while C fiber nociceptors have an average adaptation time of 2.5s (Treede et al., 1995; Treede et al., 1998). Both types of fiber nociceptors' response were suppressed by repeated heat stimuli at intervals of 30 seconds. C fiber nociceptors recover in 4-10 minutes, 70% of A type II fiber nociceptors need at least 10 minutes to recover (LaMotte and Campbell, 1978; Treede et al.,1998). During repeated heat stimuli the inactivation of the afferents such as C and type II A fiber nociceptors may lead to the decrease of heat sensation magnitude (LaMotte and Campbell, 1978; Peng et al., 2003).

However, A fibers and C fibers also show different behaviors in response to stimuli with varied rates of temperature change. Studies indicate that the activation of A-delta fiber nociceptors depends on the rate of temperature rise. More specifically, A-delta fibers fire in response to skin being heated from 37 ℃ to 58 ℃ at a relatively high rate of 6.5 ℃/s. C fibers can be classified into several types, including mechano-heat-responsive C units (CMH) that respond to both heat and mechanical stimuli, the ones that only respond to mechanical stimuli (CM), the ones that only respond to heat (CH), and the ones that are not sensitive to either heat or mechanical stimuli (CMiHi) (Schmidt et al., 1995). The heat thresholds for C fibers range from 37 to 49 ℃ in hairy skin (Tilman et al., 1990; Schmidt et al., 1997). Other research on C fiber behavior is inconsistent. Yeomans and Proudfit (1996) found that C fibers responded at a rate of 0.9 ℃/sec, although whereas Yarnitsky et al. (1992) found that C fiber nociceptor responses do not depend on the rate of temperature change, for example, the mean response threshold was consistent between 41.5 ℃ to 41.9 ℃ for rates of temperature rise of 0.3, 2.0 and 6.0 ℃/s. However, in Tillman's studies (Tillman et al., 1995a,b) C fibers (CMHs) heat threshold was found to increase as the rate of temperature rose from 0.095, 0.85 to 5.8 ℃/s. The discharge frequency of the C fibers increased with the rate of increase of stimulus temperature in all these studies (Yarnitsky et al., 1992; Tillman et al., 1995a,b).

Two types of pain sensations have been described after a heat stimulus is applied to skin: one is a sharp instant pain about 0.4s after stimulation, and the other is a burning pain that occurs 1 to 2 seconds after stimulation (Bigelow et al., 1945; Hardy et al., 1952; Chery-Croze, 1983). The two pains can merge when the stimulated areas are proximate areas such as the arm, shoulder and back, and only one pain sensation occurs with glabrous skin areas such as thenar eminence (Campbell and LaMotte, 1983). The first sensation of pain involves activation of the A-delta fibers and the subsequent second sensation of pain involves activation of the C fibers: the delay occurs because of the difference in fiber conduction velocities (Campbell and LaMotte, 1983; Chery-Croze, 1983; Julius and Basbaum, 2001).

Some warm fibers are also active with noxious heat stimuli and their peak discharge is found to be around 45 ℃. However, at higher static temperatures these afferents became inactive (Hensel and Kenshalo, 1969; Duclaux and Kenslao, 1980).

TRPV1 and 2 are the transducer molecules for noxious heat stimuli. TRPV1's temperature threshold is at 43 ℃ and above (Caterina et al., 1997; Jordt and Julius, 2002), while TRPV2 is active for stimuli with high temperatures of more than 52 ℃, but does not respond to the stimuli that activate TRPV1. TRPV2 may be the thermosensor that mediates the A-delta type nociceptor I heat response (Caterina, et al., 1999). Besides TRPV1 and 2, TRPV3 can also transduce noxious heat sensation, with activation temperature of more than 50 ℃ (Peier et al., 2002; Smith et al., 2002).

The active zones of receptors and fibers at different static temperatures are plotted in Figure 2.1 according to the literature above (Hensel and Iggo, 1971; Lamotte and Campbell, 1978; Darien-Smith et al., 1979; Duclaux and Kenshalo 1980; Caterina et al., 1997; Treede et al., 1998; Campero et al., 2001; ISO 13732-2, 2001;

Jordt and Julius, 2002; Peier et al., 2002; Smith et al., 2002; Watanabe, et al., 2002; Parsons, 2014; ISO 13732-1, 2006; Schepers and Rinkamp, 2009). It should be noted that the temperatures are static temperatures and the general thermal sensation may vary according to the thermal conductivities of materials, the skin area, duration and pattern of thermal stimulation, and the body region. All temperatures shown in Figure 2.1 are bare skin temperatures and some temperature thresholds are still uncertain, such as the activation threshold of TRPV4.

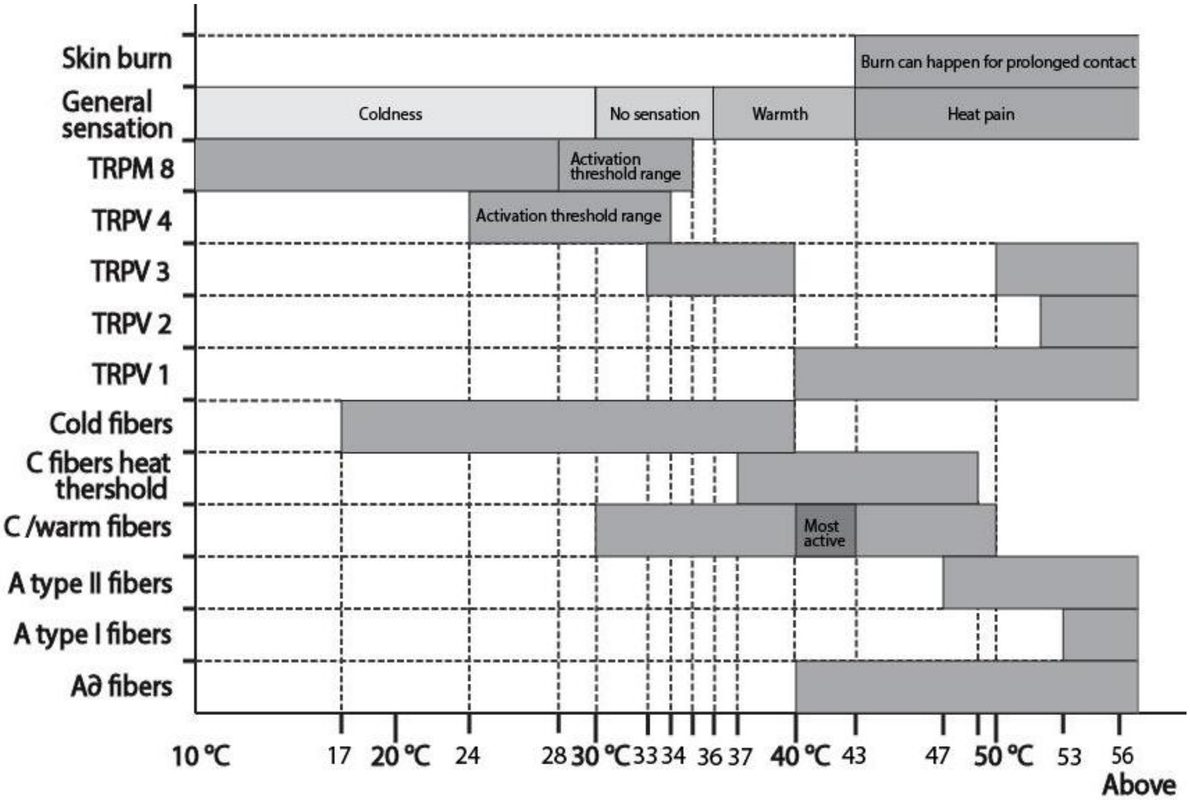


Figure 2.1. Thermoreceptors and ion channels activity temperature zones

Note: Grey scale for the general sensation from left to right means different levels of thermal sensation; the darker color of “most active” means indicates the temperature zone that the fibers are most active.

2.2 Human perception of heat

Typically, no thermal sensation is noticed if the skin temperature is maintained between 30 to 36 ℃ (Jones and Berris, 2003). In the range of 15 to 25 ℃, thermal sensation may be different when the thermal conductivity of the surface materials varies, even at the same contact temperature (Halabi and Parsons, 1995; Parsons, 2014). However, when the skin temperature rises to 42 to 45 ℃ there can be a sensation of pain and damage to the skin, though these effects vary by different body region (Darian-Smith and Johnson, 1977; Defrin et al., 2002; 2006). The difference may depend on the thickness of the epidermis and the density of distribution of thermal receptors across different body regions (Jamal et al., 1985a, b; Green and Cruz, 1998; Steven and Choo, 1998; Defrin et al, 2006). Head areas such as the mouth, forehead and cheek are more sensitive to heat, while lower extremities are less sensitive, such as the calf, sole and toe. The sensitivity of fingers and forearms lies in between the most and least sensitive skin areas (Claus et al., 1987, Stevens and Choo, 1998, Hagander, 2000).

Skin’s reaction to a hot surface can be affected by the heat transfer rate between the surface and the skin, and which is affected by both the nature of the surface and skin conditions (Parsons, 2014). The factors in a solid surface that can affect the heat transfer from the surface to the skin include the number of layers, surface roughness, surface wetness, surface temperature, material thermal conductivity, material specific heat, material density, material thickness, and surface cleanness (Parsons, 2014). Skin conditions can vary with intra-subject factors, such as area of the body and state of vasodilation or vasoconstriction, and inter-subject factors, such as age, occupation, sex and ethnic differences (Parsons, 2014). With sufficient contact time, skin vasodilation and sweating can occur, however, the reaction of the skin in contact with local heat stimuli is affected by the initial skin temperature, for example, in warm environment skin may become wet because of the high skin temperature, rich blood supply and sweating, thus cooling down the skin (Parsons, 2014).

2.2.1 Non-noxious warmth sensation and noxious heat sensation thresholds

Several studies have tested warm and heat-pain thresholds and the summary of the results are listed in Table 2.1. In geneneral, the thresholds for warm sensation over all body sites fall in between 33 ℃ and 35 ℃. The thresholds provide reference for the thermal testing range in the experiments of the dissertation.

Table 2.1 Warm and heat (℃) pain sensation thresholds of human skin. (standard deviations in parentheses)

Upper body

Studies	**Probe area**	**Method**	**Threshold**	**Maxillary face**	**Lateral upper Chest**	**Belly periumbilical**	**Lateral shoulder**	**medial upper arm**	**Volar Forearm**	**Dorsolateral forearm**	**Volar wrist**	**Mid Dorsal hand**	**Thenar eminence**	**Fingers**
Defrin et al., 2006	3*3 cm	MLE	Warmth	/	34.8 (1.3)	/	/	/	33.8 (1.4)	/	/	33.9 (1.6)	/	
		MLI	Warmth	/	36.2 (1.4)	/	/	/	35.3 (3.0)	/	/	35.2 (1.2)	/	
		MLE	Heat pain	/	41.8 (3.1)	/	/	/	42.3 (2.9)	/	/	41.9 (3.4)	/	
		MLI	Heat pain	/	42.0 (2.6)	/	/	/	43.6 (3.5)	/	/	43.8 (2.7)	/	
Dyck et al., 1993	10 cm^2	MLI	Warmth	33.3 (1.3)	/	33.8 (1.0)	33.6 (1.4)	/	32.9 (1.1)	/	/	32.7 (1.4)	/	
	2.9 cm^2	MLI	Hot	35.0 (1.6)	/	37.6 (3.2)	39.0 (2.0)	/	36.4 (2.6)	/	/	37.0 (3.0)	/	
		MLI	Uncomfortably hot	39.0 (3.0)	/	41.7 (4.4)	41.9 (4.1)	/	40.0 (4.4)	/	/	43.1 (3.3)	/	
		MLI	Painfully hot	43.0 (4.5)	/	44.9 (3.7)	45.3 (4.0)	/	43.5 (4.4)	/	/	46.8 (2.1)	/	
Hagander et al., 2000	30*30mm	MLI	Cool	/	/	/	/	/	/	/	31.5	34.5	31.5	
		MLI	Warmth	/	/	/	/	/	/	/	32.6	32.6	32.5	
		MLI	Cold	/	/	/	/	/	/	/	14.2	16.2	9.8	
		MLI	Hot	/	/	/	/	/	/	/	42.9	43.9	43.4	
Meh and Denislic, 1994	25*50mm	MLI	Heat pain (Female)	39.65 (3.71)	37.41 (3.29) lateral mammary	37.42 (3.03) lateral umbilical	/	36.8 (3.14)	36.93 (3.32)	/	/	/	37.69 (4.21)	
		MLI	Heat pain (male)	37.51 (4.13)	37.60 (3.54) lateral mammary	38.2 (3.35) lateral umbilical	/	30.01 (3.37)	38.54 (3.56)	/	/	/	40.18 (4.81)	
Parsons, 2014					/		/	/	/	/		/		
Fruhstorfer et al., 1976	25*50mm	Marstock	Warm	35.5 (right cheek)	/	36.5	/	/	/	/		/	35	
Kemler et al., 2000	5*2.5 cm^2	MLE unaffected	Warm	/	/	/	/	/	/	/	32.7 (0.5)	/	/	

(1st test listed)		MLE affected	Warm	/	/	/	/	/	/	/	33.1 (1.0)	/	/	
Yarnitsky et al., 1995	46*30mm	MLI	Heat pain	/	/	/	/	/	/	/	/	/	45.7	/
Kiesa et al., 2005	25mm*25mm	MLE	Warm	/	/	/	/	/	33.21medial forearm	/	/	/	32.79	/
		MLE	Cool	/	/	/	/	/	30.91medial forearm	/	/	/	31.37	/
		MLE	Hot pain	/	/	/	/	/	44.49medial forearm	/	/	/	45.56	/
		MLE	Cold pain	/	/	/	/	/	11.79medial forearm	/	/	/	5.58	/
Harju, 2002	25mm	Women 55-65	Warm	/	/	/	/	Lateral 37.6	/	/	/	/	34.7	/
	MLI		Heat pain	/	/	/	/	Lateral 46.1	/	/	/	/	44.7	/
			H-P tolerance	/	/	/	/	Lateral 47.9	/	/	/	/	48.7	/
			Cold pain	/	/	/	/	Lateral 27.4	/	/	/	/	27.9	/
		Men 55-65	Warm	/	/	/	/	Lateral 33.9	/	/	/	/	35.1	/
			Heat pain	/	/	/	/	Lateral 38.1	/	/	/	/	43.4	/
			H-P tolerance	/	/	/	/	Lateral 42.1	/	/	/	/	48.1	/
			Cold pain	/	/	/	/	Lateral 28.5	/	/	/	/	28.3	/
		Women 20-30	Warm	/	/	/	/	Lateral 38.4	/	/	/	/	33.2	/
			Heat pain	/	/	/	/	Lateral 43.9	/	/	/	/	41.2	/
			H-P tolerance	/	/	/	/	Lateral 47.1	/	/	/	/	44.4	/
			Cold pain	/	/	/	/	Lateral 28.5	/	/	/	/	28.9	/
		Men 20-30	Warm	/	/	/	/	Lateral 38.3	/	/	/	/	34.4	/
			Heat pain	/	/	/	/	Lateral 46.9	/	/	/	/	43.8	/
			H-P tolerance	/	/	/	/	Lateral 48.5	/	/	/	/	47.4	/
			Cold pain	/	/	/	/	Lateral 28.0	/	/	/	/	29.5	/

Taylor et al., 1993	1.13 cm^2	Right	Heat pain	/	/	/	/	/		44.6 (1.5)	/	/	46.1 (2.5)	/
		Left	Heat pain	/	/	/	/	/		44.5 (1.9)	/	/	45.4 (2.6)	/
Hirosawa, 1984		Right	Warmth											34.8 (2.21)
	room 25C	Left	Warmth											35.6 (2.76)

Table 2.1 (Continued)

Lower body										
Studies	**Probe area**	**Method**	**Threshold**	**Lateral leg**	**Lateral Knee**	**Dorsal Thigh/anterior thigh**	**Medial leg**	**Dorsal foot**	**Sole of foot**	**Average**
Defrin et al., 2006	3*3 cm	MLE	Warmth	/	/	34.0 (1.1)	/	34.6 (1.5)	/	
		MLI	Warmth	/	/	35.5 (3.0)	/	36.8 (1.2	/	
		MLE	Heat pain	/	/	41.8 (2.8)	/	42.0 (2.6)	/	
		MLI	Heat pain	/	/	43.8 (2.5)	/	44.58 (2.6)	/	
Dyck et al., 1993	10 cm^2	MLI	Warmth	34.3 (2.5)	/	32.5 (1.1)	33.8 (1.6)	33.7 (1.9)	34.6 (2.9)	33.5 (0.71)
	2.9 cm^2	MLI	Hot	40.0 (0.8)	/	36.5 (2.8)	38.1 (2.0)	39.0 (5.0)	40.7 (4.2)	37.8 (1.74)
		MLI	Uncomfortably hot	45.6 (1.9)	/	41.1 (4.2)	42.6 (3.4)	43.7 (3.6)	44.3 (3.0)	42.3 (1.99)
		MLI	Painfully hot	46.1 (2.7)	/	45.5 (2.9)	46.0 (3.2)	44.7 (3.6)	46.9 (1.1)	45.3 (1.3)
Hagander et al., 2000	30*30mm	MLI	Cool	/	/	/	/	31.4	/	
		MLI	Warmth	/	/	/	/	34.3	/	
		MLI	Cold	/	/	/	/	11.7	/	
		MLI	Hot	/	/	/	/	43.7	/	
Meh and Denislic, 1994	25*50mm	MLI	Heat pain (Female)	39.06 (2.93)	/	37.6 (3.21)	/	38.22 (3.01)	/	
		MLI	Heat pain (male)	40.73 (3.2)	/	39.32 (3.82)	/	39.59 (2.76)	/	

Parsons, 2014				/	/	/	/		/
Fruhstorfer et al., 1976	25*50mm	Marstock	Warm	/	/	/	/	36.5 (lateral foot)	/
Kemler et al., 2000	5*2.5 cm^2	MLE unaffected	Warm	/	/	/	/	35.7 (3.8)	/
(1st test listed)		MLE affected	Warm	/	/	/	/	36.5 (4.2)	/
Yarnitsky et al., 1995	46*30mm	MLI	Heat pain	/	/	/	/	45.5	/
Kiesa et al., 2005	25mm*25mm	MLE	Warm	36.12	/	/	/	35.2	/
		MLE	Cool	30	/	/	/	30.71	/
		MLE	Hot pain	46.27	/	/	/	45.4	/
		MLE	Cold pain	7.65	/	/	/	10.36	/
Harju, 2002	25mm	Women 55-65	Warm	/	35.2	/	/	/	41.6
	MLI		Heat pain	/	44.8	/	/	/	45.3
			H-P tolerance	/	47.9	/	/	/	48.5
			Cold pain	/	28.6	/	/	/	27.6
		Men 55-65	Warm	/	34.6	/	/	/	39.4
			Heat pain	/	39.8	/	/	/	44.4
			H-P tolerance	/	43.6	/	/	/	47.5
			Cold pain	/	28.8	/	/	/	27.8
		Women 20-30	Warm	/	38.9	/	/	/	41.8
			Heat pain	/	44.3	/	/	/	47.3
			H-P tolerance	/	48.5	/	/	/	50.2
			Cold pain	/	28	/	/	/	27.4
		Men 20-30	Warm	/	35.9	/	/	/	36.4
			Heat pain	/	41.6	/	/	/	41.8
			H-P tolerance	/	46.4	/	/	/	44.8
			Cold pain	/	28.8	/	/	/	28.4

Taylor et al., 1993	1.13 cm^2	Right	Heat pain	44.6 (1.6)	/	/	/	46.1 (3.0)	/
		Left	Heat pain	44.6 (1.4)	/	/	/	45.8 (2.3)	/

In general, when the local human skin temperature reaches about 42 ℃ to 45 ℃, pain sensations begin. The threshold for thermal discomfort was identified to be 43 ℃, by asking participants to hold a temperature controlled copper handle and make ratings (Lawrence and Bull, 1976). The heat pain threshold for skin temperature was found to be 44.6 ℃ (Loyd-Smith and Mendelssohn, 1948). Similarly, Hatton and Halfdanarson (1982) identified 44 ℃ as the beginning of reported pain from participants. Defrin et al. (2006) showed that the pain threshold was between 42 ℃ for chest skin to 44.5 ℃ for foot skin. Ungar and Stroud (2008) specified the maximum temperatures to be 45 ℃ to prevent burning and pain. The limits were for the skin contact with surfaces of different materials within NASA spacecraft.

Similar to warmth threshold studies, human subjects were also tested with higher temperatures. The resulting heat-pain thresholds are listed in Table 2.1. The consistency of results varied (Fruhstorfer et al., 1976; Dyck et al., 1993; Taylor et al., 1993; Meh and Denislic, 1994; Yarnitsky et al., 1995; Hagander et al., 2000; Kemler et al., 2000; Harju, 2002; Kelly et al., 2005; Defrin et al., 2006). Generally the heat pain thresholds are between 42 ℃ and 45 ℃, with an exception of 37.5 ℃ for maxillary face skin (Meh and Denislic, 1994). The general heat pain thresholds are also close or the same to the activation threshold of nociceptors (Treede et al., 1992; Millan, 1999; Julius and Basbaum, 2001). The noxious heat thresholds for distal body parts, such as hands and legs, are generally higher than for proximal parts, such as the chest and abdomen (Meh and Denislic, 1994; Dyck et al., 1994). However, not all results are consistent. Meh and Denislic (1994) and Kemler et al. (2000) found that the legs had the highest threshold, but Dyck et al. (1994) found that the legs had a lower threshold than the hands. Warm or heat pain temperature thresholds differ between the abdominal area and other body regions but results from different studies conflict. As mentioned previously some studies have found that proximal body parts have lower thresholds but Hanger et al. (1994) reported no significant difference between proximal and distal skin locations.

One reason for the inconsistencies in temperatures could be different measurement methods (Defrin and Peretz, 2004) and different types of stimuli, testing methods, experimental conditions and individual differences (Chery-Croze, 1983; Defrin et al., 2006). Besides variations in testing methods, several other factors can affect the thermal sensation thresholds. Skin area, age, gender, and body sites are associated with variations in sensation thresholds and perceived intensities (Harju et al., 2002). Furthermore, variables such as type of device, rate of temperature change, probe size, testing procedure, race, body mass index, smoking/alcohol consumption, and local skin temperature were listed as possible covariates that affect thresholds (Hagnder et al., 2000).

In some studies, the heat toleration threshold is defined as tolerance threshold, meaning the participants are exposed to stimuli until they could not tolerate (Webb, 1964; Woodrow et al., 1972; Harju, 2002). The heat pain tolerance threshold is not discussed here since most of the consumer devices should not require users to tolerate the heat.

An overview of the effects of factors that may affect thermal sensation are described in details in the following paragraphs. This part of the review helps to understand how thermal sensation and comfort might be affected, and thus provides a scope of variables to be investigated. The factors include the testing methods, temperature change, stimulus duration, heating algorithms, local skin temperature, skin type, size of the stimulus, gender, ethnicity, age, height, body sites, neurological conditions, mechanical contact, materials, and ambient temperature. The described factors are not a full list of variables that can affect thermal sensation, but they are frequently mentioned in multiple literature sources.

2.2.2 Effect of testing method

Some researchers have used the ‘Methods of Limits’ (MLI) to test local thermal sensation thresholds (Dyck et al., 1993; Meh and Denislic, 1994; Yarnitsky et al., 1995; Hagander et al., 2000; Harju, 2002). Others have used the ‘Methods of Levels’ (MLE) for thermal sensation testing (Hagander et al., 2000; Kelly et al., 2005; Defrin et al., 2006). In the MLI participants experience temperature increases at the skin surface from a baseline temperature, and participants need to press a button to indicate when they start to have warm or pain sensations. In the MLE participants start with stimulus at a baseline temperature that then rises to a preset temperature and they are required to press “yes” or “no” to indicate whether they feel the tested sensation of warmth or pain. If participants report “no”, the probe temperature is increased by a fixed small amount (e.g. 3 ℃) and this procedure is repeated until they report a sensation. If they respond “yes”, then there is a decrease of 50% of the interval (e.g. 1.5 ℃). A further “yes” response leads to a further 50% decrease in temperature (e.g. 0.75 ℃), and this procedure is repeated until the incremental level is halved to 0.1 ℃ to set a thermal threshold. MLI has been criticized to interfere with the results because it takes time to convey thermal sensation information through afferent fibers, and with participants’ extra reaction time to press the button, the recorded temperature has been increased, which might lead to an overestimated thermal sensation threshold (Defrin et al., 2006). On the other hand, MLE might eliminate the reaction time artifact. The heat pain threshold is uniform across the body sites tested with MLE, but is higher at distal than proximal regions when tested with MLI, affected by the reaction time because of the distance from thermal receptors at tested body regions to brain varies (Defrin et al., 2006). For the warm sensation threshold, MLI produces higher temperature results than MLE (Defrin et al., 2006). In general , MLI is a faster test method but it may provide higher absolute thresholds;

MLE takes longer but may be more accurate, although in clinical application, the two methods provide similar results to (Yarnitsky and Pud, 2004).

2.2.3 Effect of temperature change rate

The rate of temperature change is a significant factor that affects the thermal sensation threshold, but the effect varies among studies (Claus et al., 1987; Dyck et al., 1993; Pertovaara et al., 1996). Different ranges of temperature change rates and different temperature rising algorithms have been used in testing. In the Dyck et al. (1993)'s study the temperatures were tested in linear ramps ranging from 0.025 ℃/s, 0.05 ℃/s, 0.1 ℃/s, 0.25 ℃/s, 1 ℃/s and 3 ℃/s. The 1 ℃/s and 3 ℃/s ramps led to an overestimated threshold on the dorsal hand and produced higher heat pain thresholds than other ramps. In Claus et al (1987) the range was from 0.9 ℃/s to 7.5 ℃/s, and the warm threshold was the lowest when the ramp was 2.5 ℃/s, and between 0.5 ℃/s to 1.5 ℃/s as the ramp increased, the threshold was increased. Yarnitsky et al. (1993) used ramps of 0.3 ℃/s, 2.0 ℃ /s, and 6 ℃/s, yet as the rate of temperature change increased the heat pain threshold was constant. Pertovaara et al. (1996) used ramps of 3 ℃/s and 10 ℃/s and also different methods of testing and this produced different results. With MLE methods the rate of temperature change (3-10 ℃/s) did not affect the heat pain threshold. However, with the MLI testing they found that a faster rate of temperature rise produces a higher pain threshold than a slower temperature rate, which is consistent with previous studies using MLI (Croze and Duclaux 1978; Pertovaara and Kojo 1985; Yarnitsky and Ochoa 1990). In Pertovaara et al. (1996) both contact and radiant heat stimuli were used to produce the desired skin temperature. A contact thermostimulator was used to present 4 to 6 stimuli with different intensities of contact stimuli. The initial skin temperature was 35 ℃. The temperature change rates were 3 ℃/s and 10 ℃/s. One explanation for this increased threshold with the higher temperature change rate is an increased discharge frequency of C-polymodal nociceptors as the rate of stimulus temperature increased (Yarnitsky et al., 1992). For the results of MLE testing the heat pain threshold remains unchanged. This may occur because the activation thresholds of nociceptors also increase by the rate of stimulus temperature rise, and this counteracts any lowering of the heat pain threshold because of the increase of impulse discharge frequency.

2.2.4 Effect of stimulus duration

Stimulus duration ranging from 2.5 to 10 seconds significantly affects heat pain thresholds and as duration increases the heat pain threshold decreases (Dyck et al., 1993; Pertovaara et al., 1996). Reasons for this result include spatial summation where the increased duration allows heat to be spread to a larger and deeper skin area which recruits more nociceptive afferent fibers, and temporal summation where frequent potentiation of repetitive input from C fibers at spinal cord level may lead to the decrease of heat pain threshold. The characteristics of C fiber nociceptor can be another reason because for CMH fiber, the firing heat threshold was found to increase as the stimuli duration decrease from 30 seconds to 1 second (Tillman et al., 1995a).

2.2.5 Effect of heating algorithms

Besides the effects of the linear ramp of temperature change, different temperature change algorithms can also significantly affect cold, warmth, and heat pain thresholds on different body sites (Dyck et al., 1993). Rapid linear ramps and exponential ramps could overestimate thermal thresholds (Dyck et al., 1993). Algorithms tested included multiple linear ramps of temperature change to defined thresholds, exponential ramps of temperature change to defined thresholds, a 421 stepping algorithm, two-alternative forced choice algorithms, and an operator chosen stepping algorithm. The body regions tested included dorsal foot, sole of foot, lateral leg, medial leg, anterior thigh, dorsal hand, and volar forearm etc., as listed in Table 2.1. Results show that rapid thermal change with linear or exponential ramps, such as linear ramps of 1 ℃/s and 3 ℃/s, and exponential ramps of 2 just noticeable differences (JND)/s lead to overestimation of cold and warm thresholds, but very slow ramps may give acceptable results. Multiple predefined levels of stimuli, such as forced choice and stepping algorithm, produce more accurate results in determining the thresholds (Dyck et al., 1993).

2.2.6 Effect of local skin temperature

Local skin temperature does not significantly affect the thermal sensation threshold (Meh and Denislic, 1994; Pertovaara et al., 1996; Hagander et al., 2000), or the heat pain threshold (Croze et al., 1977; Kojo and Pertovaara, 1987). Local skin temperature ranging from 27 ℃ to 37 ℃ have no significant effect on the warm thermal threshold and only a minor effect on the cool thermal threshold (Hagander et al., 2000). The tested areas were thenar eminence, wrist volar, hand dorsum and foot dorsum were tested (Hagander et al., 2000). However, hand areas generally are more sensitive and consistent in their responses to thermal stimuli and it should be noted that radiant heat stimulus induced increased skin temperature could lead to a decrease in latency for the first heat pain sensation (Luukko et al., 1994; Pertovaara et al., 1996).

2.2.7 Effect of skin type

Skin type has a significant effect on heat pain sensitivity, i.e. glabrous skin sites tend to produce significantly higher heat pain threshold than hairy skin sites, (Hardy et al., 1952; Pertovaara et al., 1988; Taylor et al., 1993; Pertovaara et al., 1996). Taylor et al. (1993) tested the heat pain thresholds on both glabrous and hairy skin areas for both left and right limbs. The tested body sites included two glabrous skin areas, the thenar eminence and pedis plantum, and two hairy areas, the dorsal lateral forearm and lateral calf at leg. The thermode was a plate with diameter of 1.2 cm. The tested temperature ranged from 34 ℃ up to 49.5 ℃ for the hairy skin and 52.5 ℃ for the glabrous skin areas. Glabrous skin sites were shown to have significantly higher heat pain threshold than hairy skin sites. Pertovaara et al., (1996) reported higher thresholds for hand glabrous skin than forearm hairy skin area which agrees with earlier findings (Hardy et al., 1952; Pertovaara et al., 1988). The reason for a higher heat pain threshold may be because the response rate of hairy skin nociceptors increase faster with the increase of stimuli temperature, comparing to glabrous skin nociceptors (Campbell and Myer, 1983; Taylor et al., 1993).

2.2.8 Effect of stimulus size

The heat pain threshold tends to decrease as the area of heat stimulation increases (Meh and Denislic, 1994; Hiltz et al., 1999; Hagander et al., 2000; Kelly et al., 2005). Meh and Denislic (1994) showed that at the thenar eminence the heat pain threshold was 37.7 ℃ for female participants and 40.2 ℃ for males, with a probe surface of 25x50mm. While the heat pain threshold was higher at 43.4 ℃ with a probe surface of 30x30mm (Hagander et al., 2000) and 45.6 ℃ with a probe of 25x25mm (Kelly et al., 2005). Similarly, at the lower medial calf a larger thermode (12.5 cm^2) produced a significantly lower threshold of mean warm threshold of 35.5 ℃ than a smaller thermode (3.75 cm^2) of 36.5 ℃ (Hiltz et al., 1999). A larger thermode was shown to produce lower thresholds in large-scale studies (Dyck et al., 1993; Hilz et al., 1998; Hilz et al., 1999). A 3 ℃/s rate of temperature change produced lower thresholds than a 1 ℃/s (Hilz et al., 1998; Hilz et al., 1999).

2.2.9 Effect of gender

Gender has an inconsistent effect on thermal threshold (Fillingim and Maixner, 1995; Yarnitsky et al., 1995; Kemler et al., 2000; Harju et al., 2002; Kelly et al., 2005). A few studies showed that gender did not affect the pain thresholds (Hiltz et al., 1999; Harju et al., 2002; Kelly et al., 2005; Defrin et al; 2006). However, Harju et al. (2002) found a gender difference in upper arm heat pain threshold. Findings that females showed greater thermal pain sensitivity than males have been reported in several other studies (Kenshalo, 1986; Feine et al., 1991; Meh and Dsnislic, 1994). Females also tend to show higher ratings than males to heat pain stimuli, (Kenshalo, 1986; Lautenbacher and Strain, 1991; Lautenbacher and Rollman, 1993; Filingim and Maxiner, 1995; Filingim et al., 1998). One reason for the gender difference was the difference of resting blood pressure, which was shown to be negatively associated with pain perception. Sheffield et al. (2000) found that females had lower blood pressure than males and higher blood pressure was associated with decreased pain perception.

2.2.10 Effect of ethnicity

Ethnicity has a significant effect on cutaneous pain perception (Chapman and Jones, 1944; Woodrow et al., 1972; Sheffield et al., 2000). Sheffield et al. (2000) investigated the effects of ethnicity and gender on thermal sensitivity. Thermal stimuli were at 45, 46, 47, 48, and 49 ℃. The base temperature was 37 ℃ and the tested body site was right volar forearm. Visual analogue scales were used to measure intensity and unpleasantness. African Americans rated thermal stimuli as more intense and more unpleasant than Caucasian Americans, which corresponds with findings by Chapman and Jones (1944), Woodrow et al (1972), and Walsh et al (1989).

2.2.11 Effect of age

Thermal sensitivity such as the ability to differentiate temperatures was decreased with the increase of age. Stevens and Choo (1998) tested participants' thermal sensations by using a temperature stimulator with a baseline temperature of 33 ℃ in a range of +/- 10 ℃. An increase in age was associated with a decrease in the acuity of differentiating thermal change, especially in the feet and the belly because of the increased of girth with aging. The whole body thermal sensitivity was tested, including finger, thenar, forearm, upper arm, cheek, lips, lower back, belly, thigh, calf sole and toes. In general, peripheral body parts tend to have a worse deterioration in thermal acuity than central parts, and the researchers suggested slowing of peripheral circulation because of aging. The cutaneous thermal sensitivity was also shown to linearly decrease with aging, from years of 21 to 92 (Doeland et al., 1989).

2.2.12 Effect of height

Among all the possible factors, participant's height does not have an effect on thermal sensation thresholds except a weak correlation with heat pain threshold on the hands (Pearson correlation r=0.312, p=0.037) (Kelly et al., 2005).

2.2.13 Effect of body sites

The heat pain threshold is the lowest at the chest with an average temperature of 42 ℃, and highest at the foot with mean temperature of 44.5 ℃ (Defrin et al., 2006). The warm sensation threshold was higher at the chest with an average of 36.2 ℃ and at the feet 36.8 ℃. The thresholds at other skin regions were 35.3 ℃. In most studies, the face and trunk tend to be more sensitive to thermal stimuli and have lower thresholds than the arm and hands, while the legs and feet might have similar or lower sensitivities along with upper extremities (Dyck et al., 1984; Claus et al., 1987; Taylor et al., 1993; Steven and Choo, 1998; Hagander et al., 2000; Yarnitsky and Pud, 2004).

More specifically for warmth detection and heat pain threshold, the face and volar forearms have the lowest values and the legs and feet have the highest values in comparison with other body sites (Dyck et al., 1993). For cool and warm sensation thresholds, it was shown that the hand is more sensitive than the foot (Hagander et al., 2000). Similarly the hand has a lower warm perception threshold compared to the foot (Fruhstorfer et al., 1976; Kenshalo, 1986; Yarnitsky, 1994). However, the hand has equal sensitivity to the foot for cold and heat pain thresholds (Kenshalo, 1986; Dyck et al., 1993; Yarnitsky et al., 1995). The thenar eminence is more sensitive than other areas at the palm, and the fingertips are less sensitive than the hand and arm (Steven and Choo, 1998; Wilson, 2013). The thenar eminence is most sensitive for warm and cool detection thresholds. Little individual variation in thresholds is found at the thenar eminence (Bartlett et al., 1998; Hagander et al., 2000). Thenar eminence shows a lower warm threshold than foot, regardless of the testing methods used. For example, for 7 years to 11.9 years old participants' warm thresholds were +1.4°C for the thenar eminence vs. +2.3 ℃ for the dorsal foot (Hiltz et al., 1998), and for those 40 years to 55.9 years old the warm thresholds were 32.7 ℃ for the thenar eminence vs 35.6 ℃ for the foot (Yarnitsky and Sprecher, 1994). However, the heat pain thresholds between the thenar eminence (45.7 ℃) and the foot (45.5 ℃) were not significantly different (Yarnitsky et al., 1995). In general, the rank order of skin areas for thermal sensitivity from highest to lowest are the lips, forehead, cheek, palm, shoulder, lower back, forearm, upper arm, finger, thigh, belly, calf, sole of foot, and toe (Claus et al., 1987; Stevens and Choo; 1998; Wilson, 2013).

The warm sensation threshold and heat pain threshold are not necessarily correlated across the body parts, which means that a high heat pain at a certain body areas does not necessarily mean a high warm sensation threshold at that area (Dyck et al., 1993; Defrin et al., 2006). The results from Defrin et al. (2006) show that the MLI produces higher temperatures than the MLE by an average of 1.6 ℃ higher for the heat pain temperature, and 1.56 ℃ for a warm sensation temperature. More specifically, the heat pain threshold is much higher than the warm sensation threshold for the areas of chest, forearm, hand, thigh and foot, and the difference is more than 6 ℃. The difference at chest is significantly lower than the other body parts. The mean heat pain threshold (HPT) is around 42 ℃ for MLE, over 43 ℃ for MLI; warm sensation threshold (WST) is about 34 ℃ for MLE, and about 35 ℃ for MLI, as shown in Table 1. WDT is varies largely different among body sites, but less for cold pain threshold and heat pain threshold. The reason could be the less dense warm receptors than cold and pain receptors. WDT also varied more among individuals than HPT (Dyck et al., 1993).

No significant difference was found between left and right side of a person. Although previous studies occasionally report slightly lower sensitivity for pain perception of right side of body, the researchers found that in the real world the difference of unpleasantness was not significantly different. (Taylor et al., 1993; Meh and Denislic, 1994; Sarlani et al., 2003)

2.2.14 Effect of neurological conditions

Sensory deficits can happen for different neurological conditions, such as stroke, diabetes, spinal cord injuries, small fiber neuropathy, white fingers and etc. (Fruhstorfer et al., 1976; Jamal et al., 1985b; Ziegler et al., 1988; Lindsell et al., 1999; Shy et al., 2003; Shukla et al., 2005; Yarnitsky and Granot, 2006). Jamal et al. (1995b) tested 143 patients with peripheral neuropathy for heat and cold sensation thresholds on ankle and wrist, and found that 99% of the participants have one or more abnormal thermal threshold. Patients' peripheral neuropathy in the Jamal et al. (1985b) study were caused by various conditions including diabetes, alcoholic neuropathy, blood disorders, rheumatoid arthritis, and drugs etc. Patients tended to have higher mean heat sensation threshold than normal participants (Jamal et al., 1985a, b). More specifically, about 22.5% of the tested patients with Type I diabetes had abnormality in warm sensation threshold (Ziegler et al., 1988). Participants exposed to hand-transmitted vibration (e.g. vibration-induced white finger) have a significantly higher hot sensation threshold (42.1 ℃ for the digit 3 of right hand) than the control group (39.9 ℃ for the digit 3 of right hand) (Lindsell et al., 1999). Patients with small fiber neuropathy but not diagnosed as peripheral neuropathy were also shown to have a significantly higher warm thermal sensation threshold in foot and hand than the control normal group, and the mean values are 42.4 ℃ versus 36.16 ℃ for foot and 38.1 ℃ versus 35.14 ℃ for hand (Shukla et al., 2005).

Larger scale normative data for normal human subjects on thermal sensation or heat pain thresholds has been collected with repeatability and can be used as references for clinically diagnosing neurological conditions (Claus et al., 1987; Meh and Denislic, 1994; Yarnitsky and Sprecher, 1994; Yarnitsky et al., 1995; Hilz et al., 1998; Hiltz et al., 1999). The sample sizes in the studies ranged from 106 to 225, and participants ranged from children and juveniles (Hilz et al., 1998) to adults (Yarnitsky and Sprecher, 1994; Yarnitsky et al., 1995; Hiltz et al., 1999). The testing methods used varied, from either the MLI (Meh and Denislic, 1994; Yarnitsky et al., 1995; Hilz et al., 1998; Hiltz et al., 1999) or the MLE (Yarnitsky and Sprecher, 1994).

2.2.15 Effect of mechanical contact

The nature of mechanical contact with a thermal stimulus may change the temperature perception quality and intensity (Green, 2009). During innocuous temperature ranged cooling or heating, nociceptive sensations such as burning and pricking were found during both dynamic and static touch, but dynamic contact can suppress the sensation significantly and reduce the intensity (Green, 2009). Participant were tested on the forearm and palm areas with both warm stimuli at 38 ℃, 40 ℃ and 43 ℃, as well as cool stimuli at 28 ℃, 25 ℃ and 15 ℃. Both static and dynamic contacts were tested. Static contact means that skin is in contact with thermode the whole time while in the dynamic contact means participant’s hand grasped and released the thermode, to trigger the stimuli to be heated or cooled to a target temperature, and then held the thermode again for 5 seconds. The hand was shown to be less sensitive than the forearm, i.e. less nociceptive thermal sensations were reported at hand at innocuous temperatures than at the forearm. Similarly in previous research it was shown that heat pain thresholds were higher on the palm than the forearms (Taylor et al., 1993; Kelly et al., 2005). With innocuous temperature, burning was the most reported nociceptive sensation. At 43 ℃, pain was reported significantly more on the forearm than on the hand. Green (2009) suggested that some transient receptor potential ion channels such as TRPM8 (for cold), TRPV3 and TRPV4 (for heat) were active during the contact of innocuous temperature stimuli. The author also concluded that to understand haptic thermal perception, not only thermal stimuli properties but also tactile information was necessary.

The perception of physical surfaces, including tactile sensitivity, perception of roughness, and vibrotactile sensitivity can also be affected by skin temperature, as shown by a series of studies (Green et al., 1979; Verrillo and Bolanowski, 1986; Gescheider et al., 1997; Zhang et al., 2009). In the study by Green et al. (1979), participants' index finger skin temperature was stabilized in an air-conditioned temperature box, and heat lamps were used to warm up the finger. The temperatures tested were 10, 15, 20, 25, 32, 37 and 43 ℃. The roughness stimuli were plates with different groove widths of the, 0.18, 0.38, 0.51, 0.65, 0.76 and 1.02mm wide. Sensations of roughness magnitude were reported by participants with numerical values. Ten participants were tested. Perception of roughness was degraded when skin temperature was cooled below normal skin temperature, while the perception was enhanced or remained the same when skin was warmed above normal skin temperature. Factors contributing to the results include changes in receptor function and vascular and tissue effects. Receptor sensitivity might be reduced by lowering the skin temperature.

In Zhang et al.'s (2009) study tactile information was affected by non-noxious heat. The tested temperatures ranged from 40.5 to 43 ℃. The participants' palm and digits were in contact with a stimulator. With warming of the skin the detection of vibration was improved meaning that the vibrotactile thresholds decreased with increasing skin temperature, but the amplitude discriminative capacity was not changed by the heat.

2.2.16 Effect of materials

Materials can also affect thermal sensation (Parsons,2014). Participants have been asked to touch handrails and rate their thermal sensations in a scale from 0 to 6, with 0 meaning very cold and 6 meaning warm. The tested materials include wood, aluminum, nylon and steel (Halabi and Parsons, 1995; Parsons, 2014). Similar studies have been conducted by Herrman and Parsons (unpublished) on barefoot tests on flooring with different materials ranging from ceramic, wood, concrete and carpet (Parsons, 2014). Results showed that the initial thermal sensation and comfort rating varied according to the different materials and for the surface temperatures below 30 ℃ the aluminum surface was perceived cooler than wood or nylon surfaces, but above 30 ℃, the aluminum was perceived to be warmer than the other two. The difference in sensation can be caused by different material properties, such as thermal conductivity, specific heat, and specific gravity (Wang et al., 2001).

Among the quantitative sensory testing studies few were conducted with different surface materials and clothing, since standardized procedures were required for reproducible test results. However, materials are important for heat transfer from device surfaces to human skin. Early data was provided by Webb (1964) on astronauts about conductive heating pain and burns with metal surfaces (Parsons, 2014). In Webb's study a variety of body areas were tested including hand, kneecap, fingertip, hand palm, forearm and upper arm. Clothing was also considered, ranging from bare skin to with different suits. Metal surface temperatures and average tolerance time were recorded and listed. It was shown that the tolerance temperature could vary a lot with the different clothing. Elbow (with suits) and knees (bare skin) can even get second-degree skin burns without the sensation of heat pain (Parsons, 2014). Therefore more research is needed with consideration of warm surface materials and clothing for more specific applications such as the use of laptops and tablets.

2.2.17 Effect of ambient temperature

Ambient temperature can affect the human perception of thermal stimuli and pain. Strigo et al. (2000) showed that people perceived less intensity for cold and hot stimuli presented to the skin in cool ambient temperatures but more intensity and unpleasantness for hot stimuli presented to the skin in warm environments. The tests were conducted in three indoor temperatures, 15 ℃ (cool), 25 ℃ (neutral) and 35 ℃ (warm). Humidity was held constant at 35-45%. Multiple five-second stimuli from 0 to 50 ℃ were applied to the volar forearm. The skin temperature was kept at 30 ℃. Responses were measured in two dimensions including perceived intensity and unpleasantness of the stimulus with visual analog scales. Mean measured skin temperatures (chest, arm, thigh and mid-calf) were changed by environmental temperatures, being 30.1 ℃ for the cool room, 33.4 ℃ for the neutral room, and 34.5 ℃

for the warm room. Core temperature was not affected significantly. In the cool environment, the perceived intensities for both heat (44-50 ℃) and cold stimuli were reduced. However, in the warm environment, the perceived sensitivity did not change. Hot stimuli were even rated with higher intensity and lower pain threshold in the warm environment than both the cool and neutral environment. In contrast to the pain rating, the unpleasantness of hot stimuli (50 ℃) was rated higher for the warm environment and cold stimuli were rated more unpleasant in the cool environment. Lower pain ratings for noxious stimuli in cool environments is consistent with animal studies which show that reaction times to heat increase in cool environments (Schoenfeld et al., 1985; Osgood et al., 1990), but this is in conflict with Duclaux and Russek (1977) who found that the heat pain threshold were not affected when the skin was in warm or cold water baths, and Hagander et al. (2006) who found that local skin temperature did not affect thresholds. Strigo et al. (2000) suggested that the mechanism could be that the cold environment may have changed some of the nociceptive neurons that are active for both cold (less than 25 ℃) and hot stimuli (above 44 ℃). A-delta fiber activity probably was activated in the cool environment and this may have led to inhibition of thermal nociceptive activity and thus suppressed thermal pain. The finer scales might be another reason for the result difference.

2.3 Discomfort ratings over both warmth and heat pain ranges

In addition to heat pain thresholds testing, studies have been conducted to obtain subjective ratings from human participants in contact with thermal stimuli at both innocuous and noxious temperatures. Among multiple pain scales, the visual analog scale (VAS) and numeric pain rating scale (NRS) have been widely used for both patients' pain due to disease and experiment induced pain, and it has been shown that for both acute and chronic pain, these two scales are equally sensitive and either can be used (Yarnitsky and Granot, 2006). Although gender did not affect the pain thresholds, females tend to rate higher pain for all body sites than males (Kelly et al., 2005). Pain ratings were consistent among body sites, although there was greater variability for noxious than innocuous temperature thresholds. Similarly, Harju (2002) found no age or gender differences for warmth and heat pain thresholds for the thenar, foot and knee, except there was a difference for the upper arm. In contrast, subjective perceived intensity was varied by age, gender and specific body areas.

Strigo et al. (2000) used a VAS to measure participants' responses of perceived intensity and unpleasantness for thermal stimuli, with 0 as no thermal sensation or no pain, and 100 as extremely unpleasant or extreme pain. Green (2009) had used an A 7-level general Labeled Magnitude Scale to determine the intensity and quality of thermal sensations induced by innocuous stimuli, ranging from "no sensation" to "strongest imaginable sensation".

2.4 Skin burn

Skin burn can happen at temperatures close to or overlapping with the static temperature threshold for the human perception of pain. Very early studies, such as Cohnheim (1873) using animal skins had shown that when the skin contact temperature reached to 42 to 47 ℃, for prolonged time, the skin cells could die (Parsons, 2014). With long enough contact with local warm surfaces, a skin burn can happen with temperatures above 43 ℃ (Parsons, 2014). However, for short contact times less than 10 seconds, the skin burn threshold may vary widely according to different contact surface materials. For example, in ISO 13732-1 (2006) it is shown that a skin burn will not occur at a temperature of 55 ℃, when the skin is in contact for bare uncoated metals for 10 seconds. However, the threshold can be increased to over 65 ℃ when skin is in contact with smooth ceramic, glass and stone for 10 seconds because of the lower thermal conductivity of these materials.

Skin burn data with real human participant experimental is rare because of ethical problems. Eight humans participated a study of skin contact with hot surfaces (Moritz and Henrique, 1947), and the resulting data has been used widely to predict skin burn status in different standards. According to the above study of human skin burns, one of the participants had complete epidermal necrosis when their skin was exposed to temperature of 47 ℃ for 18 minutes (Parsons, 2014). Another skin burn and pain test were conducted with fingers for the temperatures ranging of 45 ℃ to 129 ℃ on four human subjects with different materials, and the exposure time to blister was predicted (Stoll et al., 1979). High temperature tests on human skin burns is beyond the scope of the present research, but harm such as blistering and the different degrees of burns can happen for the skin in contact with high temperature surfaces.

Skin damage can be classified in several ways, and in the US skin burn is commonly classified as one of three degrees. First degree means superficial partial skin deconstruction; second degree means deep partial skin deconstruction and the third degree means whole skin destruction (Parsons, 2014). In another classification the skin damage from a burn can be classified from 1st degree to 4th degree (Diller, 1985). Researchers have not found a relationship between discomfort and skin burn severity (Parsons, 2014)

To prevent skin burns, multiple standards on surface temperatures have been created for product designs. The following section will discuss most current standards and guidelines for limiting surface temperatures from different international agencies.

2.5 Previous standards and guidelines on warm or hot device surfaces

Current design guidelines and standards for electronic device surface temperature limits are usually based on the temperature that leads to the burning of skin, rather than user comfort. In the American Society for Testing and Materials (ASTM)'s C1057 – 12 Standard practice for determination of skin contact temperature, two methods were presented for determining the skin contact temperature: mathematical approximation with formula, and the use of thermesthesiometer as an analogue for the human sensory system. The procedures presented in the standard practice define the acceptable contact time to prevent any degree of skin burning, and to identify burn hazard potential. ISO 13732-1 (2006) provides human skin burn threshold in contact with a hot surface, along with methods to assess the risks of skin burning. However, the method from ISO has no information on human thermal pain information and none of the above standards or published procedures address the issues of different levels of thermal discomfort when human skin is in contact with warm/hot surfaces.

In addition to burn thresholds, British and European standards also provided pain thresholds. In BS 4086 (1966) and BS PD 6504 (1983), the skin burn threshold and pain sensation threshold in contact with different materials such as metals, porcelain, plastics and rubber. In BS 4086 (1966), three levels of exposure times were classified for the maximum surface temperature of domestic equipment, handle during use (long contact time), knobs touched for short period (short time contact), and accidental contact or very short periods. BS PD 6504 (1983) also contains discomfort thresholds, pain thresholds and skin burn information for different materials for temperatures above 50 ℃. European standards EN 563 (1994) was based on the human skin burn data from Moritz and Henriques (1947) and thermesthesiometer by Siekmann (1990), and provided burn thresholds and contact temperature data for 1 to 10 seconds exposure, but no discomfort information (Parsons, 2014).

ISO 13732-2 (2001) showed human subjects' initial sensation ratings for human skin in contact with moderate temperatures (10-40 ℃). Several factors that could affect thermal sensation were listed, including a person's thermal state, body part thermal state, skin temperature, environmental temperature, type of object and surface materials. Therefore, it is possible that warm surfaces might be comfortable for people in cool environment and vice versa (Parsons, 2014). In the standard the initial thermal sensation prediction was presented for hand in contact with rail, foot in contact with floor and sitting on the floor. For hand thermal sensation, bare hand was in contact with handrail of a staircase and a door handle with different materials such as wood, plastic, steel and aluminum.

2.6 Current research on laptop heat effects on human

Multiple cases of skin damage from the prolonged use of laptops have been reported in medical studies (Billic and Adams, 2004; Paulius et al., 2008; Bachmeyer, 2009; Arnold and Itin, 2010; Patel and Leon-Villapalos, 2011; Fernández-Portilla et al., 2012). The skin damages ranged from a deep skin burn to more commonly the condition of erythema ab igne, clinically characterized as reticular, pigmented skin lesions (Riahi and Cohen, 2012). Further, prolonged use of a hot laptop can increase the thigh temperature, leading to an increase in scrotal temperature up to 2.8 °C, which may be even associated with male infertility (Sheynkin et al., 2005).

Erythema ab igne is caused by repetitive exposure to mild heat that is either cutaneous or radiation (Kibbi and Tannos 1998; Riahi and Cohen, 2012). Heat ranging from 43 to 47 °C usually can cause this condition (Kibbi and Tannos 1998; Riahi and Cohen, 2012). Historically, erythema ab igne has been found among elderly patients and people in cold climates being too close to hot devices such as a fireplace, heater, radiator, heating blanket, stove etc. (Bachmeyer et al., 2009). However, in recent years erythema ab igne has been reported with mobile devices, such as laptops (Riahi and Cohen, 2012) and cell phones (Dela and Satter 2012). Since the first reported case of laptop induced erythema ab igne reported in 2004, 15 reports were found in different languages (English, French, German, Portuguese and Swedish journals) and listed up to 2012 by Riahi and Cohen (2012), as shown in Table 2.2. The table includes the duration of exposure, patients' description and clinical appearance in each case.

Table 2.2. List of past cases of laptop-induced erythema ab igne, adopted from Riahi and Cohen (2012)

Case	Age (y) Race Sex	Duration of exposure	Clinical Appearance
1	12/C/F	11 months	Extensive violaceous marks on the dorsal surface of both thighs, more intense on the right
2	17/ NR/F	1 year	Patchy, reticulated mildly erythematous to brownish lesions on the front of thighs, more pronounced on left
3	18/C/F	NR	8x6 cm area of reticulated, browning, macular pigmentation on the left breast
4	20/C/F	2 months	Asymptomatic pigmentation in a net-like distribution on the thighs bilaterally
5	21/AA/F	2 years	Hyperpigmented, reticulated lesions on lower legs more pronounced on the left. The lesions corresponded to the underside and border of her laptop computer
6	25/C/F	6 months	Asymptomatic, reticular pigmentation on the thighs, more pronounced on the left
7	26/SA/F	2 months	Large, asymptomatic patch of reticulated hyperpigmentation on right anterior thigh
8	40/C/F	NR	Asymptomatic, reddish-brown, reticulated eruption
9	48/C/F	NR	Patchy, reticulate pigmentation on thighs with increased pigmentation on the right
10	9/C/M	NR	Reticular hyperpigmentation on left thigh
11	12/C/M	Several months	Reticulate pigmented macular dermatosis with telangiectasia on the left thigh
12	15/C/M	Several months	Livedo reticularis-like eruption on both thighs, more pronounced on the left

13	21/C/M	3 months	Reticulated, dark reddish-brown pigmented patch with undefined border on left thigh
14	26/C/M	NR	Reticular and brown pigmentation on anterior aspect of right thigh
15	50C/M	2 weeks	Well-defined, brown, mildly erythematous, reticulated patch on the anterior left thigh

AA = African American; C = Caucasian; CR = Current Report; F = female; M = male; NR = not reported; SA = South Asian American.

The typical cases reported for laptop induced erythema ab igne are mostly young adults with age of 26 (12 out of 15 in Table 2.2) or younger, however, only a minority are middle school students (Riahi and Cohen, 2012). A possible reason inferred by the authors is that middle school adolescents were more likely to use a desktop at school or home instead of laptops (Riahi and Cohen, 2012). It is commonly observed that erythema ab igne or skin burn appears after the user's use of a laptop on the thighs for 2 to 3 hours per day for a period of time, and the patients tend to be college students or similar aged information technology workers.

More serious skin damage, such as second and third degree skin burns, caused by laptop computers has been reported (Paulius et al., 2008; Patel and Leon-Villapalos, 2011; Tsang et al 2011; Paprottka et al., 2012). For example, a patient had a deep second-degree skin burn on the right thigh he left a laptop on his highs for 6 hours (Paulius et al., 2008). Under optimal ventilation on a hard surface desk the laptop bottom's maximum surface temperature was shown to be 37.2°C, which is lower than the superficial skin burn threshold (Suzuki et al., 1991). The authors explained the reason to be the thigh blocking the hot air flow of the ventilation exhaust and leading to a higher surface temperature. Similarly, three more full thickness skin burns that required surgery were reported (Paprottka et al 2011; Patel and Leon-

Villapalos, 2011; Tsang et al., 2011). Tsang et al. (2011) reported that a patient fell asleep and left the computer on his lap, and woke up 3 hours later with a right thigh burn. Paprottka et al. (2011) reported that a wheel chaired patient with paraplegia had second and third degree burns on both of her feet after 1 hour using a laptop on her lap. A laptop power adaptor was reported to lead to a young man's full thickness burn of his lower leg and the patient had to undergo surgery (Patel and Leon-Villapalos, 2011).

2.6.1 Computer heat production

The components in laptop computers that generate most heat are the central processing unit (CPU) and graphic processing unit (GPU), the power supply and some other integrated circuits (Giraldi et al., 2011). The battery, optical drive, hard drive and external power adaptor can also generate large amounts of heat (Arnold and Itin, 2010; Paprottka et al., 2012). The heat can be either dissipated with air cooling or liquid cooling, and the use of fan cooling is commonplace (Giraldi et al., 2011). However, as dust accumulates, small objects can obstruct and jam the fan, or insufficient space is left for ventilation, and the computer can overheat and cause erythema ab igne or skin burn (Giraldi et al., 2011). An hour use of laptop on a user's thighs can cause a significant increase of skin temperature (Sheynkin et al., 2005). The laptop bottom surface can reach up to 50 ℃, beyond the threshold of skin burn if in contact for prolonged time (Paulius et al., 2008; Bachmeyer et al., 2009; Riahi and Cohen, 2012). The left anterior thigh tends to be involved in more reported erythema ab igne cases (53%) than the right anterior thigh (27%) or both thighs and in total 14 out of 15 laptop related erythema ab igne cases happen on the thighs (Riahi and Cohen, 2012). The prevalence of unilateral thigh burns corresponds to the location of heating elements such as the power input, CPU, GPU and ventilation in laptop computers (Riahi and Cohen, 2012).

Laptop surface temperature has been measured when placed on a hard solid surface in optimal ventilation conditions (Paulius et al., 2008; Tsang et al 2011). The study (Paulius et al., 2008) showed that the surface temperature of certain laptops can exceed the threshold of skin burn, and thus could be risk factors for skin burns. In an air-conditioned room, Paulius et al., (2008) used an infrared thermometer to measure bottom surface temperature after 4 hours use of on a table for 11 laptop computers. Most temperatures did not exceeded 43.3 ℃ for normal use on the table (Table 2.3). Results showed the major heat sources were the ventilation fan exhaust, laptop base and the power cord (Paulius et al., 2008). However, in a similar test by Tsang et al. (2011), the temperature was shown to be higher (Table 2.3). In this study ten laptops were measured and their hottest zones were reported. The laptops were placed on the tables operating at optimal conditions. However, the maximum temperature reached 55.4 ℃ but for 70% of the laptops surveyed the it was below 42 ℃, which is the deep dermal contact burn threshold (Suzuki et al., 1991). Researchers in both studies expected the laptop temperature to be much higher if in contact with skin or softer surfaces (Paulius et al., 2008; Tsang et al 2011)

In Zhang and Hedge (2014)’s study, researchers surveyed over 100 normally working laptop computers in the field and correlated the surface temperature with users’ thermal discomfort ratings (see Chapter 3). It was found that participants’ thermal discomfort had a positive relationship with the maximum temperature of the bottom surface. Overall about 20% surveyed users reported discomfort on the thigh area. The maximum bottom surface temperature of a laptop ranged from 22 ℃ to 45.4 ℃. Finally a few factors that were identified to be related to the maximum surface temperatures of a laptop, including the years of manufacturing, screen size, the use of a power cord and the software that was running.

Table 2.3 Listing of notebooks operating temperatures with blocked air circulation underneath devices (Paprottka et al., 2011; Tsang et al., 2011).

Listing of notebooks operating temperatures with blocked air circulation underneath devices by Paprottka et al (2011)						
Notebook model	Release date	Max. temp	Min. temp	Hottest zone	Power adaptor	Additional
Apple Macbook White 13"	2006	53.5 ℃	27 ℃	Back upper middle	48.5 ℃	
Apple Macbook Pro 15"	2006	47 ℃	33 ℃	Back upper middle	51.5 ℃	
LG W1-KPCBG 17"	2007	61 ℃	26 ℃	Back centre	52 ℃	Vent at left side heats up to 65 ℃
Acer Aspire 6930G 17"	2008	62 ℃	25 ℃	Back right corner	48 ℃	
Sony Vaio VGN FZ31Z 15"	2008	45 ℃	33.5 ℃	Right middle	55.5 ℃	Vent at left side heats up to 62 ℃
Apple Macbook Pro 15"	2009	46 ℃	29 ℃	Back right corner	46.5 ℃	
Apple Macbook White 13"	2009	46 ℃	32 ℃	Back right corner	42 ℃	
Samsung R780 17"	2010	39 ℃	19 ℃	Back right corner	31 ℃	
Sony Vaio VPCEA3Z1R/N 14"	2010	57 ℃	31 ℃	Back right corner	54 ℃	Vent at left side heats up to 63.5 ℃
Samsung 900X SSD 13"	2011	45 ℃	25 ℃	Back upper middle	41 ℃	
Apple Macbook Air SSD 13"	2011	39.5 ℃	28 ℃	Back right corner	50.5 ℃	
Apple MacBook Pro 13"	2011	44.5 ℃	35 ℃	Back upper middle	50 ℃	
Temperatures at the undersurface with optimal ventilation by Tsang et al. (2011)						
Dell Vostro 3300	/	55.4 ℃	31.3 ℃	Back middle	/	
Apple MacBook Pro	/	47.8 ℃	32.9 ℃	Back right corner	/	
Toshiba A500-15H multimedia	/	45.8 ℃	26.8 ℃	Right middle	/	
Asus K50IN	/	44.2 ℃	26.3 ℃	Back middle	/	
Sony Vaio VPC-F12Z	/	43.8 ℃	25.5 ℃	Back right corner	/	
Fujitsu-Siemens Amilo SA3650	/	42.6 ℃	24.3 ℃	Front right corner	/	

Samsung NP-R590	/	42.5 ℃	23.3 ℃	Back right corner	/
Lenovo Thinkpad SL300	/	38 ℃	28.9 ℃	Right middle	/
HP Touchsmart TM2-1090ED	/	37.5 ℃	32.1 ℃	Right middle	/
Fujitsu M2010	/	36.7 ℃	30.8 ℃	Back right corner	/

To simulate a 3rd degree skin burn caused by laptops, Paprottka et al. (2011) tested the effect of laptop suboptimal ventilation on a soft surface. At a room temperature of 20 ℃, twenty randomly selected laptops played videos for 3 hours with a blanket under the computer to block the ventilation. The base surface temperature was measured with an infrared thermometer. Maximum temperatures for all the tested computers ranged from 39 ℃ to 62 ℃, listed in the Table 2.3. The ventilation and power adaptor could be at very high temperature up to 65 ℃ because of the block of the blanket, which could be correlated with skin burns.

The solution provided by most physicians to prevent erythema ab igne or skin burns is to place the laptop on a solid surface such as a table rather than on the thighs (Bachmeyer et al., 2009; Sudhir et al., 2012). Further medication or even surgery might be needed for skin burns (Paulius et al., 2008; Paprottka et al., 2011; Tsang et al 2011). Previous researchers also suggested that computer manufacturers should be aware of the possible cause of skin lesion when the laptop computer is in direct contact with the users' skin, and warm consumers in the manual (Giraldi et al., 2011; Paprottka et al., 2011).

From the point of view of heat dissipation, heat is unwanted energy from the activities of electronic components. However, heat has been tested in multiple studies as a method to provide feedbacks to users in the field of human-computer interaction. Using thermal feedback has a few advantages such as privacy, rich information, and high accuracy (Lee and Lim, 2010; Suhonen et al., 2012; Wilson et al., 2012).

2.7 *Thermal feedback in Human Computer Interaction (HCI)*

2.7.1 General applications

Temperature changes from electronic devices that produce heat have been used as thermal feedback for human-computer interaction. Thermal feedback has the potential to express emotional messages, to be a casual way of communication, to be used as a notification (Lee and Lim, 2010). Heat as a way of thermal feedback is of little intrusion and well accepted at body parts of hands and wrists (Lee and Lim, 2010). Thermal feedback was used for users to recognize different materials such as copper, aluminum, brass, and bronze etc., in a virtual reality environment (Jones et al., 2003). Wilson et al. (2011) studied the effects of perceived thermal feedback for different skin areas for mobile device use. It was shown that the thenar eminence was optimal for thermal feedback, and 1 ℃/s and 3 ℃/s of temperature change was necessary for participants to perceive the signals (Wilson et al., 2011). HCI researchers categorized cutaneous sense as a comprehensive sense that integrative pressure, temperature, sense of pain, and tactile sense as sense of pressure (Richter, 2012). For the cutaneous sense, when the skin temperature is below 30 ℃ people perceive constant coldness; and when it is above 36 ℃, people sense warmth (Richter, 2012). Thermal feedback can also help with emotional expression, and the haptic modality increased closeness (Lee and Lim, 2010; Suhonen et al., 2012). More specifically, warm and cold thermal feedback can indicate or positive and negative meaning.

Thermal feedback is a valid feedback channel that allows users to accurately identify up to 96.9% thermal icons (Wilson et al., 2012). Thermal icons were defined as the thermal notification that contains information to indicate multiple parameters, such as the source of information (work or personal), and the importance of the message (important or standard). The thermal feedback and vibration were combined to create intramodal stimuli. Participants were tested on thenar eminence with both thermal stimuli and intramodal stimuli about the accuracy. It was shown the intramodal stimuli was 96.9% accurate.

2.7.2 Rate of change and body areas and HCI

Studies have been conducted about stimulus's rate of temperature change, and about the ambient environment's effect on human perception of thermal stimuli (Halvey et al., 2011; Halvey et al., 2012; Wilson et al., 2011; Wilson et al., 2012). The effect of rate of temperature change on thermal sensation had been researched in previous psychological studies (Claus et al., 1987; Yarnitsky et al., 1992; Dyck et al., 1993; Pertovaara et al., 1996), but the their research purpose was to examine thresholds for pain or sensations, not for particular interface design requirement.

In Wilson et al.'s (2011) study, two rates of change (ROC) were tested: 1 ℃/s and 3 ℃/s. The temperature intensities of the stimuli were 1 ℃, 3 ℃ and 6 ℃ changes from starting temperature. The thenar eminence, dorsal surface of forearm and dorsal upper arm were tested. Participants were asked to click a mouse once they felt a temperature change, and to rate the stimulus in terms of intensity and comfort. The reactions were evaluated in indoor statically and walking. It was shown that warm stimuli were less comfortable and more difficult to detect than cool stimuli in both siting and walking scenarios. The thenar eminence was shown to have the highest sensitivity in terms of number of stimuli detected, detection time and the Just Noticeable Difference (JND) in comparison to other body areas. Previous studies (Bartlett et al., 1998; Hagander et al., 2000) have also shown that the thenar eminence is the most sensitive and consistent area for warm and cool detection. Forearm and upper arm areas produced better results than fingers on the JND and detection time. A

3 ℃/s was for faster to be detected but less comfortable than 1 ℃/s. Therefore a 3 ℃/s is recommended for feedback for a time critical event. The thermal just noticeable difference was defined as the minimum amount of temperature change for participant to perceive a temperature change. When the rate of change was below 3 ℃/s, the JNDs decreased as rate of change increased, but from 3 ℃ to 7 ℃ the JND increased as rate of change increased (Pertovaara et al., 1996; Wilson et al., 2011).

2.7.3 Ambient temperature and humidity and HCI

Since thermal feedback may be prone to environmental temperature change, the effect of the ambient environment was also investigated (Harvey et al., 2012). Ambient temperature was proved to have a significant effect on the human detection and perception of stimuli, but humidity had a negligible effect (Givoni et al., 2006; Harvey et al., 2012). Psychological studies of ambient temperature had shown that this affects human perception of the intensity and pleasantness of hot stimuli (Strigo et al., 2000).

In Harvey et al. (2012)'s study, two rates of stimuli's temperature change were tested: 1 ℃/s and 3 ℃/s. The temperature intensities of stimuli were 1 ℃, 3 ℃ and 6 ℃. Thenar eminence and the back of wrist were tested, where watches or other wearable devices can be worn. Two outdoor locations, a garden area and an entranceway were used as test sites. Temperature was not controlled but recorded, from March to July, and the ambient temperature ranged from 8.45 ℃ to 27.75 ℃. 7-point Likert scales were used to measure stimuli intensity and comfort. Ambient temperature had a significant impact on the thermal feedback parameters, such as detection time, number of stimuli detected and perceived comfort. The optimal temperature was in the range of 15-20 ℃, with a detection rate of 84.25% and time of detection of 3.03 seconds and was rated more comfortable.

2.7.4 Clothing

Clothing was not included as a variable in most cutaneous thermal stimuli studies because areas of naked skin are being tested, but it is a necessary consideration for more applied settings, such as the use of thermal feedback in mobile devices. Clothing significantly affected perceived comfort, detection time, and the number of detections, but not the perceived intensity, and the effect of clothing varied among body areas (Harvey et al., 2012). The rate of change, intensities of stimuli and rating scales were the same as previous studies (Wilson et al., 2011; Harvey et al., 2012). Two clothing materials, cotton and nylon with the same thickness were put in between the thermal stimuli and the skin surfaces. Tested body areas included the thenar eminence, left leg upper thigh, and the waist. With clothing there was a need for higher changes in thermal stimuli, but the changes were perceived to be more comfortable than direct contact. Thenar eminence was the most preferred location for thermal feedback in terms of shorter detection time, higher number of detections. Waist was rated as the second best area. In terms of time to detect stimuli and perceived comfort, it was shown that as the thermal conductivity decreased, the time and comfort increased. Therefore, the effect of no material was greater than that of nylon, which was greater than that of cotton. As the thermal conductivity decreased, the number of detections decreased, and more detections were made with no material than with nylon than with cotton. Materials had no effect on subjective stimulus intensity.

2.8 Conclusion

A broad body of literature has been reviewed on thermal receptor fibers, factors that affect thermal sensation, and international standards on thermal comfort and on limiting surface temperatures to prevent skin burns. More recent studies were also reviewed and summarized on the use of thermal feedback for human computer interaction, and the electrical devices such as laptop surface temperature and user thermal comfort. Factors that can affect how human subject perceive cutaneous thermal stimuli has been identified and summarized. Among the factors, several can be manipulated by engineers and designers to improve user thermal comfort. In the dissertation, these factors were tested in a series of experiments, including the characteristics of the stimuli, such as the surface temperature level, the surface material, the rate of temperature change, the environmental temperature, and duration etc. Users' characteristics that cannot be controlled by product designers were not tested, such as age, gender, skin type, the tested body site, and neutral conditions etc.

CHAPTER 3

PRELIMINARY STUDY ON LAPTOP COMPUTER USER THERMAL COMFORT

3.1 Introduction

By the end of 2013, about 64% of Americans own a laptop computer, according to the survey by Gallup (Dugan, 2014). However, overheated laptops because of blocked ventilation and prolonged contact can cause discomfort and even skin issues including some cases of second and third degree skin burns (Paprottka et al 2011; Paulius et al., 2008; Tsang et al., 2011). Laptop use has also been linked to erythema ab igne (toasted skin syndrome) which is caused by repetitive exposure to mild heat ranging from 43 ℃ to 47 ℃ for 2 to 3 hours per day for a period of time (Kibbi and Tannous 1998; Nayak et al, 2012; Riahi and Cohen, 2012).

Current standards and design guidelines aimed at preventing potential skin burns caused by the heat from electronic devices require limiting surface temperatures to a 45.0 ℃ contact temperature (BS PD 6504, 1983; ISO 13732-1, 2006). The ISO 13732-2 (2001) standard provides information on thermal sensation for human skin in contact with moderate temperatures (10.0 ℃ - 40.0 ℃), but only for the feet and hands.

Previous research studies of both noxious and non-noxious cutaneous thermal stimuli have been conducted in laboratories with thermal stimulation provided by relatively small thermal probes in comparison to the laptop contact areas. Pain sensations generally begin when local human skin temperature reaches about 42.0 ℃ to 45.0 ℃, (Hatton and Halfdanarson, 1982; Lawrence and Bull, 1976; Lloyd-Smith and Mendelssohn, 1948). The thresholds for warm sensation for various body sites fall in between 33.0 ℃ and 35.0 ℃ (Defrin et al, 2006; Dyck et al., 1993; Hagander et al., 2000). Body sites, ambient temperatures, stimulus area, duration of stimulation, clothing, and gender are all among the factors that may affect thermal sensation thresholds (Dyck et al., 1993; Harju et al., 2002; Harvey et al., 2012; Hensel, 1981; Strigo et al, 2000).

Paulius et al. (2008) surveyed 11 laptops on a solid surface with optimal ventilation and measured the bottom surface temperature with an infrared thermometer and found the base temperature ranged from 35.0 ℃ to 43.2 ℃ under normal use. Similarly, Tsang, et al. (2011) measured 10 laptops and found that the highest base temperature was 55.4 ℃. To test the effect of suboptimal ventilation Paprottka et al. (2011) studied laptops placed on a soft surface, and found that the temperature at a vent reached 65 ℃, far beyond the skin burn threshold. To mitigate the thermal risks from laptops, there exist products and patents to help dissipate heat more efficiently and to protect users from an overheated surface (Cohen, 2002). However, no previous studies have been found to systematically survey the relationship between laptop heat and user thermal discomfort.

This study is a survey that addresses this gap in the literature by investigating laptop temperatures and surface heat distributions under normal working conditions, along with users' perceptions of laptop heat, and factors that may affect users' thermal comfort, such as clothing, to develop a predictive model. The normal working condition means regular user scenarios, such as the users use laptop computers to conduct daily tasks, such as watching moving, browsing webpages, reading, programming and etc. In these scenarios the users are assumed not to intentionally increase or decrease computer temperatures.

Hypotheses:

H1: Users generally experience thermal discomfort on either hands or laps when using laptops for prolonged time.

H2: Users experience more thermal discomfort as the laptop surface temperature increases.

H3: Users report lower lap thermal discomfort scores using laptops with plastic bottom than with other materials, such as metal or carbon.

3.2 Methods

3.2.1 Participants

One hundred participants (45 men, 55 women) aged 18 to 59 years (average age of 22.6 years) were surveyed while using laptops on their lap or on a hard surface such as a table. 27 out of 100 users wore shorts during and 73 wore jeans, pants or leggings.

3.2.2 Apparatus

A thermal imaging camera (FLIR BCAM SD ResearchIR Max 3.5), with a 120 x 120 pixels detector was used to obtain thermal images of the keyboard side and bottom side surface temperatures. A surface temperature probe (Bruel&Kjaer Indoor Climate Analyzer, Type 1213 with a surface probe) was used to take direct temperature measurements of these surfaces.

3.2.3 Procedure

The survey and thermal measurement were conducted at Cornell University Human Ecology commons area and Duffield engineering hall, both air-conditioned indoor environments. The survey took place during May and September, 2013. The study was approved by Cornell University Institutional Review Board.

A participant was selected if s/he was using laptop on his/her lap or on a table. Sampling was more emphasized on the users placing laptops on their thighs. A verbal informed consent was obtained from the participants prior to the survey. After the questions and discomfort scales were explained, participants filled out the survey. Five-point Likert visual analog scales were used for participants to rate their thermal discomfort on their hands and thighs, indicating the feeling of heat while they were using the laptop. The discomfort scale ranges from no discomfort (1), mild (2), moderate (3), noticeable (4) and considerable discomfort (5). Participants' gender, age, the clothing they wore (pants or shorts), where they place the laptop (on table or on lap), whether there was a laptop case/cover, screen size, estimated daily time he/she uses a laptop on laps, the software program currently running and laptop models were also recorded. A thermal infrared (IR) camera captured thermal images of both the keyboard and the bottom surface heat distribution (Figure 3.1) Laptops from a variety of manufacturers were surveyed, including Acer, Apple, Asus, Dell, HP, Lenovo, Samsung, Sony, and Toshiba, covering most of the popular laptop brands. Screen size ranged from 29.5 cm to 43.9 cm, and laptop model year ranged from 2008 to 2013. Each image was divided to nine 39 x 29 pixels rectangles, as shown in Figure 3.1. The three by three squares were named from number 1 to number 9 in the sequence from left to right, and from top to bottom. For each square in the infrared images, the average, maximum and minimum temperatures, and standard deviation were extracted from the infrared image for data analysis. On the bottom side, areas 1, 4, 7 are in contact with left thigh and areas 3, 6, 9 are in contact with right thigh. The temperatures were averaged among areas 1, 4, 7 as left side temperature 3, 6, 9 were averaged as right side temperature for comparison. Similarly, on keyboard side, area 7 was in contact with left palm and wrist and area 9 was in contact with right palm.

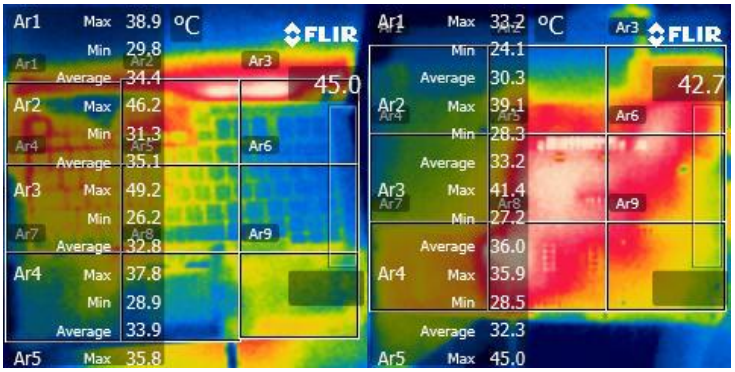


Figure 3.1. Infrared thermal images of keyboard and bottom sides of a laptop computer

Since the materials and colors of the laptop surfaces vary, corrections for emissivity and reflectivity were made. A surface temperature probe was used to make comparisons with IR camera for sampled computer materials. Black and grey plastics, which are widely used as bottom and keyboard surfaces among PC laptop computers, and white aluminum material, which is widely used as bottom and palm placement surfaces among unibody laptops, such as a Macbook pro, were checked. There exists a well-fitted linear relationship between the temperature measurement from the probe and IR camera (R-squares above 0.97). Temperatures from IR camera measurement were corrected with the linear equations derived from the probe and IR measurement data. For aluminum a linear fit was made between the two temperatures, Probe temperature=1.45+0.92IR temperature, R-square=0.991, F(1,49)=858.06, $p<0.0001$. For dark colored plastic material, the linear fit was Probe temperature=3.88+0.82IR temperature, R-square=0.97, F(1,82)=1224.61, $p<0.0001$. Temperatures for an aluminum bottom and palm surface, plastic keyboard, bottom surface, and connection areas were corrected with the above equations.

Descriptive statistics for laptop temperatures and participants demographics were calculated. T-tests were used to compare the difference between temperatures at left and right sides of computer. Cumulative logistic regression for ordinal responses was used to model the discomfort scores. All the analyses were conducted in JMP 10.0.0 (SAS Institute, NC).

3.3 Results

3.3.1 Laptop temperatures and laptop use

Among the surveyed users, 73% placed their laptops on their thigh at the time of survey, and 27% placed laptops on the table. 80% laptops were used without cover and the other 20% were used with either a cover or a case in between the laptop and the surface. On average, participants used laptops on their lap 3.5 hours a day.

The temperature range of the bottom and keyboard surfaces of laptops is shown in Figure 3.2. Although most laptop computer manufactures claim that the working temperature can only reach a maximum of 35.0 ℃, about 25% of the laptop computers' had bottom and keyboard surface maximum temperatures that exceeded 35.0 ℃ under normal working conditions.

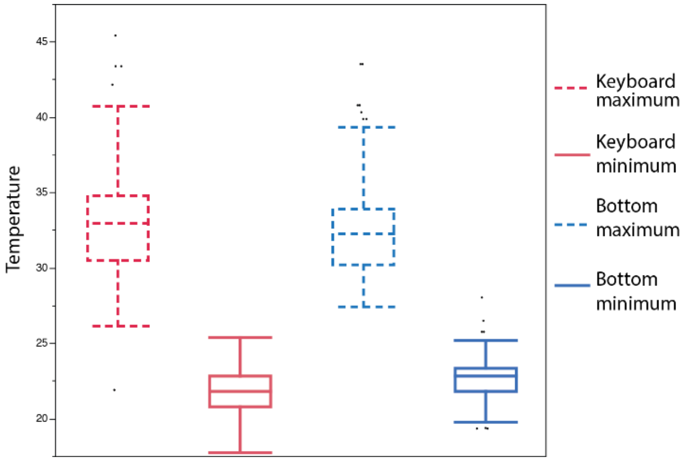


Figure 3.2. Temperatures in general of measured laptops

For the bottom surface in contact with the user's left thigh (areas 1, 4, 7 in Figure 3.1), the average temperature was significantly higher ($t(96)=4.32$, $p<0.0001$) than that in contact with the right thigh (areas 3, 6, 9), with an average of 0.71 ℃

difference. For the keyboard surface palm placement areas 7 and 9, the average temperature of left side was also significantly higher (t(95)=4.73, p<0.0001) than the right side, with an average of 0.63 ℃ difference. No significant difference was found between average temperatures of the keyboard or bottom laptop surfaces.

The software load affected the laptop bottom maximum surface temperature, and the use of video player significantly increased the temperature compared with other types of software running on the computer, F(3, 92)=3.67, p=0.015.

3.3.2 Cumulative logistic regression model for users' thermal discomfort rating

The lap and hands thermal discomfort scores were analyzed with cumulative logit models with discomfort scores as dependent variables. The independent variables were the laptop placement (dummy variable with 0 for on a table and 1 for on a lap), clothing (shorts as 1 and pants as 0), seasonal effect (May as 1 and September as 0) and cover (cover as 1, and no cover as 0). Laptop year of manufacture was transformed to the age of the laptop, ranging from 1 (2013) to 6 (2008) and treated as a continuous variable. For the materials of the laptop, metallic (aluminum, carbon fiber, metal) was set as 1 and plastic as 0. User age and the temperature difference of the left and right sides of the bottom surface (for lap discomfort) and the keyboard surface (for hand discomfort) were treated as continuous variables.

Average and maximum temperatures were highly correlated therefore only one was selected as an independent variable to avoid multicollinearity (for the keyboard surface ρ=0.80, p<0.0001; for the bottom surface ρ=0.77, p<0.0001). Maximum temperatures were selected as variables rather than average temperatures since they may better reflect possible thermal thresholds. A stepwise algorithm with p-value threshold was used to select the significant variables into the model. Multiple models were compared to determine a better-fitted prediction model with the criterion of p-value, Akaike information criterion (AIC) and Bayesian information criterion (BIC).

For the lap discomfort score:

$$logit[P(Y \leq j)] = \alpha_j - 0.21 bottom \max temperature + 0.87 gender - 1.00\ cover$$

$$\alpha_1 = 5.53, \alpha_2 = 8.44, \alpha_3 = 10.23, j = 1,2,3$$

The model was significant (χ2 =23.09, p<0.0001). Lack of fit test for the model showed no evidence for a lack of fit of this model (χ2=167.10, p=0.98). The following variables were significant: bottom surface maximum temperature (χ2=14.95, p=0.0001), gender (χ2=4.45, p=0.035), cover (χ2=3.96, p=0.047). No interaction effects was significant therefore was not added to the model. The intercepts were all significant. Intercept 1 (χ2=9.60, p=0.0019), intercept 2 (χ2=19.46, p<0.0001) and intercept 3 (χ2=25.59, p<0.0001).

For hand discomfort score:

$$logit[P(Y \leq j)] = \alpha_j - 0.14 top \max temperature + 0.22 time\ on\ lap$$

$$\alpha_1 = 4.55, \alpha_2 = 6.49, \alpha_3 = 8.84, j = 1,2,3$$

The following variables were significant: keyboard surface maximum temperature (χ2=5.36, p=0.02), time on lap (χ2=5.64, p=0.018). Intercept 1 (χ2=4.86, p=0.027), intercept 2 (χ2=9.19, p=0.002) and intercept 3 (χ2=13.91, p=0.0002). The whole model test showed the model was significant (χ2=12.94, p=0.0015). Lack of fit test for the model showed no evidence for a lack of fit of this model (χ2=140.39, p=1).

3.3.3 Temperatures at different discomfort levels

Figure 3.3 shows the relationships between maximum surface temperature and hand and lap discomfort scores. For lap discomfort scores a one-way ANOVA showed that the means of bottom surface maximum temperature were significantly different F(3, 93)=5.67, p=0.001. The Tukey test showed that temperatures at level 3 (p=0.003) and level 4 (p=0.02) were significantly higher than level 1, and no other pairs were significantly different.

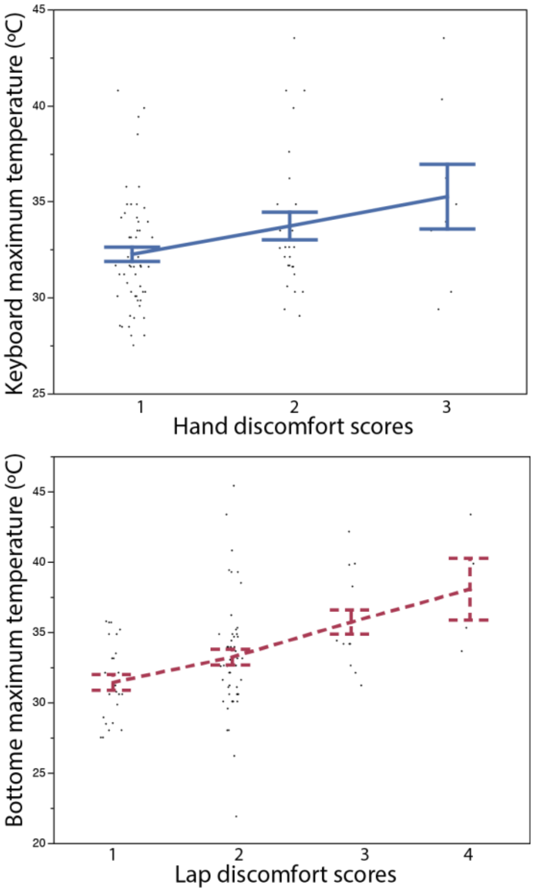


Figure 3.3 Discomfort scores at different temperatures

For hand discomfort scores, the means of keyboard surface maximum temperature were significantly different F(3, 92)=5.19, p=0.033. The Tukey HSD test showed no significant differences. However since the sample sizes were different among the different levels, Dunnett's method was also used for multiple comparisons and temperatures at level 3 and this was shown to be significantly higher than level 1 (p=0.045), but no other pairs were not significantly different.

3.4 Discussion

Laptop bottom surface temperatures were shown to be significantly asymmetrical, being higher ($p<0.0001$) on the left thigh side than the right thigh side among all of the surveyed laptops, confirming the results by Riahi and Cohen (2012) who found that one side of laptop computers has more heat generating elements such as GPU, CPU and ventilation. Corresponding to the current result, skins burning cases or toasted skin syndrome have also been reported for one leg rather than both legs (Arnold and Itin, 2010; Bachmeyer et al., 2010; Miller et al, 2011; Riahi and Cohen, 2012). Similarly, for the keyboard surface palm placement areas (7 and 9), the average temperature of left side was also significantly higher than the right side, with an average difference of 0.63 ℃. A possible explanation is most users may move their right hand to perform mouse and touch tasks. The movement of right hand may help to dissipate heat better than the left hand side, where the hands are usually in contact of the keyboard area most of the time.

3.4.1 Thermal discomfort and its related factors

In general, the ratings of more than moderate discomfort (score equal or more than 3) were more prevalent for the thighs than the palms of the hands. Among all participants, 9.5% reported more than moderate discomfort in palm area and 20.8% in thigh area. In both hands and lap discomfort score models as temperature increased the reported discomfort increased. Clothing was not a significant variable in either model. The parameters estimates for the temperatures were both negative ($\beta_{1=} - 0.14$ for hand model and $\beta_2 = -0.21$ for lap model), meaning that the cumulative probability of no or low discomfort decreased as the maximum temperature at the laptop bottom surface increased. For each 1 ℃ increase in maximum temperature, the odds of reporting a lap discomfort score at a lower level decreased 16%. The trend corresponds well to previous thermal threshold testing research in which heat pain thresholds were relatively higher than heat discomfort thresholds, which in turn were higher than warmth sensation thresholds (Defrin et al., 2006; Dyck et al., 1993; Hagander et al., 2000; Harju, 2002).

The thermal sensation thresholds for the anterior thigh area and the palm area were tested with different sizes of heat stimuli in previous research studies. In Dyck et al. (1993)'s research the hot sensation threshold for thigh area was 36.5 ℃ with a heating probe of 2.9cm^2. The uncomfortably hot or heat pain sensation was consistent across studies around 41 ℃, such as 41.1 ℃ (Dyck et al., 1993), and 41.8 ℃ (Defrin et al., 2006). The heat pain threshold also tended to decrease with a larger areas of heat stimulation, and Meh and Denislic (1994) showed that the heat pain threshold was 37.6 ℃ for female participants and 39.3 ℃ for males, with a probe surface of 25x50mm. Similarly, the hot sensation threshold of thenar eminence is 43.4 ℃ with a probe surface of 30x30mm (Hagander et al., 2000). The heat pain sensation was also lower in Meh and Denislic's (1994) study, with 37.7°C for female participants and 40.2 ℃ for males. Heat stimulus area was had a significant effect on thermal thresholds. For example, a larger thermode (12.5cm^2) produced a significantly lower threshold of mean warm threshold of 35.5 ℃ than a smaller thermode (3.75cm^2) of 36.5 ℃ at lower medial calf. (Hiltz et al., 1999).

In the current research for the lap, the mean temperature producing a no discomfort rating was 31.4 ℃, the mean for mild discomfort was 33.2 ℃, for moderate discomfort it was 35.7 ℃ and for noticeable discomfort was 36.7 ℃ (Figure 3.3). The average temperature for noticeable discomfort corresponds well to the hot sensation of 36.5 ℃ on the dorsal thigh reported by Dyck et al. (1993), but since the heating surface in the present survey is much larger than the heat stimuli with the size of 12.5cm^2 used by Dyck et al., (1993) participants might experience more discomfort than that in the thermode experimental conditions at the same temperate level.

In the present study, for the thermal sensation of the palms the mean temperature for no discomfort ratings was 32.3 ℃, the mean for mild discomfort was 33.7 ℃, for moderate discomfort it was 35.3 ℃ and noticeable discomfort was not reported. The average temperatures for the same discomfort ratings for palm area are similar to the ones with the same ratings for thigh area, however the ratings of more than moderate discomfort is much less prevalent. Among all participants, more than moderate discomfort ratings were more prevalent for the thighs than the palms, although no significant temperature differences were found between the bottom and keyboard surfaces. One explanation may be that the contact area was much smaller for the hands than the thighs and therefore the heat stimulus area was smaller, leading to a higher thermal threshold for the palms in comparison to the thighs. In addition, in previous research the heat pain or hot sensation thresholds for the thenar eminence tend to be slightly higher than those for the anterior thigh (Dyck et al., 1993; Meh and Denislic, 1994; Hagander et al., 2000; Defrin et al., 2006). Further, users may not place their palm on the laptop all the time while the computers usually stay on their lap during the use.

In lap thermal discomfort model, females reported lower discomfort scores (greater comfort) than males ($\beta_2 = 0.87$). Conflicting results have been reported in previous research and the thermal thresholds for females have been found to either be lower or not significantly different to males (Meh and Denislic, 1994; Harju, 2002).

It the lap discomfort model participants may have become less uncomfortable because of the duration of laptop use. In the model $\beta_2 = 0.22$ the cumulative probability starting at the score 1 (no discomfort) increased as duration on lap increased. It is possible that users may get used to the laptop heat because of prolonged contact with the laptop when the temperature was below the temperature that could cause skin damage. Further, the range of average bottom working temperature in the surveyed laptops was from 27.0 ℃ to 45.0 ℃, which overlaps with the adaption temperature range from 28.0 ℃ to 40.0 ℃ reported by Kenshalo (1970).

The use of a laptop case resulted in greater comfort for the users' thigh area. The lap discomfort model, $\beta_3 = -1.00$ indicated that users with a laptop case had an odds of reporting a discomfort score below a certain number of $e^{-1.00} = 0.37$ times that for users without a case, in other words users with a laptop case reported less discomfort than users without a case.

Contrary to expectations, clothing was not a significant variable, however, Harveys et al. (2011) found that cotton and nylon clothing significantly affected perceived comfort and the intensity of thermal stimuli at thighs and the thenar eminence areas. A possible reason for this is that the heat was constant and lasted in hours in the present survey whereas the thermal stimuli in this experiment were dynamic and lasted for no more than 30 seconds.

The temperature asymmetry found in the surveyed laptops, where the temperatures on the left side was significantly higher than the right side, did not affect either the hands or lap discomfort scores.

The laptop construction material did not have a significant effect on either hand or lap discomfort scores. However, in contrast Baugh and Doherty (2011) found that users gave the same opinion scores for metal surfaces with at least an 8 ℃ lower temperature than plastic surfaces. Different temperature ranges may have contributed to these different results. The range of maximum temperatures in the current study was from 27.0 ℃ to 45.4 ℃, while the range in Baugh and Doherty (2011)'s experiments this was from 40.0 ℃ to 56.0 ℃.

The use of video player can increase the laptop working temperature and indirectly affect the users' thermal discomfort. The use of computer cover is recommended since it can effectively reduce the odds of reporting higher discomfort scores (p=0.047).

3.5 Limitations

Although about 100 laptop computers and users were surveyed, it was not possible to survey all of the popular brands or types of laptops. The participants' average age was 22.6 years old, which cannot represent older user groups. Although no seasonal effect was found on users' thermal discomfort, the effect of indoor temperature was unknown. The current survey focused on the normal working conditions with a laptop, but intensive computing situations were not included. Surface temperatures may become noxious for human skin if computation is intense or ventilation is blocked and this results in a further increase in surface temperatures above those recorded in this study, but such situations not sampled in the current work.

In addition, the duration of daily laptop usage on laps daily was only a self-report of the participants. It is only an estimation. Further, no information was collected on the laptops' using duration while the survey was conducted. Therefore it is still unknown, how long participants had been using the laptop on laps, while the study was conducted.

Future work might usefully explore the impact of indoor environmental factors, such as air temperature and relative humidity on users' thermal discomfort during laptop use.

3.6 Conclusion

The study surveyed the normal working temperatures of laptops and asked users how they felt about the heat coming from both keyboard side and bottom side. Relevant factors affecting the laptop maximum temperatures included the model year, screen size, the use of a power cord and the software that was running. Factors that can affect discomfort were surface maximum temperatures, and the use of covers for both keyboard and bottom surfaces. As the surface temperature increased, users tended to report more discomfort. The temperature difference of left and right sides of the laptop did not affect users' thermal discomfort. The results from the survey can inform future laptop heat ventilation and distribution designs from the perspective of regular users under indoor daily usage conditions. The potential factors that can affect user thermal comfort such as heating rate, indoor temperature and humidity will be tested in the future studies.

In addition to laptop computers, the ownership of tablet computers keeps increasing (Zickuhr and Rainie, 2014). Similarly, tablet computer also has heat dissipation issues. In contrast to the rapid growth of tablet computers, the sales of laptops have shown signs of declining (Statista, 2015a). Therefore, it is also necessary to investigate on how user thermal comfort can be affected by tablet computers, and to make further improvement on the heat dissipation.

CHAPTER 4

DEVELOPMENT OF A HEATING SURFACE FOR THE EXPERIMENTAL STUDIES

4.1 Heating Surface Structure

A novel experimental apparatus had to be designed, constructed and programmed, prior to investigating the selected variables to be subsequently tested to understand how user thermal sensation and comfort is affected, including surface temperature, the rate of temperature change, the designated heated areas, and material replacement. In addition, the purpose of the study is to understand the effect of a tablet size stimuli on user thermal responses, thus the surface was designed to be in the size of a typical tablet computer.

For this apparatus a tablet computer sized (24.4 x 18.5 cm) heating surface was developed (Figure 4.1). The surface was designed to be the same width and length as an Apple iPad, since iPad has the highest market share globally (Statista, 2015b). The prototype comprised nine 5.1 x 2.5 cm rectangular heating pads connected with heaters (Kapton 28 Volts, 20 Watt) and Resistance Temperature Detectors (RTD) sensors (SA1-RTD-4W-80). The nine pads can be controlled separately, to test different areas that can be heated. The 20 Watt Kapton heater was chosen to maintain the heat at each heating pad. The heater has sufficient power of 10W/in2 to increase the heater's own surface from 75°F to 100 ℉ in 3 seconds, in the regular room temperature of 70 ℉. The four-wire RTD sensor is fast in response within 1 second and has very high accuracy of ±0.12% at 0 ℃. In addition, it has a large range of working temperature ranging from -73 ℃ to 260 ℃.

The frame was in Acrylonitrile butadiene styrene (ABS) plastic and the heating pads were made of aluminum. An ABS plastic cover was built to fit the top side of the heating surface and to stabilize the wires inside the prototype; the structure of the frame and the cover is shown in Figure 4.2a and 4.2b. This system allowed the surface temperatures to be controlled at different levels. The rate of temperature increase can also be controlled. In the experiments the surface temperature ranged mostly from 34 ℃ to 44 ℃.

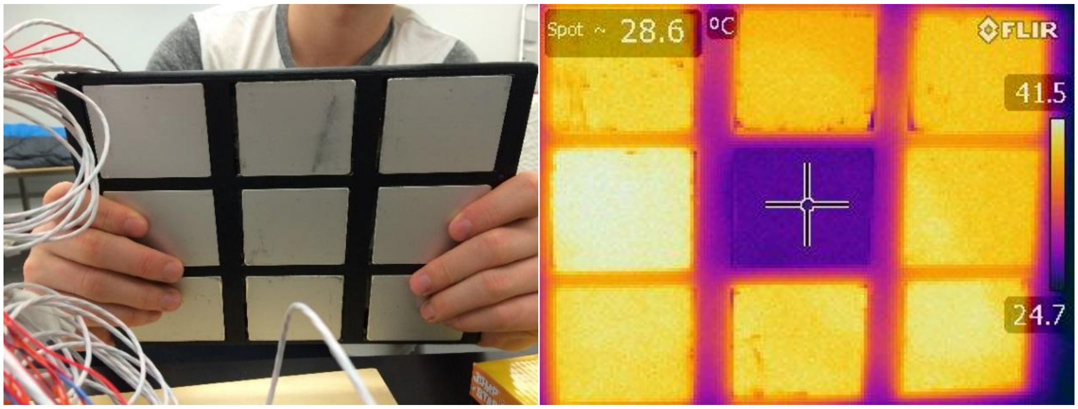


Figure 4.1. A participant holding the heating surface (left) and the Infrared (IR) image (right)

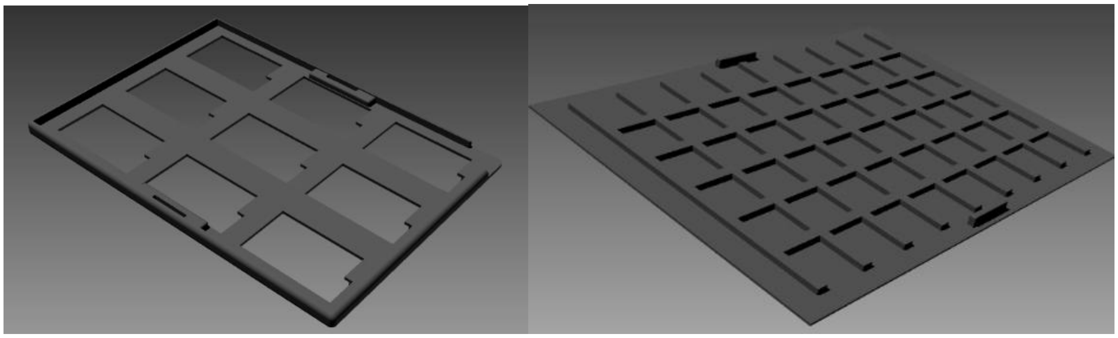


Figure 4.2a. Frame and cover of the heating surface

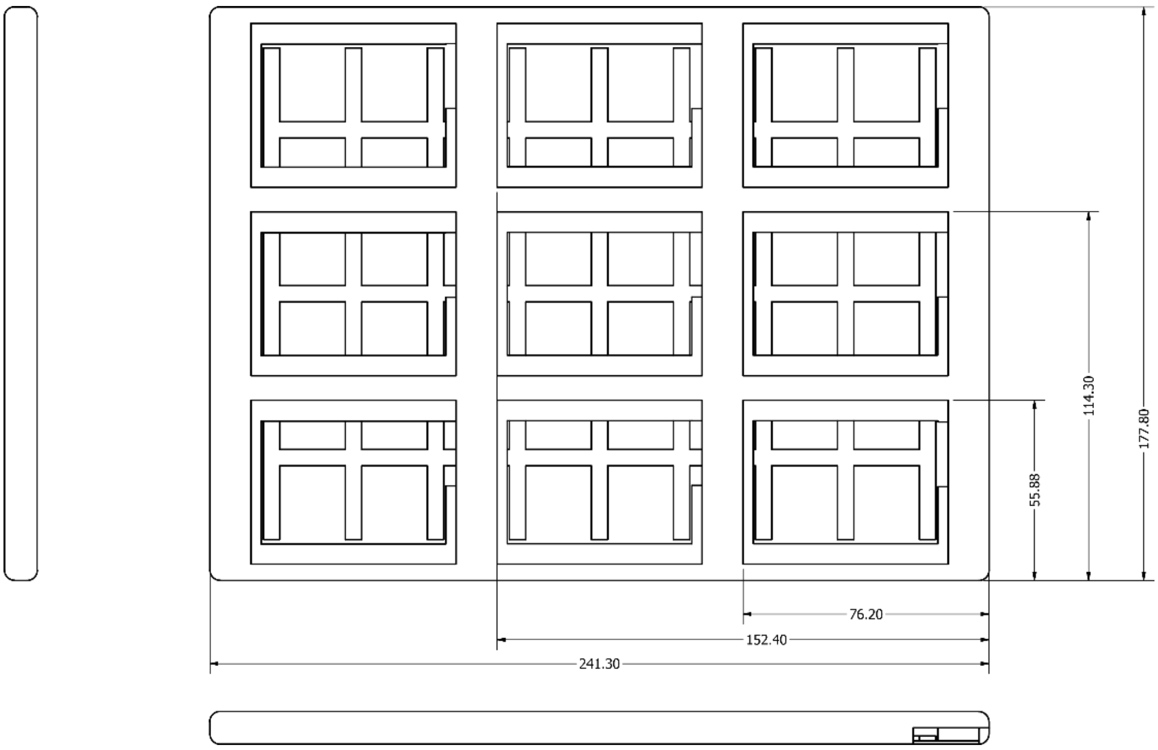


Figure 4.2b. Size of the heating surface

The conceptual structure of the heat control system is shown in Figure 4.3. The input module comprised of two National Instruments (NI) 9217 4-Channel PT 100 RTD analog input modules. The output module was NI 9474 8-Channel 24 V sourcing digital output module, which can control eight heaters. A NI PS-16 24-Volt power supply was used to provide power to the whole system. The hardware was connected to a laptop computer with Windows 7.0.1 operating system and NI LabVIEW (14.0.1f3, 64 bit).

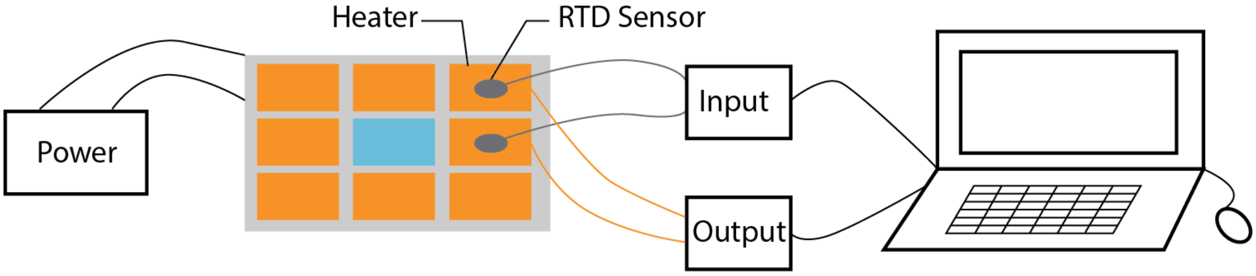


Figure 4.3. Conceptual structure of the heating surface and its controller

The RTD sensors are controlled by a proportional-integral-derivative (PID) module. Part of the LabVIEW block diagram of the PID control loop is shown in Figure 4.4. A part of programmed control interface is shown in Figure 4.5. The temperature and the rate of the temperature change of the heating surface can be set in the boxes with activation time, target temperature, and the parameters of P, I and D.

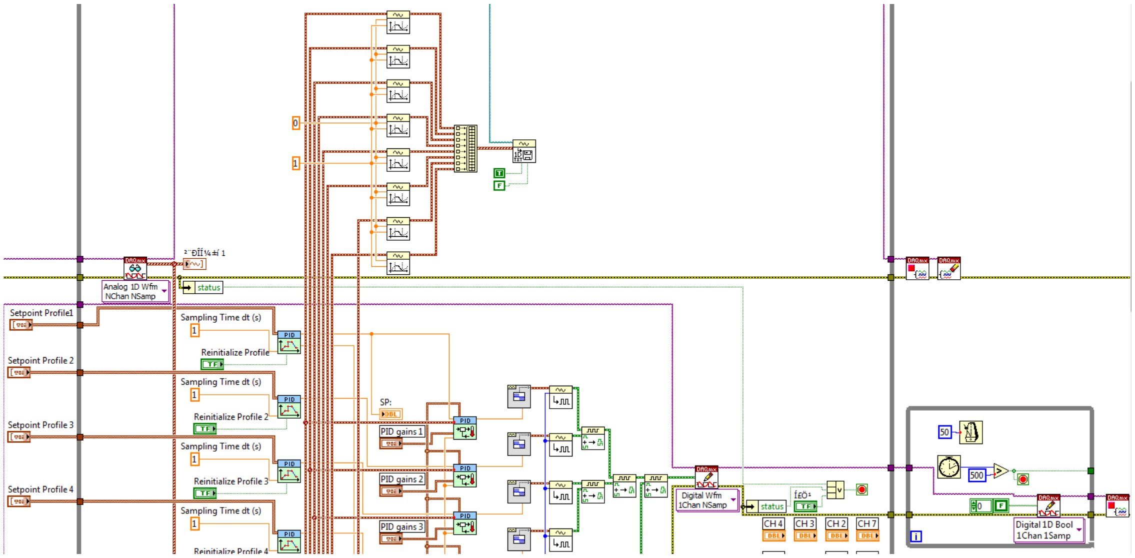
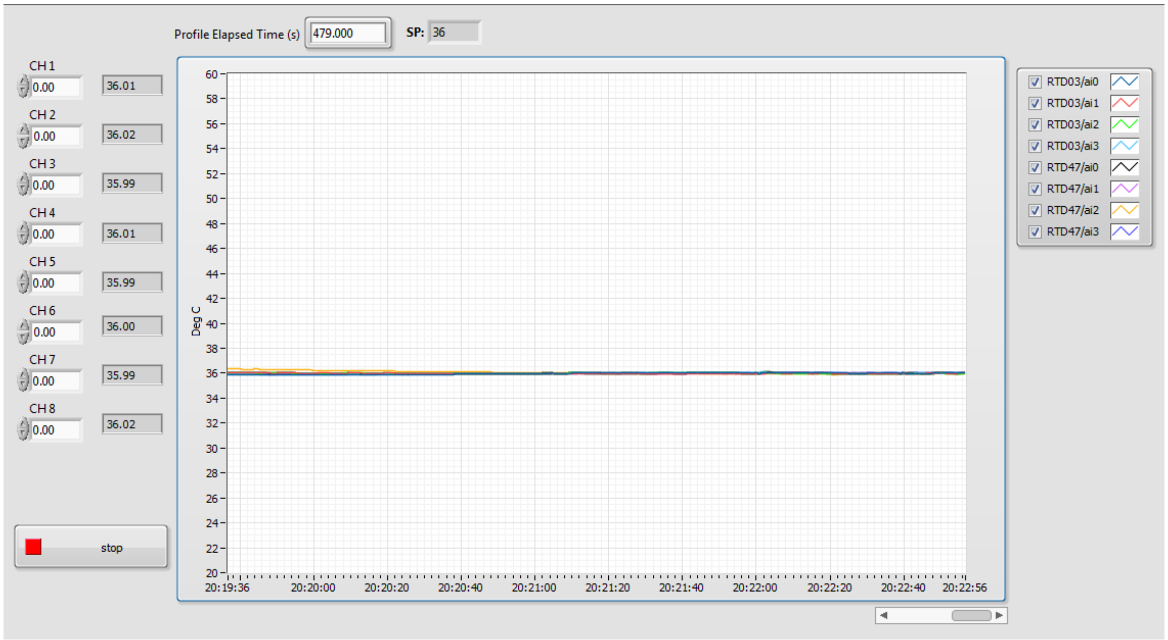


Figure 4.4. Control loop in LabVIEW


Profile Elapsed Time (s) 479.000
SP: 36

CH 1 0.00 36.01
CH 2 0.00 36.02
CH 3 0.00 35.99
CH 4 0.00 36.01
CH 5 0.00 35.99
CH 6 0.00 36.00
CH 7 0.00 35.99
CH 8 0.00 36.02

Figure 4.5 Control interface and stable heating temperature

4.2 Environmental chamber and rating scales

All subsequent experimental sessions were conducted in a controlled environmental chamber (Figure 4.6). The environmental chamber's ambient temperature can be controlled in the range of 7 ℃ to 38 ℃. The humidity can be varied, but was controlled to be 40% throughout all the experiments.

Participants verbally made their ratings according to two visual analog scales of thermal sensation and thermal comfort, as shown in Appendix I. The scales range from 0-100, with 50 as neutral. For thermal sensation the scale's labels ranges from extremely cold to extremely hot. For the thermal comfort scale, the labels ranged from extremely comfortable to extremely uncomfortable.

Figure 4.6 Environmental chamber

CHAPTER 5

EXPERIMENT 1. THE STUDY OF THE EFFECTS OF SURFACE AND INDOOR TEMPERATURES ON USER THERMAL SENSATION AND COMFORT

5.1 Introduction

By January 2014, 42% of adult Americans owned a tablet computer (Zickuhr and Rainie, 2014). The sales of tablet computer will likely keep increasing through the year of 2017 (Statista, 2015a). However, it has been reported that the temperature of a tablet computer surface can rise up to 47 ℃ when used in a warm room (Tapellini, 2012; Chatterjee, 2014). When the skin is in contact with a warm or hot electronic device's surface, the user will experience thermal discomfort and there is an increased risk of skin burns (Giraldi et al., 2011; Dela and Satter 2012; Riahi and Cohen, 2012; Zhang and Hedge, 2014).

Current standards and design guidelines aimed at preventing potential skin burns caused by the heat from electronic devices require limiting surface temperatures under 45.0 ℃ (BS PD 6504: 1983; ISO 13732-1: 2006). Similarly, the upper limit to cause any reversible skin injury is set at 44 ℃ for less than 6 hours skin contact (ASTM C1055 - 03(2014)). However, for sub-burn temperatures there is limited information on how devices' surface temperature affects thermal sensation and thermal comfort. The ISO 13732-2 (2001) standard provides information on thermal sensation for human skin in contact with surfaces of moderate temperatures (10.0 ℃ to 40.0 ℃), but only for an initial sensation when the hands are in contact with something such as a handrail or a door knob.

Typically users' fingertips and the palm areas are in contact with a tablet computer's surface (Zhang, Hedge and Guo, 2015). The warm sensation and heat pain thresholds of the fingertips and palms have been determined in previous laboratory studies. The warm sensation threshold for the index finger is 34.8 (±2.21) ℃ in a room temperature of 25 ℃ (Hirosawa et al., 1984), and for middle finger is 35.6 (±2.6) ℃ (Toibana et al., 2000). The warm sensation threshold for the thenar eminence ranges between 32.5 to 34.7 ℃ (Harju, 2002; Kelly et al., 2005). However, in most previous thermal sensation laboratory studies the tested duration of skin contact ranged from 3 seconds (Hirosawa et al., 1984) to 12 seconds (Kelly et al., 2005); while in real-life use the device will be held for a longer period of time.

Both the duration and the size of the stimulus can affect thermal sensation (Dyck et al., 1993; Pertovaara et al., 1996; Hagander et al., 2000). The heat pain threshold decreases significantly as the contact duration increases from 2.5 to 10 seconds (Dyck et al., 1993; Pertovaara et al., 1996). This may occur because of spatial summation of the thermoreceptors: the longer duration of contact allows the heat to be spread to a larger and deeper area of the skin, which recruits more nociceptive afferent fibers. Larger areas of heat stimulation also tend to decrease heat pain threshold. Meh and Denislic (1994) showed that at the thenar eminence the heat pain threshold was 37.7 ℃ for female participants and 40.2 ℃ for males, with a probe surface of 25x50mm. However, with a smaller probe surface of 30x30mm the heat pain threshold was higher at 43.4 ℃ (Hagander et al., 2000), and with a probe of 25x25mm the threshold was 45.6 ℃ (Kelly et al., 2005). Similarly, at the lower medial calf a larger thermode (12.5 cm^2) produced a significantly lower mean warm threshold of 35.5 ℃ than a smaller thermode (3.75 cm^2) of 36.5 ℃ (Hirosawa et al., 1984). Because of the effects of the stimuli's size and duration, actual users' thermal sensation and thermal comfort might shift, for fingers' prolonged contact with a tablet computer.

Ambient temperature is also a major factor that affects perception of thermal stimuli (Hirosawa et al., 1984; Strigo et al., 2000; Harvey et al., 2012; Oi et al., 2012). People perceive less intense thermal sensations for cold (0 ℃ - 25 ℃) and hot (44 ℃ -

50 ℃) stimuli in cool ambient temperature of 15 ℃, but more intense thermal sensations and unpleasantness for hot stimuli in warm environment of 35 ℃, although no such effects have been found for warm stimuli of 37 ℃ and 40 ℃ (Strigo et al., 2000). On the other hand, heat can be perceived as favorable in a cold environment. In a heated car seat thermal comfort study, participants tended to prefer higher seat-skin contact temperatures when in lower ambient temperature at 5 ℃ and 10 ℃ than higher ambient temperatures of 15 ℃ and 20 ℃ (Oi et al., 2012).

However, an environmental temperature effect has not been consistently found. Lower ambient temperatures such as 15 ℃ have been reported to have a suppressive effect on heat pain threshold (Strigo et al., 2000). The response time to a noxious heat stimulus of 60 ℃ was increased at an ambient temperature of 10 ℃ in a rat study, indicating that the heat pain threshold was increased with the low ambient temperature (Schoenfeld et al., 1985). On the contrary, Croze et al. (1977), Kojo and Pertovaara (1987) and Pertovaara et al. (1996) reported when initial skin temperature were varied between 25 ℃ - 40 ℃, the heat pain threshold at thumb was not significantly affected. Croze et al. (1977) found that the mean pain threshold remained 48 ℃ across the varied skin temperatures (25 ℃ - 40 ℃), while the mean heat pain threshold at forearm was 42 ℃ - 44 ℃ with varied skin adaption temperature (Kojo and Pertovaara, 1987). Ambient temperature has been shown to increase warm sensation thresholds at the fingers by increasing skin temperature (Hirosawa et al., 1984), and similarly skin temperature affects innocuous thermal sensation thresholds in other human studies (Kojo and Pertovaara, 1987; Molinari et al., 1977) and animal studies (Greenspan and Kenshalo, 1985; Sumino and Dubner, 1981). However, no significant effects of environmental temperatures were found on reported thermal sensation for warm stimuli of 37 ℃ and 40 ℃ (Strigo et al., 2000).

The effect of the ambient environment on thermal stimuli has been investigated in recent computer related studies (Baugh and Doherty, 2011; Harvey et al., 2012). Harvey et al. (2012) tested the thenar eminence and the back of wrist for thermal feedback as mobile device notification. Environmental temperature was not controlled but recorded and it ranged from 8.45 ℃ to 27.75 ℃. In general, ambient temperature had a significant effect on the user's thermal stimuli detection time and perceived comfort. In the range of 15-20 ℃ users experienced the greatest comfort with thermal stimuli of 16 ℃ to 38 ℃. However, in a laptop surface temperature study, no significant effect on thermal comfort was found between an environment at 23 ℃ and 35 ℃ (Baugh and Doherty, 2011).

5.2 Objectives and hypotheses

Tablet computers can be used in a variety of ambient environments, and ambient temperature has been shown to affect thermal sensation though previous research on its effect on non-noxious warm stimuli is inconsistent. In addition, in previous cutaneous thermal sensation laboratory studies the skin-stimulus contact area was commonly around $10mm^2$ with a probe touching the skin for a short duration under 15 seconds. The use of a tablet often requires holding the device for prolonged periods of time with multiple fingers and palm skin areas in contact with the bottom surface of the tablet. Thus, previous research results may not accurately predict tablet computer users' real thermal experiences. The present study tests how users' thermal sensation and comfort change with a range of tablet's surface temperatures at different ambient temperatures.

Hypotheses:

H1: As the surface temperature goes up, the thermal comfort will decrease.

H2: Thermal sensation ratings on hot stimuli will be lower at a room temperature of 13 ℃ than 33 ℃.

5.3 Methods

5.3.1 Participants

In total 75 participants were recruited from students and employees in Cornell University. Thirty-three participants were male and forty-two were female. The participants' ages ranged from 18 to 64, with an average age of 27.7 years old. Participants with previous upper extremity injuries, neurological disorders, or diabetes were excluded from the study, to preclude possible variations in thermal sensation, based on prior literature (Jamal et al., 1985a, b; Ziegler et al., 1988; Lindsell et al., 1999; Shukla et al., 2005).

5.3.2 Apparatus

The developed heating surface was used for the experiments. Indoor air temperature was controlled with the environmental chamber. An infrared camera (E30, FLIR Systems, Inc.) was used to measure participant's initial hand surface temperatures. An indoor climate analyzer (Bruel&Kjaer, Type 1213) with air temperature probe and humidity measurement probe was used to measure the humidity and indoor temperature for calibration purposes.

5.3.3 Procedure

Before the start of the experiment, participants spent about 20 minutes in the laboratory acclimating to the environment. During this time the researcher gathered participants' demographic information such as age, weight, height and hand dimensions. Participants' hand dimensions were measured with a ruler. The researcher photographed the participants' hands holding the surface from the bottom of the prototype, and measured the initial palm skin surface temperature with the IR camera.

The tests were carried with three levels of ambient temperature: 13 ℃, 23 ℃ and 33 ℃; while the humidity was controlled at 40% RH. The temperature 23 ℃ and 40% RH was chosen because it is near the center to the thermal comfort zone for 1.0 clo in the ASHRAE Standard 55-2010. The temperature of 13 ℃ and 33 ℃ with 40% RH are both outside the comfort zone, to be either uncomfortably cold, or uncomfortably hot. Within each level of ambient temperature, 25 participants were randomly selected. Each participant experienced all the tested surface temperatures.

The tested surface temperature was controlled from 34 ℃ to 44 ℃, with 2 ℃ as an interval. In total 6 levels were tested, and each level was tested twice. The tested temperatures simulate the range of tablet computer temperatures from close to skin temperature to under 45 ℃, which is the skin burn threshold for prolonged contact with metal for 8 hours and longer (ISO 13732-1:2006). The upper limit of the tested temperature was also considered to be safe not to cause any reversible skin injury for short periods of 6 hours or less contact (ASTM C1055 - 03(2014)). Meanwhile, 44 ℃ was the threshold between hot sensation and heat pain (Harju, 2000; Kelly et al., 2005; ASTM C1055 - 03(2014)). The testing procedure is similar to Methods of Levels (MLE), instead of Methods of Limits (MLI). MLI may introduce an artifact of varied participants' responses time (Croze and Duclaux, 1978; Pertovaara and Kojo 1985; Yarnitsky and Ochoa 1990). Therefore, different temperature levels were tested, instead of the application of MLI.

For each level of surface temperature, participants were asked to hold the prototype in the way they would normally hold a tablet computer for 90 seconds (as shown in Figure 5.1) , and to report their thermal sensation and thermal comfort on fingers and palms, 3 times at each temperature level (0, 45 and 90 seconds). The duration of 90 seconds were to extend the test durations of most previous laboratory thermal test studies (Fruhstorfer et al., 1976; Dyck et al., 1993; Taylor et al., 1993; Meh and Denislic, 1994; Yarnitsky et al., 1995; Hagander et al., 2000; Kemler et al., 2000; Harju, 2002; Kelly et al., 2005; Defrin et al., 2006). However, since each participants will be tested with all the surface temperatures for twice, and for each level of temperature they need to report 3 times, the duration was limited for 90 seconds to prevent the participants from fatigue.

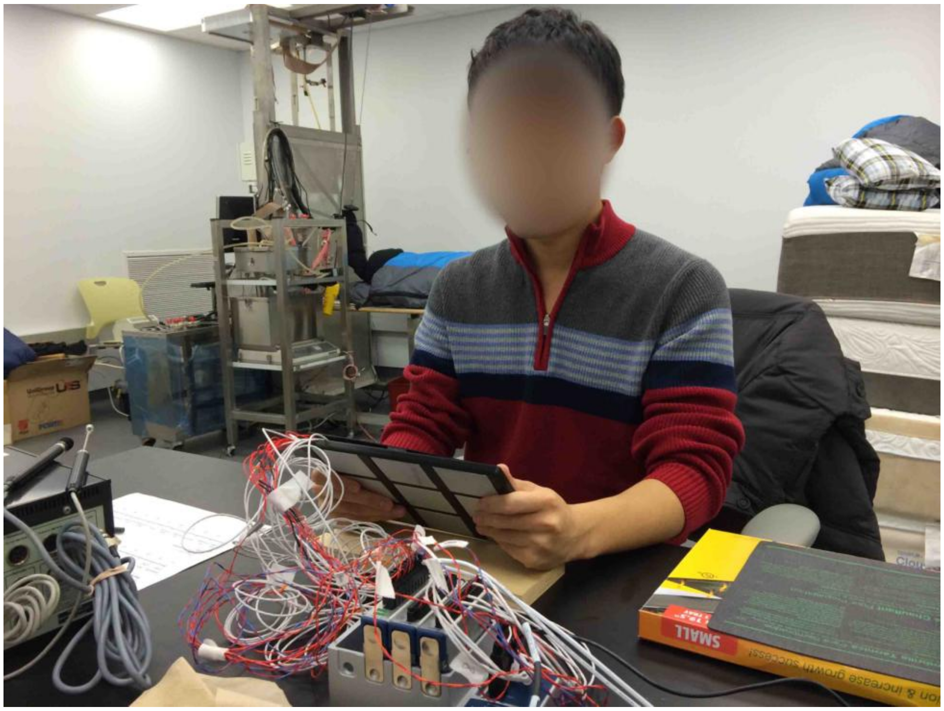


Figure 5.1. A participant was tested in the environmental chamber

Participants reported verbally their thermal sensation and thermal comfort on both fingers and palm areas, with the two visual analog scales mentioned in the previous chapter. Verbal report allows the participants to keep holding the heating surface. Between each temperature level test, the participant put their hands on a controlled temperature surface of 32 ℃ for 60 seconds and rested them in the air at 23 ℃ for 2 minutes. The experiments were conducted from December 2014 to

February 2015. The study protocol was approved by the Cornell University Institutional Review Board.

5.3.4 Data Analysis

The data were analyzed using statistical software (JMP 10.0.0). Repeated measure analysis of variance (ANOVA) was used to test the significance of the main effects and interactions of surface temperature and indoor temperatures for thermal sensation and comfort. The variables of holding duration, gender, height, weight, and hand size measurements were also tested in the ANOVA model. Tukey’s HSD procedure was used for post-hoc analysis to test significance between different levels within a main effect or interaction. $P<0.05$ was considered significant.

5.4 Results

The ratings of thermal sensation and comfort on indoor temperatures are shown in Table 5.1. In general, participants feel cool at indoor temperature of 13 ℃, neutral at indoor temperature of 23 ℃, and have slightly uncomfortable warm/hot sensation at 33 ℃. The thermal comfort is also shown in Table 5.1. No significant effect of age, gender, height, weight, palm width or length was found on the reported finger and palm thermal sensation or comfort.

Table 5.1. Participants' average ratings on room temperatures

Ambient temperature (℃)	Thermal sensation score Mean (standard deviation)	Description on scale	Thermal discomfort score Mean (standard deviation)	Description on scale
13	29.4 (8.1)	Cool	44.3 (15.4)	Close to Neutral
23	51.7 (11.8)	Neutral	39.6 (13.7)	Slightly comfortable
33	74.8 (7.4)	Warm- Hot	59.9 (11.6)	Slightly Uncomfortable

5.4.1 Ambient temperature effect

Ambient temperature had a significant effect on finger thermal sensation (F(5, 1964)=10.76, p<0.0001) and finger thermal comfort (F(2, 2447)=77.47, p<0.0001). The scores here were the average ratings over the three time points (0, 45, 90 seconds), at each temperature level. No significant difference was found for finger thermal sensation between room temperatures of 13 ℃ and 23 ℃, but the average finger thermal sensation score (65.8) at 33 ℃ was significantly lower than at a room temperature of 23 ℃ (score 68.7). Finger thermal discomfort score was highest (score 56.8) at a room temperature of 33 ℃, and lowest (score 42.9) at a room temperature of 13 ℃, while at 23 ℃ the thermal discomfort score was reported to be 50.0.

Ambient temperature also had a significant effect on palm thermal sensation (F(2, 2356)=22.66, p<0.0001) and palm thermal comfort (F(2, 2557)=106.36, p<0.0001). There was no difference in palm thermal sensation between 13 ℃ (score 53.2) and 23 ℃ (score 53.0) but both were higher than at 33 ℃ (score 49.06). Pairwise comparisons showed differences in palm thermal comfort between the three ambient temperatures, with scores of 37.0, 40.2, and 47.6 for 13 ℃, 23 ℃, and 33 ℃ respectively.

5.4.2 Surface temperature effect

Surface temperature was found to have significant main effects on both fingers thermal sensation (F(5, 2594)=709.27, p<0.0001) and fingers thermal comfort (F(5, 2594)=402.40, p<0.0001). In general, the fingers sensation score increased as the surface temperature increased, at all three ambient temperatures (Figure 5.2). The thermal sensation scores at all of the tested levels of surface temperatures were above 50, which means that the perception of heat above neutral. Similarly, the fingers thermal discomfort increased with increased surface temperature. However, unlike thermal sensation scores, the threshold for thermal discomfort (scores above 50), varied among the three indoor temperatures.

Surface temperature also had significant main effects on palm thermal sensation (F(5, 2594)=115.34, p<0.0001) and thermal comfort (F(5, 2594)=46.69, p<0.0001). Nevertheless, the average palm thermal sensation scores did not vary by a large magnitude. For example, the sensation score was 47.8 at 34 ℃ versus 55.6 at 44 ℃. Similarly the thermal discomfort scores ranged from score 37.9 at a surface temperature of 34 ℃ versus 45.7 at 44 ℃. The actual scores increased were both less than 8 for a change of 10 ℃ surface temperature. On the scale it was less than the change of one verbal description, such as from slightly comfortable to neutral, for the change of thermal discomfort scores.

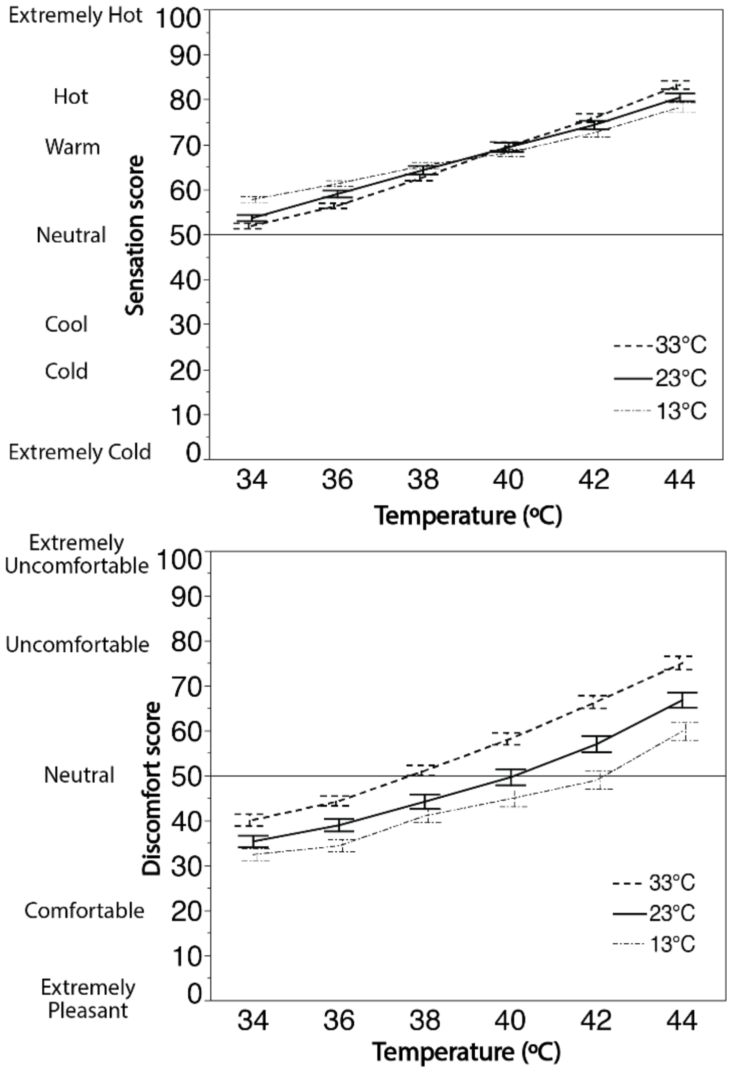


Figure 5.2. Fingers' thermal sensation and comfort scores with surface temperature (Error bar is constructed with 1 standard error from the mean)

5.4.3 Environment and surface temperature interaction

There was a significant interaction effect of indoor temperature and surface temperature for both fingers' thermal sensation (F(10, 2594)=12.68, p<0.0001) and fingers' thermal comfort (F(10, 2594)=3.46, p=0.0002). When the surface temperature was at 44 ℃, participants reported higher sensation scores at a high ambient temperature of 33 ℃ (score 82.4) than at a low ambient temperature of 13 ℃ (score 78.3), as shown in Figure 5.3. For surface temperatures of 40 ℃ and 42 ℃, no significant difference was found in rating scores between different room temperatures. However, the trend was reversed at surface temperatures of 34 ℃ to 38 ℃, where the sensation scores were lower at 33 ℃ than 23 ℃, though no significant difference was found between 13 ℃ and 23 ℃. Sensation score and discomfort score are shown in Table 5.2.

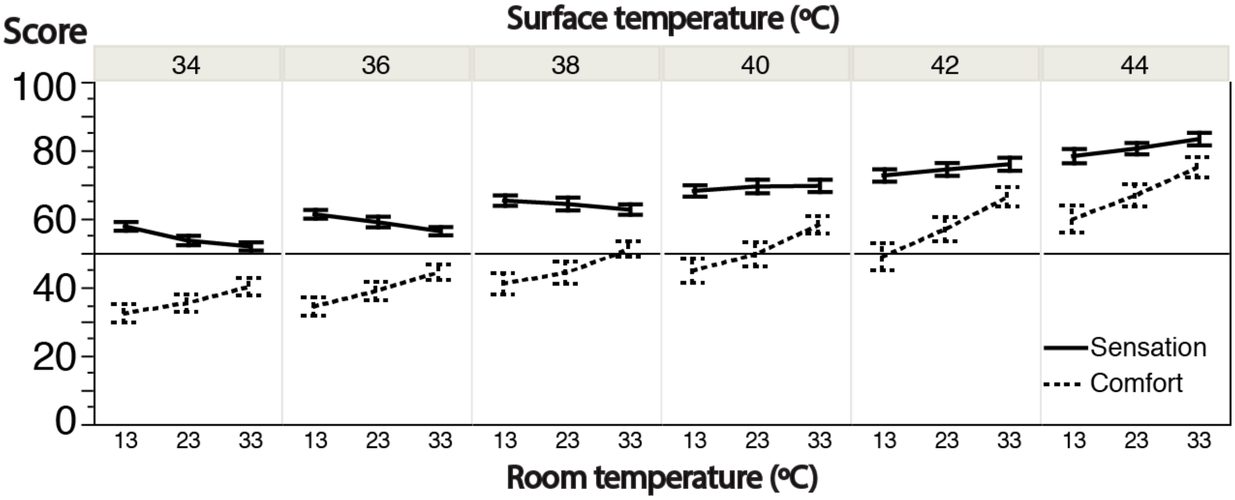


Figure 5.3. Interaction effect of ambient and surface temperature on fingers

(Error bar is 1 standard error from the mean)

Table 5.2. Mean sensation scores and mean discomfort scores for fingers at each temperature level. The mean was least square mean produced by mixed model.

Ambient temperature (℃)	**Surface temperature (℃)**	**Sensation score (mean)**	**Discomfort score (mean)**
13	34	57.9	31.8
13	36	61.4	33.7
13	38	65.4	40.4
13	40	68.2	44.2
13	42	72.7	48.3
13	44	78.4	59.2
23	34	55.4	36.4
23	36	60.7	40.0
23	38	66.0	45.3
23	40	71.2	51.2
23	42	76.2	58.6
23	44	82.3	68.4
33	34	51.0	41.0
33	36	55.5	45.2
33	38	61.8	52.0
33	40	68.7	59.1
33	42	75.0	67.3
33	44	82.4	75.9

Thermal discomfort had a relatively consistently increasing trend with environmental temperatures among different levels of surface temperatures. From surface temperatures of 38 ℃ to 44 ℃ there was a significant difference between ambient temperatures of 13 ℃, 23 ℃, and 33 ℃, and the scores at 33 ℃ were higher than those at 23 ℃, which in turn were higher than those at 13 ℃, as shown in Figure 5.3. For surface temperatures of 34 ℃ and 36 ℃, scores at 33 ℃ were higher than at 13 ℃ but no significant differences were found between ambient temperatures of 13 ℃ and 23 ℃, or 23 ℃ and 33 ℃.

5.4.4 Duration

No significant effect was found in the duration of 90 seconds on fingers thermal sensation and thermal comfort at the three ambient temperatures (F(2, 2592)=0.54, p=0.58; F(2, 2592)=0.42, p=0.66). A significant effect of duration on palm thermal sensation was found (F(2, 2592)=9.22, p=0.0001), yet the difference in scores was small (51.1 at the initial touch and 51.9 at the 45 second, and 52.3 at the 90 second). No such effect was found on palm thermal comfort.

5.5 Discussion

The study investigated tablet computer users' thermal responses to multiple levels of a simulated tablet's underside surface temperatures at three ambient temperatures. The first hypothesis was supported that the thermal comfort decreased with the increase of surface temperatures. The results showed that both the ambient temperatures and surface temperatures had significant effects on participants' fingers' thermal sensation and comfort. Fingers' thermal sensation ratings in response to higher temperature warm surface (44 ℃) were significantly affected by the different ambient temperatures. These findings correspond well to Strigo et al. (2000)'s finding that participants perceived a hot stimulus (44-50 ℃) as more intense at room temperature of 35 ℃ but less intense at 15 ℃, as well as other research evidence that a cool environment can change the heat pain threshold (Schoenfeld et al., 1985). The findings also support the second hypothesis, that the sensation ratings for hot stimuli were lower at 13 ℃ than 33 ℃. However, our current study found no significant effect of the environmental temperatures on the thermal sensation with surface temperatures from 40 ℃ to 42 ℃. For surface temperatures from 34 to 38 ℃ there was a trend for lower thermal sensation scores in ambient temperatures of 33 ℃ than 13 ℃. Heat stimuli of 37 ℃ and 40 ℃ were not found to be significantly affected by changes in environmental temperatures (Strigo et al., 2000). The different thermal sensation results at 36 ℃ and 38 ℃ surface temperatures in our test experiments in comparison to Strigo et al. (2000)'s results might be due to the body sites that were tested. Strigo et al. (2000) tested the volar forearm, while in the current study multiple fingers and the palms were tested, which have different thermal sensation thresholds and slightly lower thermal sensitivities than the volar forearms (Defrin et al., 2006; Hirosawa et al., 1984; Stevens and Choo, 1998; Taylor et al., 1993).

The significant interaction of surface temperatures and ambient temperatures on thermal sensations may arise from skin temperature changes in various ambient temperatures. According to Hirosawa et al. (1984), the fingers' warm sensation threshold had a positive relationship with an increase in room temperature. As the room temperature increased from 15°C to 30°C, the right hand fingers' warm threshold increased from 32.4 ±3.58 ℃ to 36.6 ±1.62 ℃, while the finger tips skin temperature rose from 26.3 ± 5.92°C to 33.7 ± 0.64°C. Since the participants' finger warmth sensation threshold can be higher at a room temperature of 33 ℃ than 13 ℃, the moderate surface temperatures, such as 34 ℃ to 38 ℃ might not exceed the threshold for participants to have as strong a warm sensation at 33 ℃, as at a lower room temperature such as 13 ℃. Yet for hot stimuli (44 ℃), in the cool environment (13 ℃) the cool-sensitive neural pathways, such as A-delta fibers, can be active and this leads to reduced nociceptive activities when in contact with thermal stimuli (Kenshalo and Isensee, 1983; Craig and Bushnell, 1994; Strigo et al., 2000).

The ambient temperature also had significant effects on the reported thermal comfort of fingers in contact with the heating surface. This contrasts with Strigo et al. (2000) who found that environmental temperature did not affect unpleasantness ratings for innocuous warm stimuli of 37 ℃ and 40 ℃. A major reason for this discrepancy in results may be that Strigo et al. (2000) kept the forearm skin temperature at 30 ℃ before each level of tests, and this was also noted by the authors as a major reason for no change on thermal sensation ratings. In the present experiment, the participants were allowed to rest their hands on a controlled surface at 32 ℃ for 30 seconds and then for 2 minutes in the air before touching the surface. Therefore their skin had some time to adapt to the air temperature instead of being controlled at a fixed temperature. Another reason might be the duration of holding. In most previous studies (Hirosawa et al., 1984; Strigo et al., 2000; Defrin et al., 2006), the thermal stimulus lasts from 1 second to 15 seconds, while in the current study, the participants needed to hold the heating surface for 90 seconds. However, no effect of duration on users' thermal sensation or comfort for the fingers and palms in the current study.

CHAPTER 6

EXPERIMENT 2. THE STUDY OF THE EFFECT OF THE RATE OF TEMPERATURE CHANGE

6.1 Introduction

The normal working temperature of a mobile electronic device surface, such as the back cover of a tablet or a laptop, can approach or exceed the skin burn threshold of 45 ℃ (Riahi and Cohen, 2012). With intense computing and suboptimal ventilation of the computer, the surface temperature can be much higher than this threshold. For example, Zhang, Hedge and Guo (2015) found that the base surface temperature of a laptop can reach 45.4 ℃ under normal working conditions. Moreover, Tsang et al. (2010) surveyed normal working laptops and for some models the base temperature reached 55.4 ℃. According to recent public media reports (Tapellini, 2012; Chatterjee, 2014), the surface temperature of new tablets can reach up to 47 ℃ when running graphic intensive computing tasks. Furthermore, there have been legal cases in which manufacturers have been sued by consumers because of overheated tablet computers (Ogg, 2010). In sum, the thermal issues for mobile devices need more attention for improvement.

Guidelines and standards have been developed to limit the surface temperature less than the burn threshold to protect users from skin burn risks (BS PD 6504, 1983; ISO 13732-1, 2006; ASTM C1055 – 03, 2014). ISO 13732-2 (2001) includes information on how people feel about moderate warm surfaces at temperatures below the skin burn threshold. However, the surface temperatures tested were only static temperature, meaning that the surface temperature was kept stable without thermal fluctuations. No information was found in the past standards on the sensation with dynamic temperature change.

Previous research suggests that heat thermoreceptors in the skin may react differently to thermal stimuli with various temperature change rates and contact durations, providing evidences for possible new heat dissipation designs by changing surface temperature at different temperature change rates. Studies (Yarnitsky et al., 1992; Yeomans and Proudfit, 1996) indicate that the activation of A-delta fiber nociceptors depends on the rate of temperature rise. More specifically, A-delta fibers are activated primarily at a relatively high rate of temperature rise of 6.5 ℃/sec (Yeomans and Proudfit, 1996). C fibers are activated at a lower rate of 0.9 ℃/s, however the C fiber nociceptor threshold is not dependent on the rate of temperature change (Yarnitsky et al. 1992; Yeomans and Proudfit, 1996). For example, the mean threshold of activating C nociceptors is consistent between 41.5 and 41.9 ℃ for a rate of temperature rise of 0.3, 2.0 and 6.0 ℃/s, but the C nociceptor discharge rate increases significantly with an increase in stimulus temperature rates (Yarnitsky et al., 1992). Yet contradictory evidence exists, showing that C Mechanoheat (CMH) fibers' heat threshold increases as the rate of temperature change increases (Tillman et al., 1995a,b). In earlier research, warm stimuli that increased at rates of 2 ℃/s or 0.5 ℃/s led to an initial intense response from warm fibers but these fibers could then adapt to a static warm temperature in the range of above 30 ℃ and below 50 ℃ (Duclaux and Kenshalo, 1980). However, repetitive warm pulses lasting 10 seconds from 34 ℃ to 42 ℃ with less than 60-second intervals can reduce the neuronal response of these warm fibers, and therefore may suppress the sensing of stimuli (Darian-Smith et al., 1979). Therefore, besides controlling the device surface temperature under the burn threshold, dissipating heat at a low temperature change rate may allow higher user thermal comfort

Previous thermal testing has shown that as the stimulus temperature ramp rate increases, participants have a tendency to report more heat pain or discomfort, and there is a decrease in the heat pain or warm sensation threshold. The mean heat pain threshold tends to decrease from 46 ℃, 44.2 ℃ to 42.7 ℃ as the temperature rise rate increases from 0.095 ℃/s, 0.85 ℃/s to 5.8 ℃/s (Tillman et al., 1995a). The heat pain threshold was also shown to remain the same as the temperature rise rate increased from 0.3 ℃/s to 6 ℃/s, or from 3 to 10 ℃/s (Molinari et al, 1977; Yarnitsky et al. 1992; Yarnitsky and Ocho, 1990; Pertovaara et al., 1996). Heat pain thresholds was overestimated because of the artifact of reaction time (Croze and Duclaux, 1978; Pertovaara and Kojo, 1985; Yarnitsky and Ocho, 1990). The warm sensation threshold (within 3 ℃ higher than skin temperature) was shown to be higher when the stimulus was at a rate of temperature change between 0.01 ℃/s to 0.1 ℃/s, but it remained relatively constant when the change rate was below 0.1 ℃/s and above to 0.3 ℃/s (Kenshalo et al., 1968). The pain rating scores induced by the heat stimuli increased as the stimulus temperature rise rates increased from 0.3 ℃/s to 6 ℃/s, corresponding to the increase of C nociceptor discharge frequency (Yarnitsky et al., 1992). Similarly, the comfort level was lower for 3 ℃/s warm stimuli than 1 ℃/s when used for thermal feedback (Wilson et al., 2013). Therefore, it is possible to find a set of rates of temperature change that can lead to a relative low thermal discomfort, at the same target surface temperature.

6.2 Objectives and hypotheses

It is suggested that new heating dissipation designs for repetitive heating with lower temperature change rates could reduce thermoreceptor responses and in turn improve users' thermal comfort. We explored what temperature change rate could allow for a higher user thermal comfort. The heating surface mentioned in Chapters 4 and 5 was used to control the rate of temperature change to simulate a tablet undersurface. The temperature change rates tested here were 0.02 ℃/s and 0.15 ℃/s, in comparison to a constant temperature. The rate of temperature change was designed to be close to or below the range where the warm fibers' activities are reduced with the decrease of rate of temperature change (Molinari et al, 1977; Yarnitsky et al. 1992; Yarnitsky and Ochoa, 1990; Pertovaara et al., 1996).

It is hypothesized that:

H1: Repetitive heating leads to lower thermal discomfort than a constant temperature.

H2: A slower rising temperature rate leads to less thermal discomfort than a relatively fast rising temperature.

6.3 Methods

6.3.1 Participants

Twenty-four participants were recruited from students and employees at Cornell University. Participants age range from 21 to 65 years old, with an average of 29.75 years and a standard deviation of 11.1 years. Among the participants 11 were female and 13 were male.

6.3.2 *Apparatus*

The simulated tablet computer heating surface in combination with an iPad Air (Model# A1566, Wi-Fi 16 GB, iOS 8.1.3) was used to play videos. A Nature documentary “Parrots: Majestic Birds” was played in YouTube for the participants while they were holding the surface. All experimental sessions were conducted in a controlled environmental chamber. Indoor air temperature was maintained at 23 ℃, while the humidity was controlled at 40% RH.

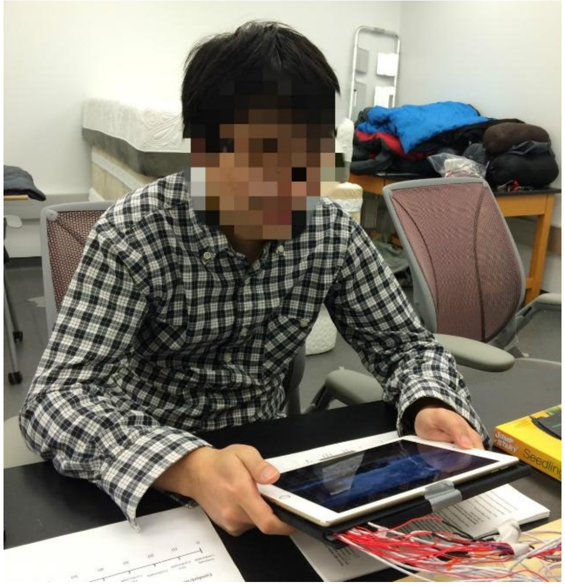


Figure 6.1. A participant holds the heating surface combined with an iPad

6.3.3 *Procedure*

The experiment is a within-subject design. Each participant experienced all four conditions and was asked for thermal sensation and comfort five times for each condition. Participants spent approximately 20 minutes becoming accustomed to the controlled environment, while the researcher introduced the experiment and collected their weight, height, and hand size information. The participants were instructed to hold the heating surface in combination with a tablet computer, shown in Figure 6.1.

Participants were asked to watch a 10-minute movie clip. In the previous experiment 1, the tested duration was 180 seconds. However, users might hold a tablet computer for a longer time. For example, it has been estimated that the maximum holding time of a tablet computer with left hand is 11.5 minutes for female, and for male the time is 15.9 minutes (Chau and Wells, 2015). It is likely that the average holding time for a regular tablet user in reality is lower than the maximum holding time. Since the duration can be a factor that affect thermal sensation and comfort, a prolonged duration of 10 minutes were tested.

Frequent repetitive heat stimuli with frequency of less than 0.33HZ can lead to a more intense discomfort or pain, also known as temporal summation (Stevens, Okulicz and Marks, 1973; Kong et al., 2012). To avoid temporal summation, the frequency of the stimuli was set to be above 0.33HZ. In addition, warm sensation threshold is expected to be decrease when the rate of temperature change increased between 0.01 ℃/s to 0.1 ℃/s, while it remains constant outside the range (Kenshalo et al., 1968). Therefore, the tested rate was set to be 0.02 ℃/s and 0.15 ℃/s.

Figure 6.2. Heated areas

For each tested condition, participants rated local thermal sensation and thermal comfort at their fingers and palms with the thermal sensation and comfort scales (shown in Chapter 4) when they held the surface. Participants were tested in all the following conditions. Between each tested condition, the participant rested for three minutes. The order of the test conditions was randomized. At the end of the tested sessions, participants also ranked the four conditions according to their preferences in thermal comfort.

A. Control condition (Condition A): both left and right areas were heated up to 42 ℃ before the tests, and kept constant for the whole session, as shown in Figure 6.2A and Figure 6.3.
B. Slow temperature rise at 0.02 ℃/s (Condition B): both left and right areas (Figure 6.2A) were heated at a lower temperature rise rate of 0.02 ℃/s from 34 ℃ to 42 ℃, then fluctuates between 38 ℃ and 42 ℃, as shown in Figure 6.3.
C. Temperature rise at 0.15 ℃/s (Condition C): the heating surface were heated to 34 ℃ initially. The participants were instructed to hold the heating surface and the heating areas were heated to 42 ℃ at a rate of change of 0.15 ℃/s and then stopped heating and naturally cool down to 38 ℃. The heating process repeated, as shown in Figure 6.3.
D. Alternating heating sides (Condition D): both sides were pre-heated to 34 ℃. While participants held the surface, the left side was heated first to 42 ℃ at 0.15 ℃/s and the other side remained 34 ℃ until heated up to 42 ℃ at the same temperature change rate (Figure 6.2B and 6.3).

For condition A, participants reported their thermal sensation and comfort at the time points of 5 seconds (T1), 1 minute (T2), 4 minutes (T3), 7 minutes (T4), and 10 minutes (T5). For conditions B, C and D, participants reported their thermal sensation and comfort at the starting point (T1), at the time point when the surface temperature reached 38 ℃ (T2), when the surface temperature reached 42 ℃ (T3), when the surface temperature reached 38 ℃ fort the second time (T4), and when the surface temperature reached 42 ℃ for the second time (T5).

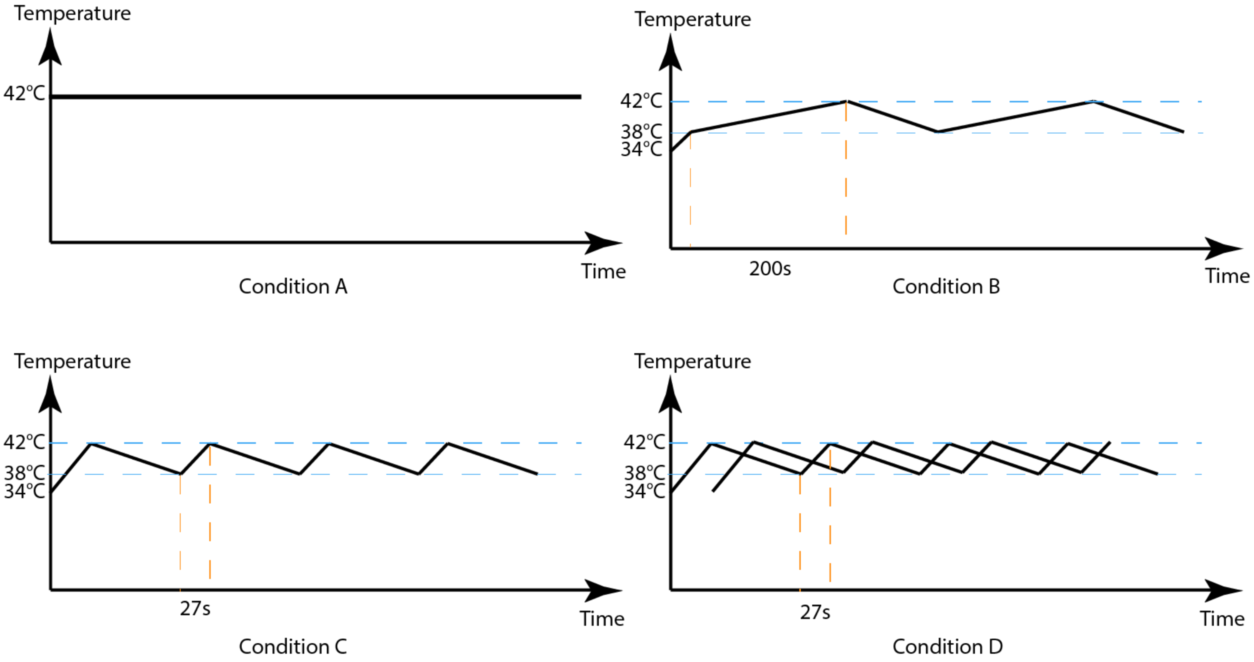


Figure 6.3. Thermal sensation and comfort rating change over time and the designed surface temperature change. Each graph shows the trend of surface temperature as constant temperature (A), 0.02 ℃/s change rate (B), at 0.15 ℃/s change rate (C) and at 0.15 ℃/s change rate at two sides (D)

6.3.4 Data Analysis

Mixed effect models were used to analyze the reported thermal sensation and thermal discomfort scores for the test conditions over time. The random effect variables were participant number, and condition by participant number. The fixed effect variables were the tested condition (temperature change rate), the point in time when questions were asked, and the interaction term of the tested condition by time point. Tukey (honest significant difference) HSD was used for multiple comparisons. The ranking data was analyzed using a Friedman test. Friedman test is a non-parametric method that can account for the random effect of participants. α=0.05 is considered statistically significant. The data were analyzed using statistical software (JMP 10.0.0 and R 3.2.1).

6.4 *Results*

6.4.1 Holding duration effect

Throughout the holding session, the four test conditions all led to significant changes in ratings of finger thermal sensation and thermal comfort, as shown in Figure 6.4 A and Figure 6.4B.

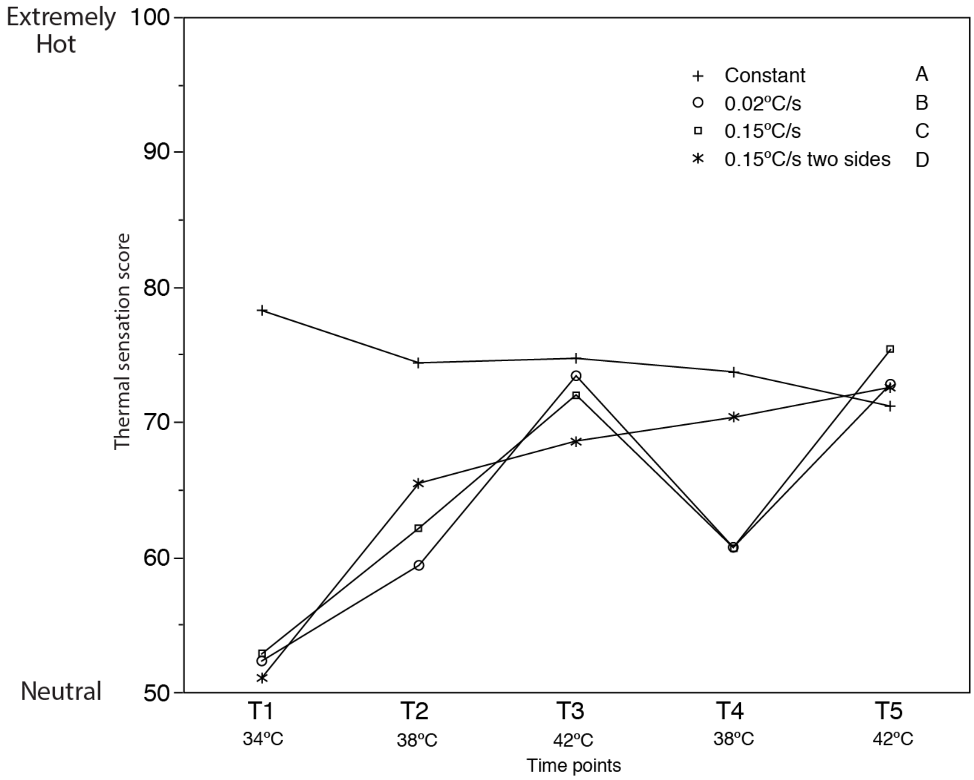


Figure 6.4A. Finger thermal sensation change over time

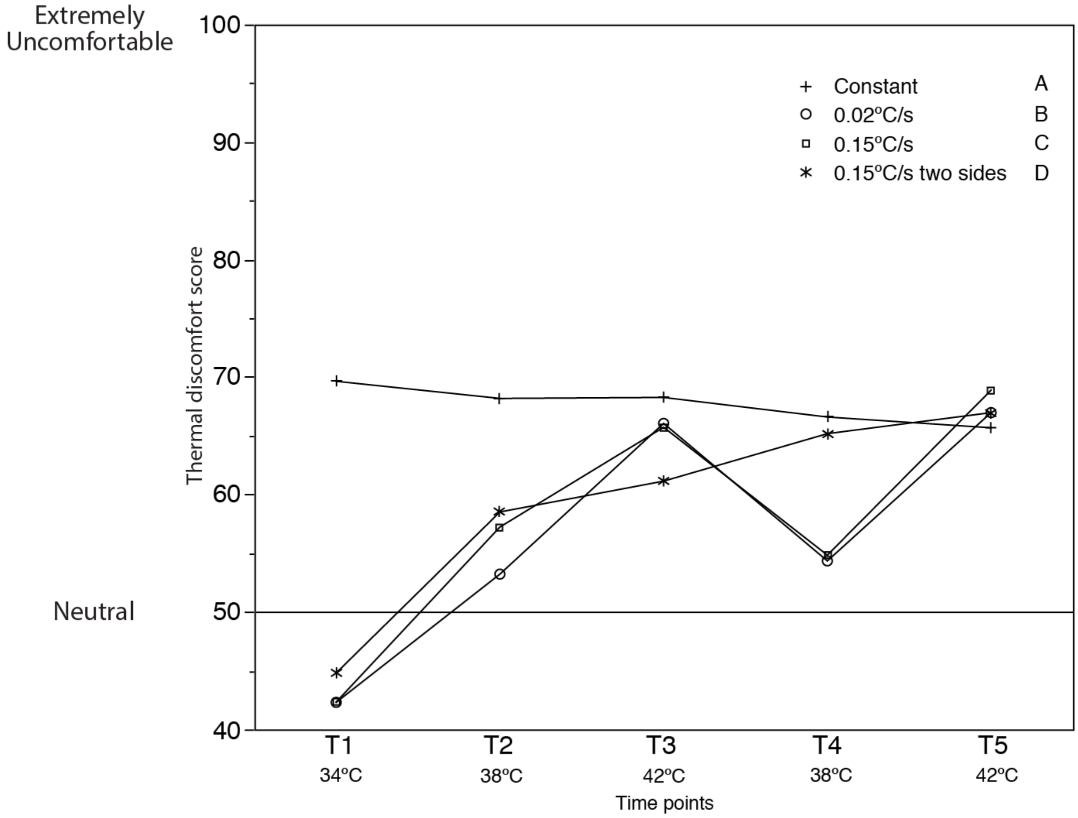


Figure 6.4B. Finger thermal discomfort scores change over time

6.4.1.1 Condition A (Constant)

Finger thermal sensation scores tended to decline over time (F(4, 363)=3.65, p=0.006). The trend is also illustrated in Figure 6.4A. Significant difference was found between the time point T1 with a rating of 78.3, and the last time point of T5 with a rating of 71.2. No significant difference was found among other pairs. In contrast, no significant difference was found in reported thermal discomfort scores over time (F(4,361)=0.79, p=0.53).

6.4.1.2 Condition B (0.02 ℃/s)

Under the condition in which the surface temperature was increased at a rate of 0.02 ℃/s, the thermal sensation score changed through the multiple time points, as illustrated in Figure 6.4. Significant differences existed among various time points

(F(4, 363)=47.37, p<0.0001). At the initial time point of T1 participants reported a significant lower thermal sensation score (52.3) than at T2 (score 59.4) and at T4 (score 60.7), which were in turn lower than at T3 (score 73.4) and at T5 (score 72.8). However no significant difference was found between T2 and T4, and between the T3 and T5.

Thermal comfort followed a similar trend, with scores varying significantly (F(4, 361)=34.6, p<0.0001). The discomfort score was lowest at T1 (score 42.3), but higher at T2 (score 53.2) and T4 (score 42.3), and the highest discomfort scores were at T3 (score 66.0) and T5 (score 67.0).

6.4.1.3 Condition C (0.15 ℃/s)

Significant differences were found among the time points on both thermal sensation (F(4, 365)=45.09, p<0.0001) and thermal comfort (F(4, 364)=36.53, p<0.0001). The thermal sensation score (52.6) and the thermal discomfort score (41.1) were significantly lower at T1. The thermal sensation (61.6; 60.6) and thermal discomfort scores (57.0; 54.5) were higher at T2 and T4. The highest scores were at T3 and T5, at which points the thermal sensation scores were 72.0 and 75.3, and the thermal discomfort scores were 65.7 and 68.5.

6.4.1.4 Condition D (0.15 ℃/s heat at two sides)

Significant differences were found among thermal sensation scores (F(4, 365)=45.09, p<0.0001) and thermal discomfort scores (F(4, 364)=36.53, p<0.0001). The initial sensation score (51.0 at T1) was significantly lower than the score at T2 (score 65.5), T3 (score 68.6), T4 (score 70.3) and T5 (score 72.1). No other pairs are significantly different. Similarly the initial thermal discomfort score (44.8) was significantly lower than the score (58.5) at T2, T3 (score 61.1), T4 (score 65.2) and T5 (score 66.7). No other pairs were significantly different.

6.4.2 Overall user preference

Participants gave overall ratings of thermal sensation and thermal comfort at each session. In addition, they were also required to rank their preference of the four conditions.

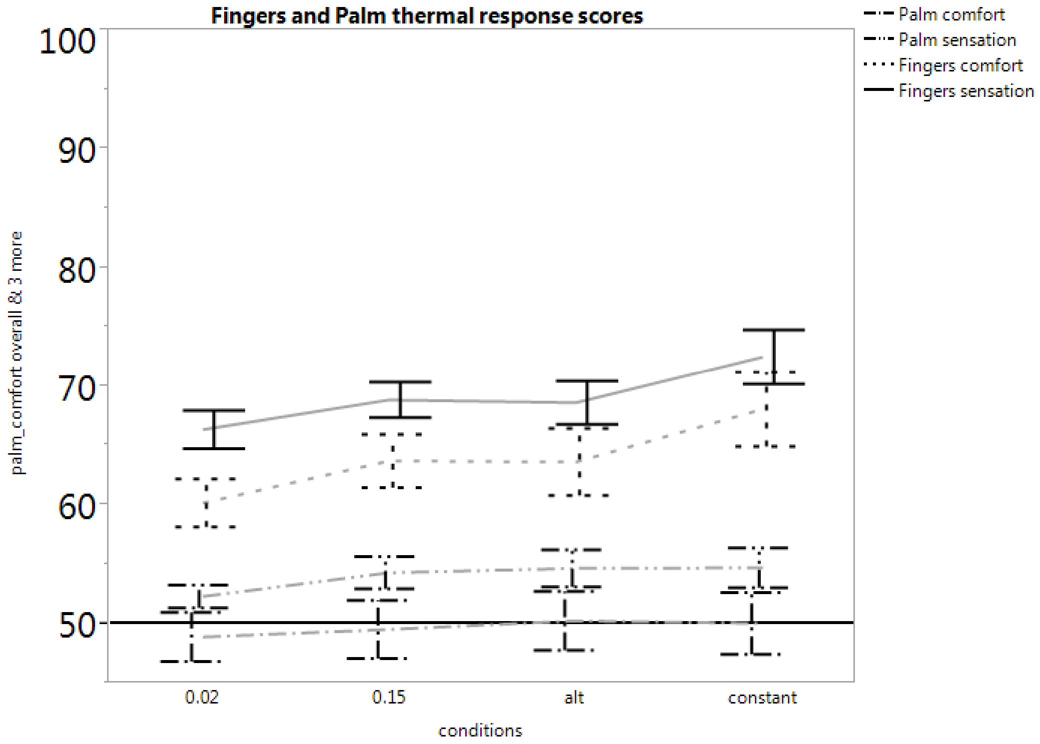


Figure 6.4. Overall rating on thermal sensation scores and thermal discomfort scores (Error bar is constructed with 1 standard error from the mean)

The overall ratings on the finger thermal sensation and thermal comfort have the same trend (Figure 6.4). Among all the conditions, the thermal sensation scores were found to be significantly different (F(3, 63)=3.69, p=0.016), and so were thermal discomfort scores (F(3, 63)=3.01, p=0.037). Condition B led to an overall lower thermal sensation score (score 66.4) than condition A (score 72.5). The same pattern was seen for the thermal discomfort score, where thermal discomfort scores were lower at condition B (score 60.2) than condition A (score 68.1). However, no significant difference was found between any other pairs in thermal sensation or thermal discomfort scores.

Significant difference was found among the conditions, Q=14.66, p=0.0021. Post-hoc tests showed that the slower rate change at condition B is more comfortable than the other three conditions, i.e. Condition A, C, and D, while no significant difference was found in the three conditions.

6.4.3 Effect of temperature change rate on ratings for the same temperature

Among the conditions, differences in the ratings scores were found at the same surface temperatures. However, at the time point of the second 42 ℃, no significant difference was found among all the four conditions.

6.4.3.1 First 38 ℃ (T2)

Thermal sensation score differences existed among the four tested conditions (F(3, 310)=18.84, p<0.0001). Pairwise comparison showed that condition A was higher than the other three conditions, yet no significant difference was found between the other three conditions for the first 38 ℃. The thermal sensation score for condition B was relatively low at 59.4, and the score for condition C was 61.5 and the score for condition D was 65.5. Similarly, no significant was found in thermal discomfort scores among the three conditions excluding condition A. The mean score was 53.2 for condition B, and the score for condition D was 58.5.

6.4.3.2 Second 38 ℃ (T4)

Significant thermal sensation score difference existed among the four conditions, F(3, 310)=19.15, p<0.0001. Pairwise tests show that condition D (score 70.3) led to a significantly higher thermal sensation score than condition C (score 60.6) and 0.02 ℃/s (score 59.4) at the second 38 ℃ time point. It should be noted that in condition D only one side of the tablet was 38 ℃, but the other side was around

42 ℃. No significant difference was found between condition A and condition D, or between condition B and condition C.

Similarly, a significant difference existed in thermal discomfort scores, F(3, 355)=12.49, p<0.0001. Pairwise tests show that condition D (score 65.1) led to significantly higher thermal discomfort than condition C (score 54.2) and condition B (score 54.3) at the second 38 ℃ time point. Condition D (score 65.2) does not have a significant difference from condition A (score 66.6) in thermal discomfort score.

6.4.3.3 First 42 ℃ (T3)

Conditions with different temperature change rates led to significant different thermal sensation scores (F(3, 308)=3.00, p=0.03) . Participants reported a lower average thermal sensation score 68.6 on condition D than condition A (score 74.7). However, no significant difference was found among other pairs. Condition B had a score of 73.4 and condition C had a score of 72.0.

No significant was found among thermal discomfort scores (F(3, 353)=2.49, p=0.06). The thermal discomfort scores for the conditions were: 68.3 for condition A, 66.0 for condition B, 65.7 for condition C and 61.1 for condition D.

6.4.3.4 Second 42 ℃ (T5)

No significance was found for either thermal sensation scores (F(3, 312)=2.49, p=0.28) or thermal discomfort scores (F(3, 356)=0.29, p=0.83) among tested conditions at the time point of the second 42 ℃.

6.5 Discussion

6.5.1 The effect of temperature change rate

The overall thermal sensation rating and ranking results showed that the slower temperature change rate at 0.02 ℃/s (condition B) had a significant effect on overall thermal sensation. The slower temperature change rate (0.02 ℃/s) tended to lead to an overall perception of less intense heat than a faster temperature change rate 0.15 ℃/s (condition C), and constant temperature (condition A). Both hypotheses of H1 and H2 were supported. The finding confirms results from previous studies that temperature change rates can affect thermal sensation (Claus et al., 1987; Dyck et al., 1993; Wilson et al., 2012). Claus et al (1987) tested the rate of temperature change ranging from 0.5 ℃/s to 1.5 ℃/s, and found that as the rate increased, the thermal sensation threshold was increased. Dyck et al. (1993) found 1 ℃/s and 3 ℃/s changes led to overestimation of warm thresholds. In the Wilson et al. (2012)'s study the rate of change of 3 ℃/s produced a more intense and less comfortable sensation of heat than that of 1 ℃/s. Our data is consistent with the above studies, and shows that overall the lower rate of temperature change (0.02 ℃/s) was rated as less heat intensive than the higher rate (0.15 ℃/s). However, one limitation is that the condition of 0.02 ℃/s produced more heat than condition of 0.15 ℃/s. The more heat can possibly lead to more discomfort.

At the time points when the surface temperature reached 38 ℃ or 42 ℃, no significant difference in thermal sensation ratings was found between the conditions of 0.02 ℃/s and 0.15 ℃/s. The results suggest that at the same surface temperatures, the temperature increase rate did not affect thermal sensation or thermal comfort. In contrast, participants still ranked the lower temperature change rate as the most preferred condition in terms of thermal sensation and thermal comfort. The difference may suggest that the temperature change rate may not affect people's sensation at a certain temperature, but can still affect the overall thermal experience.

In terms of thermal comfort, the results from this study show the potential to improve thermal comfort by varying the surface temperature at a low temperature change rate. However more combinations of the temperature change rate and surface temperature need to be tested to determine the optimal thermal comfort. Both the overall thermal sensation and thermal discomfort scores and the ranking of preferred conditions have demonstrated that the rate of 0.02 ℃/s (condition B) was preferred over the constant 42 ℃ (condition A) by the participants in term of thermal sensation and comfort. The difference is significant, with a thermal discomfort score of 60.2 (slightly uncomfortable) for 0.02 ℃/s versus a score of 68.1 (fairly uncomfortable) for constant temperature. However, it should be noted that with the constant temperature of 42 ℃, a larger amount of heat was dissipated than with the condition of 0.02 ℃/s.

6.5.2 Unbalanced heat

Alternating the heated sides (Condition D) of a tablet might reduce finger thermal discomfort at the initial temperature increase, but it may not be effective for overall thermal experiences. Condition D showed a significant lower thermal sensation and thermal discomfort scores than the constant temperature at the time point of the first 42 ℃. However no significant difference was found in either overall thermal comfort rating or overall preference ranking between condition D and condition A.

6.5.3 Thermal responses to constant 42 ℃ for prolonged time (600 seconds)

In a previous study (Zhang, Hedge and Guo, 2015), the same thermal sensation and thermal discomfort scales were used for participants to report their thermal responses to static temperatures at a room temperature of 23 ℃. For a surface temperature of 42 ℃ over a duration of 90 seconds, the reported thermal sensation score was 76.2, and the thermal discomfort score was 58.6. A statistically significant declining trend was found on thermal sensation scores, F(2, 24)=4.23, p=0.0015. However, the difference was as small as a score of 2 for the thermal sensation scale.

The declining trend of finger thermal sensation scores among the different time points were illustrated in Figure 6.4. For a constant surface temperature of 42 ℃, the initial rating was 78.3 (hot) and at the last time point at 600s the rating was 71.1 (warm). The participants' thermal sensation scores declined significantly. This finding confirms the trend discovered by Zhang, Hedge and Guo (2015) that thermal discomfort decreases with an increase in duration. However, the present study shows a sharper decline in the participants' ratings over the 600 second holding period.

The declining trend may indicate that the participants adapted to the surface temperature of 42 ℃ after prolonged contact. Past research has shown that when thermal stimulation at the forearm was in the range of 29 ℃ -37 ℃, participants could completely adapt to the temperature after 25 minutes of contact, meaning they no longer felt hot nor cold (Kenshalo and Scott, 1966; Parsons, 2014). In the current study, although participants still felt warm or hot sensations, the sensation or discomfort levels did not increase. Previous studies have suggested that when the duration of thermal stimulation was under one second, the magnitude of the thermal sensation rating decreased quickly when the duration increased; but when the duration was above one second, the magnitude was not affected (Steven, 1991; Wilson et al., 2013). The current study has confirmed that the perception magnitude decreased with a longer duration of 600 seconds. A possible reason is that the warm fibers could adapt to the static warm temperature in the range of above 30 ℃ and below 50 ℃ (Duclaux and Kenshalo, 1980).

However, the current study's finding contradicts the findings of previous studies on heat pain threshold (Dyck et al., 1993; Pertovaara et al., 1996), in which the pain threshold was decreased with an increase of duration. One reason may be that the tested temperature range in the current study is from 38 ° to 42 ℃, while the pain threshold is usually above 44 ℃. Therefore the participants in the current study were able to acclimate to the surface temperatures that were under heat pain threshold. On the other hand, no significant difference was found on finger thermal comfort. The mean rating score remained relatively constant from 69.6 to 65.5.

CHAPTER 7

EXPERIMENT 3. THE STUDY OF TABLET COMPUTER USERS' GRIP AREAS AND THE EFFECT OF SPATIAL DISTRIBUTION OF HEAT

7.1 Introduction

Users can hold tablets in different orientations and with varied grips. If the areas that are less frequently in contact with users' fingers are identified, more heat can be dissipated in these areas. A user typically holds a tablet with one hand, using either flat or ledge grip (Pereira et al., 2013). A flat grip is defined to have fingers to cover the object's flat surface, while a ledge grip is to have part of the fingers wrapped at the edge of an object (Patkin, 2001; OSH, 2002). Similarly, when performing gesture-based tasks, most users (15 out of 20) were observed to hold the tablet with one hand with modified lateral pinch grip, and the rest (5 out of 20) used idiosyncratic grips (Chau and Wells, 2015). Less fatigue was found in the portrait orientation compared to landscape orientation (Pereira et al., 2013). Researchers have also observed that one handed tablet grip can be in the forms of flat hand grip, thumb wrapped at the screen with flat hand at device bottom, or thumb extended at the back of device with thenar support (Feathers and Zhang, 2012). If a user holds the tablet with two hands, fingertips were observed to be in contact with the back of the tablets with both landscape and portrait orientations (Trudeau et al., 2013). It is useful to find the areas that the fingers are in contact with, so that the user comfort can be improved by avoiding these areas to dissipate heat, or by reducing the surface temperature and the contact duration.

Furthermore, people perceive hot stimuli less uncomfortable at a lower ambient temperature (Zhang, Hedge and Guo, 2015). As a result, more heat can be dissipated at the areas where the users hold the tablets if the environmental temperature is low, and heat should be controlled to be away from the areas in contact with users' hands. Ultimately the goal of the study is what heating areas can allow for a higher user thermal comfort.

On the other hand, tablet computer's heat dissipation can be unevenly distributed. When different body parts are in contact with stimuli of different temperatures, thermal sensation can be altered by the unevenly distributed heat. In the phenomenon of thermal grilled illusion, a person dips the middle finger into cold water (14 ℃) while the index and ring fingers in warm water (43 ℃), and the middle finger will feel much hotter than if the other two fingers are in room temperature water (Kammers et al., 2010). One explanation of the phenomenon by Craig (2002) was that cold water reduced A-delta fiber activities of the middle finger that senses cooling. This led to a dis-inhibition of C fiber thus inducing pain. It is also possible to reduce A-delta or C-fiber activities by using warm stimuli initially, which creates a less uncomfortable sensation, if the skin is in contact with stimuli of higher temperatures. In the case of unevenly distributed heat on a tablet's surface, a user's hand may be in contact with areas of different temperatures, and thus might lead to thermal discomfort, such as thermal grill illusion. Therefore, it is also necessary to avoid thermal discomfort in the tested conditions.

7.2 Objectives and hypotheses:

The objective of this experiment is to test whether dissipating heat at certain areas of the tablets can improve thermal comfort. Finding the areas that can be heated without causing user thermal discomfort is also meaningful for future tablet computer heat dissipation designs.

Hypotheses:

H1: In general, fingers are less likely to be in contact with the center columns of the back of the tablet.

H2: Heating tablet central areas will lead to a lower thermal sensation score than heating peripheral areas.

7.3 Methods

7.3.1 Participants

Twenty-five participants were recruited from students and employees at Cornell University. Participants were recruited through posters at the buildings of Martha Van Rensselaer and the Human Ecology Building. The Cornell SONA psychology experiment online system was also used to recruit participants. Each participant was paid with 10 dollars for the 45 minute experiment. The age of the participants ranged from 19 to 32 years old, with an average of 23.2 years and a standard deviation of 4.0 years. Among the participants, 14 were female and 11 were male.

7.3.2 Apparatus

The simulated tablet computer heating surface in combination with an iPad Air (Model# A1566, Wi-Fi 16 GB, iOS 8.1.3) was used in combination with the heating surface to play videos. A Nature documentary “The Private Life of Deer” was played in YouTube for the participants while they were holding the device. All sessions were conducted in a controlled environmental chamber. Indoor air temperature was controlled at 23 ℃, while the humidity was controlled at 40% RH.

7.3.3 Procedure

Before the experiment participants came in the climate chamber to be familiar with the environment for 20 minutes while signing the consent form, and introduced to the experiment. Participants were asked to hold the heating surface with an iPad and watch a 7-minute movie clip. After each tested condition, participants rated their local thermal sensation and comfort on fingers and palms, with visual scales shown in Chapter 4. The participants were asked after they held the surface for 5 seconds, 1 minute, 4 minutes, and 7 minutes. In addition, participants also needed to report whether each of the fingers perceived heat, while they were watching the movie. In addition, participants were asked if both of their hands or only one hand perceived the heat.

Each participant was tested with all the following test conditions, including both horizontal (Figure 7.1) and vertical layouts (Figure 7.2). In the figures the orange colored areas are heated to 42 ℃ while the blue areas are not heated. A target temperature of 42 ℃ was chosen because it can cause thermal discomfort at room temperature (Chapter 3). If participants were in contact with heated areas, they would explicitly report discomfort.

The tested layouts were categorized as horizontal conditions (Figure 7.1) and vertical conditions (Figure 7.2). Among the horizontal conditions, H2 and H3 were to test the possibility in touch with the upper areas of the tablet. H4 is to test if the participants’ fingers could reach the middle area. H5 was to simulate the heat from elements such as 3D-camera at the corner. H1 was used as a reference layout for comparisons.

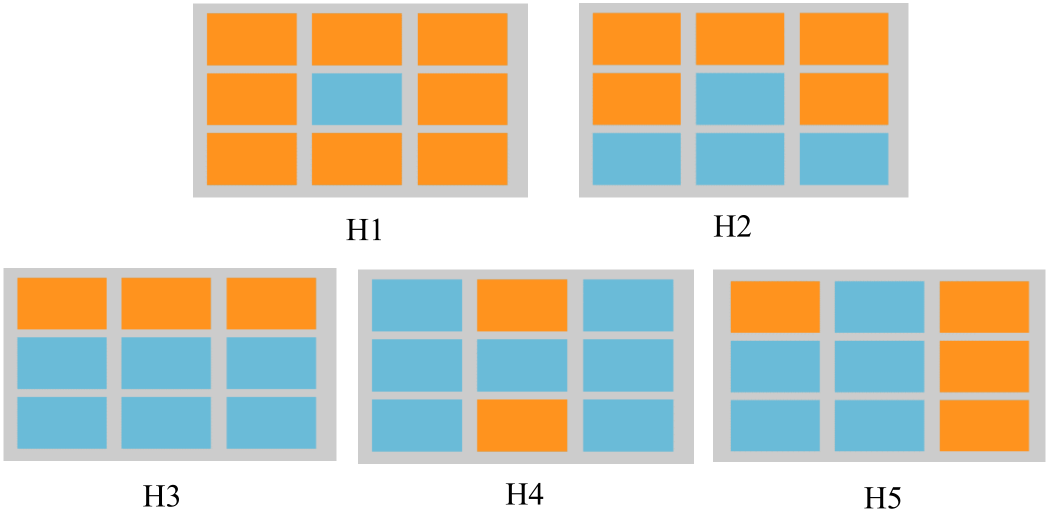

H1 H2 H3 H4 H5

Figure 7.1. Horizontal layouts

Among the vertical conditions, V1 was to test if the participants' fingers can reach the middle area. V2 and V3 were to test the possibility in touch with the upper areas of the tablet. V4 and V5 were to simulate the heat from elements such as 3D-camera at the corner.

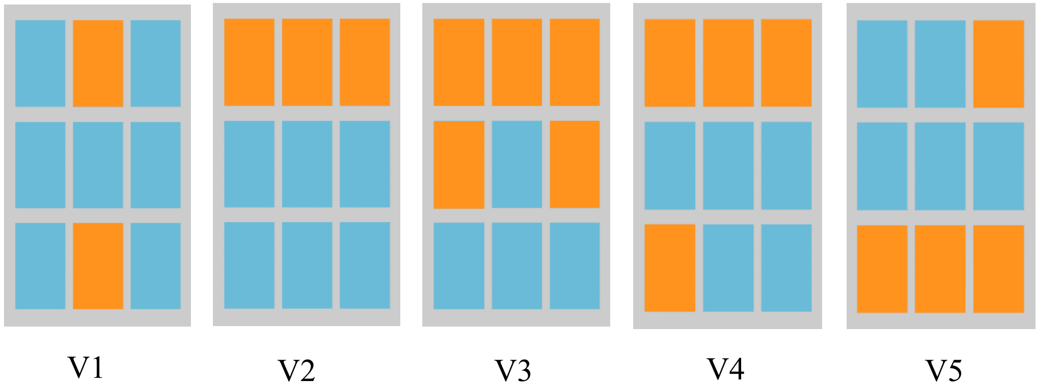

V1 V2 V3 V4 V5

Figure 7.2. Vertical layouts

7.4 Results

7.4.1 Most preferred conditions

7.4.1.1 Horizontal conditions

When participants held the tablet computer horizontally, their ratings on finger thermal sensation and thermal comfort were significantly different among the tested conditions (F(4,340)= 261.95, p<0.0001, F(4,340)=159.63, p<0.0001). Pairwise comparisons showed that H4 had a significantly lower score than H3, which was in turn lower than H1, H2 and H5, for both thermal sensation and thermal discomfort scores. Therefore for horizontal conditions, H4 was the most preferred in terms of thermal comfort, and H3 was the next preferred, while no significant difference existed among the other three conditions. The specific average scores generated by the model are shown in Table 7.1.

The thermal sensation and thermal discomfort scores on the palm areas also varied significantly, F(4,340)= 14.18, p<0.0001, F(4,340)=22.67, p<0.0001 (Figure 7.3). For palm thermal sensation scores, H3 and H4 were significantly lower than H1, H2 and H5. Yet no significant difference was found between H3 and H4, or among H1, H2 and H5. For palm thermal discomfort scores, H3 and H4 were significantly lower than H1, H2 and H5, and H5 was lower than H1. No significant difference was found between any other pairs. Holding duration or the interaction of duration and conditions did not have a significant effect on either finger or palm scores.

Table 7.1 Finger and palm thermal sensation and comfort scores

	Finger Sensation		Finger Comfort		Palm Sensation		Palm Comfort	
Level	Least Sq Mean	Std Error	Least Sq Mean	Std Error	Least Sq Mean	Std Error	Least Sq Mean	Std Error
H1	75.8	1.6	69.1	1.9	49.7	1.9	48.4	2.2
H2	74.5	1.6	66.5	1.9	49.2	1.9	47.8	2.2
H3	51.1	1.6	44.5	1.9	44.6	1.9	42.2	2.2
H4	44.1	1.6	36.9	1.9	44.1	1.9	39.7	2.2
H5	73.6	1.6	66.5	1.9	47.6	1.9	45.3	2.2
V1	51.2	2.0	43.9	2.4	46.9	1.4	41.7	2.0
V2	47.6	2.0	42.5	2.3	46.9	1.4	42.1	2.0
V3	68.9	2.0	62.9	2.3	50.3	1.4	46.7	2.0
V4	62.3	2.0	54.7	2.3	49.6	1.4	46.4	2.0
V5	68.9	2.0	60.5	2.3	48.8	1.4	46.5	2.0

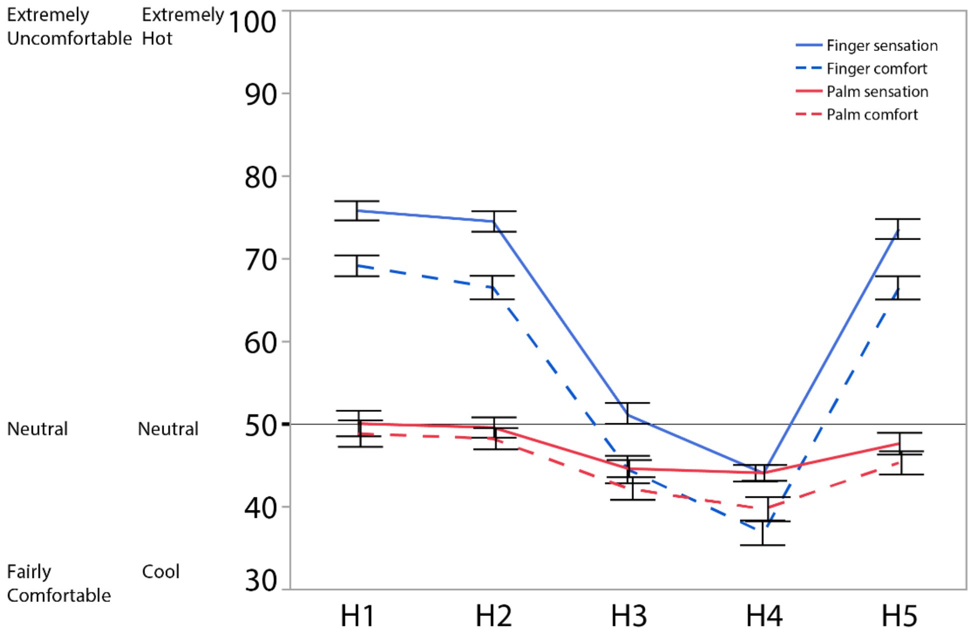


Figure 7.3 Thermal sensation and comfort ratings for horizontal conditions

7.4.1.2 Vertical conditions

When participants held the tablet computer vertically, their ratings on finger thermal sensation and thermal comfort were significantly different, F(4,343)= 58.42, p<0.0001, F(4,343)=36.43, p<0.0001. Pairwise comparisons showed that V1 and V2 had a significantly lower score than V4, which were in turn lower than V3 and H5, for both thermal sensation and thermal discomfort scores. Yet for thermal discomfort scores no significant difference was found between V4 and V5. Therefore, for horizontal conditions, V1 and V2 are the most preferred in terms of thermal comfort. The specific average scores generated by the model are shown in Table 7.1.

The thermal sensation and thermal discomfort scores on palm also varied significantly, F(4,343)= 5.88, p<0.0001, F(4,343)=11.93, p<0.0001 (Figure 7.4). For palm thermal sensation scores, V1 and V2 were significantly lower than V3 and V4, while V5 was in between the two groups. No significant difference was found among V1, V2, and V5, or among V3, V4 and V5. For palm thermal discomfort scores, V1 and V2 were significantly lower than V3, V4 and V5. No significant difference was found between V1 and V2, or among V3, V4 and V5.

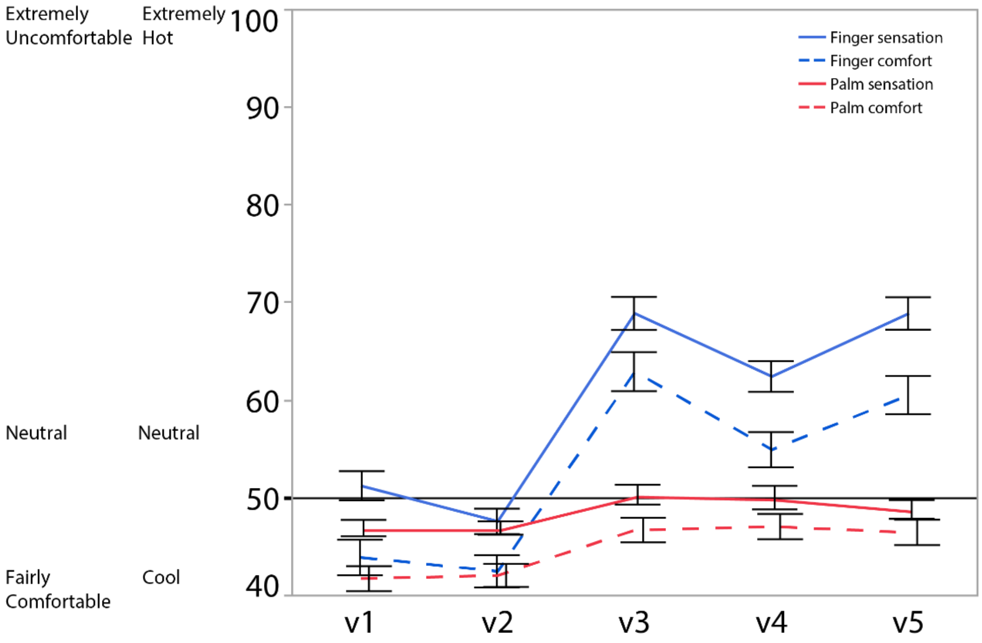


Figure 7.4 Thermal sensation and comfort ratings for vertical conditions

7.4.2 Fingers in contact

7.4.2.1 Horizontal conditions

As shown in Table 7.2 and Figure 7.5, when participants held the heating surface horizontally, H4 affected none of the fingers. In H4 none of the participants reported the perception of heat on any of their fingers. For H3, digit 4 was slightly affected (4.2%), and digit 5 was not affected (0%). However, participants reported heat on digit 2 and 3. For H1, H2, and H5 over 80% participants reported that they perceived the heat on digit 2 and 3.

Table 7.2. Percentage of the fingers that perceived heat for all the conditions

Conditions	**Digit 2**	**Digit 3**	**Digit 4**	**Digit 5**	**Both hands**
H1	91.7%	95.8%	100.0%	95.8%	95.8%
H2	87.5%	100.0%	66.7%	33.3%	95.8%
H3	37.5%	16.7%	4.2%	0.0%	29.2%
H4	0.0%	0.0%	0.0%	0.0%	0.0%
H5	79.2%	91.7%	100.0%	70.8%	66.7%
V1	8.3%	20.8%	16.7%	29.2%	37.5%
V2	12.5%	0.0%	0.0%	0.0%	12.5%
V3	87.5%	70.8%	45.8%	20.8%	87.5%
V4	29.2%	33.3%	50.0%	50.0%	20.8%
V5	41.7%	54.2%	79.2%	70.8%	79.2%

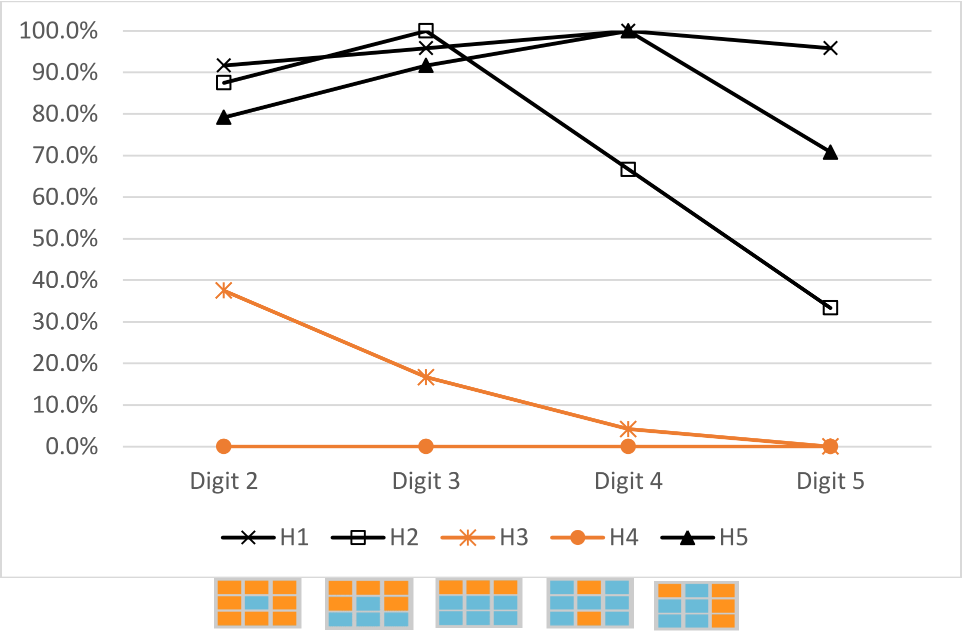


Figure 7.5. Percentage of the fingers that perceived heat for horizontal conditions

7.4.2.2 Vertical conditions

As shown in Table 7.2 and Figure 7.6, when participants held the heating surface vertically, the condition that participants reported least heat with was V2, in which digit 2 was reported by 12.5% of the participants, while no other fingers were reported. For the condition of V1, fewer participants (8.3%) reported the perception of heat on the digit 2, yet 20%-30% of participants reported the perception of heat on digits 3, 4 and 5. For the other conditions of V3, V4 and V5, over 50% of the participants perceived heat on digits 4 and 5.

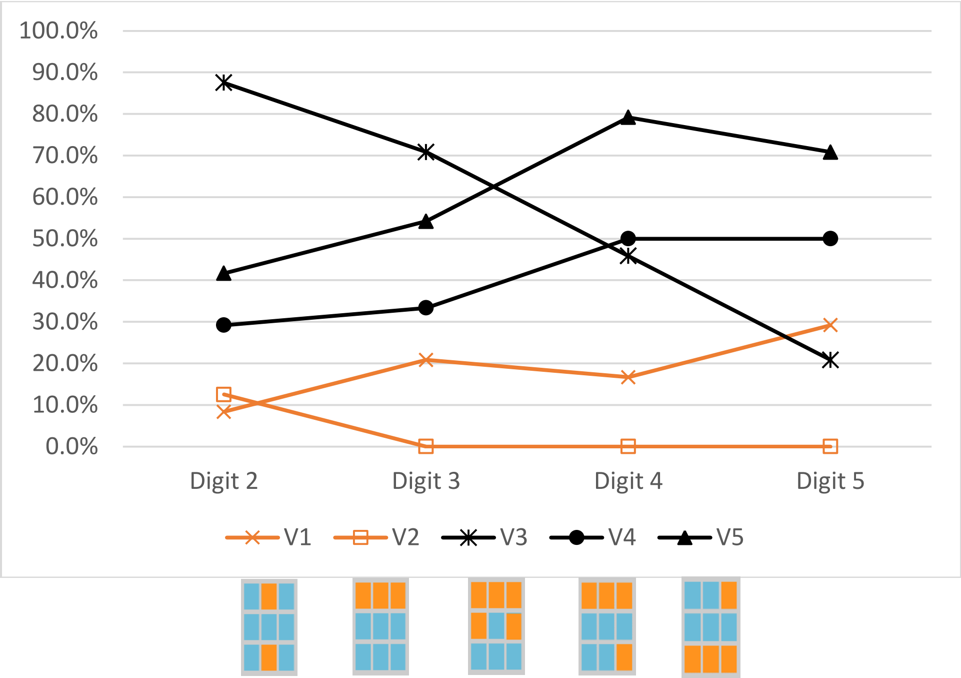


Figure 7.6. Percentage of the fingers that perceived heat for vertical conditions

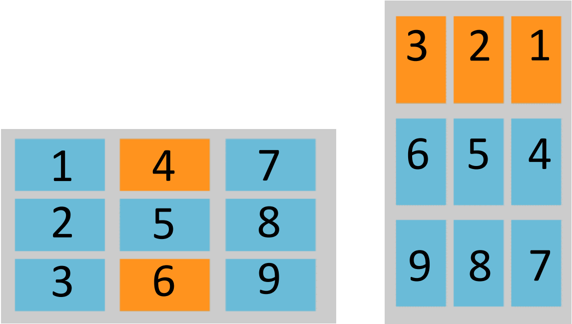


Figure 7.7. The areas in contact with fingers.

Note: The orange color indicates the areas that were not touched in the experiments.

The blue areas are the ones that were touched.

In summary, based on reported percentage of fingers in contacted with the heated pads in each condition, the areas of 4 and 6 in the middle were not touched by any of the tested participants, when the tablet-size heating surface was held horizontally. The less touched areas also include areas 1 and 7 at the top of the surface, which were touched by 40% of the participants' digit 2 and 20% of the digit

3. When the surface was held vertically, the least touched areas were 1, 2, and 3 at the top, which were touched by 10% of the participants' digit 2. 20%-30% of the participants reported they would touch the middle areas of 2 and 8 with their fingers of digit 3, 4, and 5, shown in Figure 7.7.

7.5 Discussion

7.5.1 Most preferred conditions and finger contact

The tested surface temperature of 42 ℃ can lead to a thermal sensation rating between"warm" and "hot" and a thermal comfort rating of "slightly comfort" at the room temperature of 23 ℃ (Zhang, Hedge and Guo, 2015). Since part of the surface was heated to 42 ℃, it was expected that if any fingers or palms were in contact with the heated areas, participants should report thermal discomfort. Figure 7.5 shows that H3 and H4 seems to have fewer fingers reported in contact with the surface comparing to other conditions. Figure 7.6 shows that V1 and V2 seems to have a smaller percent of the fingers reported than other conditions. The conditions with fewer fingers in contact with the heated areas tend to have slightly lower thermal discomfort ratings than the ones with more fingers in contact.

In both horizontal and vertical conditions, the ones with lower overall thermal discomfort ratings correspond well with the ones with lower percentages of contacted fingers. More specifically, when participants held the tablet horizontally, the most thermally comfortable conditions are H4 and H3. In the two conditions, both finger and palm thermal discomfort scores are lower than all other conditions. The thermal discomfort score of fingers for H4 was 36.9, and the one for H3 was 44.5, meaning "somewhat comfortable" on the scale. For H4, no fingers were reported to be in contact with the heated area. For H3, very low percentages (0-16.7%) were reported on digit 3-5, and 37.5% on digit 2. In contrast, all the scores of the other conditions of

H1, H2, and H5 were above 60, meaning “uncomfortable”. Correspondingly, in these conditions most fingers were reported by over 60% of the participants to be in in contact with the heated areas. Similarly, in the vertical conditions, V1 and V2 had the lowest thermal discomfort scores, and fewer participants reported the perception of the heat than the other conditions.

7.5.2 Contact area and stimuli size

Results suggest that as more fingers were exposed to the heat, higher discomfort was reported. The trend matches previous findings that that larger stimuli on skin could produce lower thermal sensation thresholds (Kojo and Pertovaara, 1987; Meh and Denislic, 1994; Hiltz et al., 1999; Hagander et al., 2000; Kelly et al., 2005). In the previous findings, warm sensation and heat pain sensation threshold was decreased as the stimuli size increased, and the tested skin areas included thenar eminence and lower medial calf (Meh and Denislic, 1994; Hiltz et al., 1999). In the current experiment, no statistical significant difference was found in thermal discomfort among H1, H2, and H5. However, the finger discomfort score of H1 was 69.1, and for H2 and H5 it was 66.5 and 66.5, respectively. While in H1, as shown in Figure 7.5, the whole surface was heated, and over 90% of the participants reported all four digits were affected by the heat. It is also shown in Table 7.2 that among the conditions of H1, H2 and H5, at least one finger was reported by all the participants (100%) to have perceived heat. However, the percentages of all the contacted fingers, or the sizes of the stimuli, are smaller in the conditions of H2 and H5, comparing to H1. Spatial summation is defined as the size of the stimuli increases, the perceived intensity increased or the sensation threshold decreased (Kenshalo et al., 1968; Marchand and Arsenault, 2002). Spatial summation may account for the lower thermal sensation thresholds in the previous literature, as well as the higher thermal discomfort ratings in the current study. The increased size allowed heat to be spread to a larger area of the skin, leading to more recruited nociceptive afferent fibers.

7.5.3 Areas in contact, fingers, and related hand size

In general, participants' fingers of digit 2 to 4 were observed to be in contact with the back of the tablet, while digit 1 was usually in contact with the touch screen, as shown in Figure 6.1. The thermal sensation and thermal comfort ratings on the palms changed with the change of heated areas, suggesting that a part of the palms might be in contact with the back of the tablet.

Figure 7.8 shows the fingers' range of contact with the tablet. Table 7.3 shows the lengths of the middle finger for both genders (Pheasant and Haslegrave, 2005). Since the middle finger (digit 3) is the longest among the five digits, the range of the finger contact with the heated areas is described in the figure. If participants hold the tablet horizontally, the range of the middle finger for the 5th percentile female can cover all the areas on the heating pads on both sides. However, little chance exists even for 95th percentile male's middle finger to be in contact with the middle column of the heating pads. If the participants hold the tablet vertically, almost all the participant, ranging from 5th percent female to 95th percent male can reach the middle of the tablet. From the actual observation and reported affected fingers, Figure 7.7 shows the actual areas that were less frequently in contact with the fingers. The less touched areas are the middle column (pad 4 and 6) when the device was held horizontally, and the top row (pad 1, 2, 3) when the device was held vertically. In the horizontal orientation, the middle row corresponds well to the indicated range as shown in Figure 7.7. In the vertical orientation, the top row could be reached as shown in Figure 7.8, however, in the actual observations, the top row were not frequently reached by the participants.

Table 7.3. Middle finger length by gender, adapted from Pheasant and Haslegrave (2005)

	Men				Female			
Percentile	5th	50th	95th	SD	5th	50th	95th	SD
Middle finger length (mm)	76	83	90	5	69	77	84	5

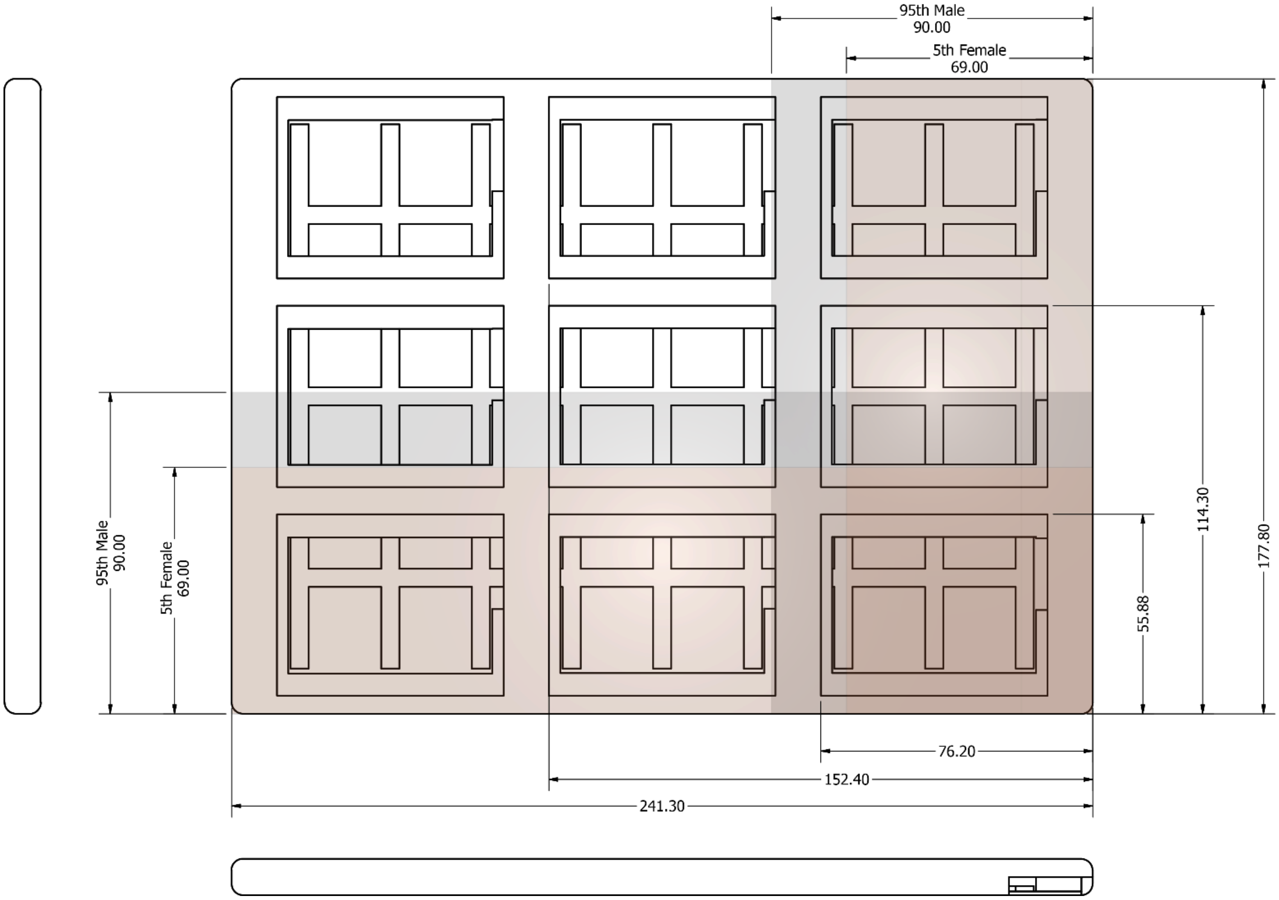


Figure 7.8 Heating surface size and finger range

CHAPTER 8

EXPERIMENT 4. THE EFFECT OF SURFACE TEXTURE ON THERMAL SENSATION AND COMFORT

8.1 Introduction

The surface materials can affect cutaneous thermal sensation and the threshold of skin burn. The nature of the material surface and skin conditions can affect the heat transfer rate thus affect thermal sensation and skin reactions (Parson, 2003). A solid surface has a few factors that can affect the heat transfer from the surface to the skin, including the number of layers, surface roughness, contact pressure, surface wetness, surface temperature, material thermal conductivity, material specific heat, material density, material thickness, and surface cleanness, etc. (Parson, 2003; Galie et al., 2009). ISO 13732-2 (2001) showed human subjects' sensation ratings for human skin in contact with surfaces of moderate temperatures (10-50 ℃). For initial contact between hand and handrail and a door handle, different materials led to different responses. In the range of 36 ℃ to 50 ℃, materials such as wood and plastic were rated to be close to "neutral" or "slightly warm". In comparison, steel and aluminum were rated as "warm" or "hot". Participants were able to discriminate between materials at the same temperature because of the differences between thermal capacity and conductivity (Jones and Berris, 2003). Burn thresholds also vary among different material surfaces. In ISO 13732-1 (2006) the burn threshold for 1-minute contact period for metal is 51 ℃, but higher for ceramics and glass to 56 ℃ and as high as 60 ℃ for plastics and wood. Therefore, the material surface can affect the transfer of the heat.

For the same material, the roughness of a surface can affect the contact area between the skin and the material surface; therefore, it can affect the heat flux, the change of skin temperature, and perception of the heat (Galie et al., 2009). Researchers tested six levels of copper blocks at 23 ℃ with spatial periods ranging from 0.8mm to 3mm on ten healthy adults. Larger spacing among the dots on the texture was defined as rougher, and the peak of subjective roughness magnitude is at 3.0mm (Connor et al., 1990; Galie et al., 2009). Researchers found that if the surface was rougher, the skin temperature had a larger decrease. In general participants also reported the rougher surface was cooler. However, from the theoretical thermal model it was predicted that a smooth surface should have a slightly higher heat flux than a rougher surface (Ho and Jones, 2008). Heat flux is defined as the rate of energy transferred through a given surface per unit time (Spakovszky, 2009). Galie et al. (2009) found that a rougher (with larger spacing) surface could lead to more deformed finger skin surfaces around the textured surfaces, thus a larger contact area for heat transfer. Meanwhile, the contact pressure might be another variable in the experiment (Galie et al., 2009). Since surface roughness can affect the heat transfer between skin and the stimuli, it is necessary to understand how surface roughness can affect thermal sensation when the surface temperature is higher than skin temperature.

8.2 Objectives and hypotheses

Currently new materials with higher heat transfer rate are being developed to dissipate heat more efficiently. Rough material surface texture can be a possible solution to improve thermal comfort. Although the previous predictive model suggested smoother texture could have higher heat flux, the later experiment study showed that the rougher texture had a higher heat flux and contact area (Ho and Jones, 2008; Galie et al., 2009). The actual heat transfer and the change of skin temperature depend more on the specific material. In addition, the weight of a tablet computer can be higher than the experimental conditions tested with 1N of contact force by Galie et al. (2009). Therefore, it is necessary to obtain thermal sensation and discomfort data with a rough texture with a tablet computer. It will also be interesting to compare the user thermal comfort between rough and smooth texture, to understand whether a rough surface can reduce thermal comfort comparing with a smooth surface.

Hypotheses

H1: Participants will report lower thermal discomfort scores with the rough surfaces, than the smooth surface.

H2: A surface with a larger spacing (6.35mm) is less thermally comfortable than a smaller spacing (1.59mm) at 42 ℃.

8.3 Methods

8.3.1 Participants

Sixteen participants were recruited from students and employees at Cornell University. Participants age range from 21 to 60 years old, with an average of 25.1 years. Among the participants, 8 were female and 8 were male.

8.3.2 Apparatus

Galie et al. (2009) tested copper coarse texture with spatial periods ranging from 0.08mm to 3mm, and they found that a larger spacing helps with heat transfer. Therefore, smaller spacing may reduce heat transfer and thus improve thermal comfort. In the current experiment, the mesh size ranges from 1.59mm to 6.35mm, to confirm and the extend the findings of Galie et al. (2009).

Three sizes of aluminum meshes (Amaco Wireform) were tested, 1.59mm, 3.18mm, and 6.35mm. The size is defined as the distance between the centers of one grid to another grid on the side. The meshes are 1mm in thickness. The aluminum meshes were attached tightly to the bottom of the heating surface during the tests, as shown in Figure 8.1. Before each test the mesh was firmly pressed against the aluminum heating surface to ensure that the two surfaces were tightly in contact. An extra sensor was attached at the outside mesh surface to calibrate the mesh surface temperatures to be 38 ℃ and 42 ℃, depending on the conditions.

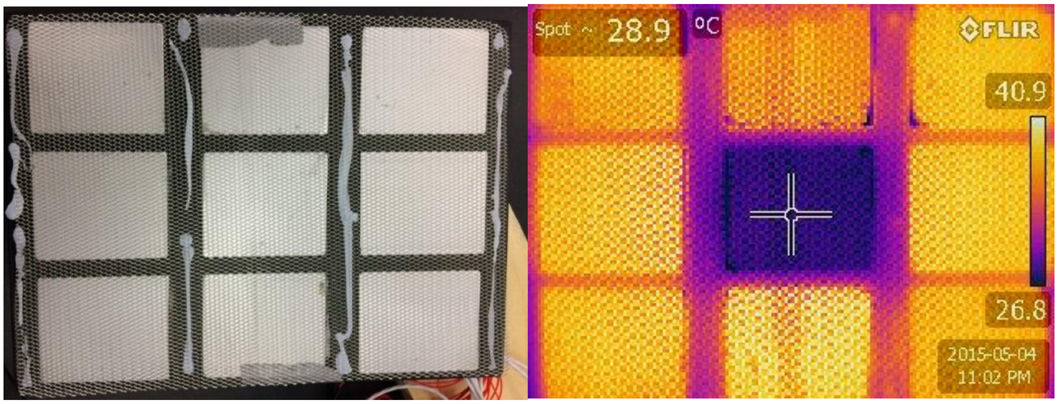


Figure 8.1 Heating surface with a mesh surface

The simulated tablet computer heating surface in combination with an iPad Air (Wi-Fi 16 GB, iOS 8.1.3) was used in combination with the heating surface to play videos. A Nature documentary “The Private Life of Deer” was played in YouTube for the participants while they were holding the device. All sessions were conducted in a controlled environmental chamber. Indoor air temperature was controlled at 23 ℃, while the humidity was controlled at 40% RH.

8.3.3 Procedure

The experiment is a within-subject design. Each participant experienced all three meshes (1.59mm—m1, 3.18mm—m2, and 6.35mm—m3) in combination with two surface temperature levels (38 ℃ and 42 ℃) and were asked for thermal sensation and comfort for three times for each condition. At the room temperature of 23 ℃, participants will feel warm and slightly comfortable with the surface temperature of 38 ℃, and hot and slightly uncomfortable at 42 ℃ (chapter 5). With the two levels of temperatures, participants may feel significantly different. At 38 ℃, they may not differentiate thermal comfort between mesh surface and smooth surface because 42 ℃ is more uncomfortable. However at 42 ℃ they are more likely to feel the difference in thermal comfort between mesh and smooth. In total seven conditions were tested: m1-38, m1-42, m2-38, m2-42, m3-38, m3-42, smooth-42.

Participants spent approximately 20 minutes becoming accustomed to the controlled environment, while the researcher introduced the experiment and obtained demographic information, such as gender, age, weight, and height. The participants were introduced to hold the heating surface in combination with a tablet computer. Participants were asked to hold the surface to watch a 3-minute movie clip from the documentary movie. For each tested condition, participants rated their local thermal sensation and thermal comfort at their fingers and palms with the visual scales in Appendix I. In addition, participants also report their subjective physical comfort and their ratings of materials roughness/smoothness when in contact with the materials with 7-point Likert scales. The Likert scales range from one to seven as shown in Appendix II. For the physical comfort, the scale ranged from uncomfortable (score 1) to comfortable (score 7). The roughness scale ranged from rough (score 1) to smooth (score 7). The scales about roughness and physical comfort are used to understand how their physical comfort may change with the mesh surfaces. Likert scales were used to allow the participants to differentiate them from the thermal sensation and comfort scales.

For each condition participants made the ratings on fingers and palms at three time points: when they initially touched the surface, at 90 seconds, and at 180 seconds. Information was collected at multiple time points to measure the change of thermal sensation and comfort with the time, especially with the mesh surface. The duration of 180s was the same as Experiment 1 for further comparisons. Participants rated thermal sensation comfort at all the time points while only reported physical comfort and material roughness after the test of each mesh material. Between each tested condition, the participant rested for three minutes. The order of the test conditions were randomized.

8.4 Results

In experiment 4, three types of aluminum meshes were tested. M1 represents 1.59mm mesh, m2 represents 3.18mm mesh, and m3 represents 6.35mm mesh.

8.4.1 The effect of different textures on thermal sensation and discomfort scores

Holding duration and participants' demographic information (such as weight and height) were not significant variables and were not taken account in the model.

The variables of surface temperature (38 ℃, 42 ℃) and surface texture (Smooth, m1, m2, m3) were combined as one variable, with 5 levels (m1-38, m1-42, m2-38, m2-42, m3-38, m3-42, smooth-42). Comparisons of thermal sensation and discomfort scores under the tested conditions were shown in Figure 8.2 and Figure 8.3.

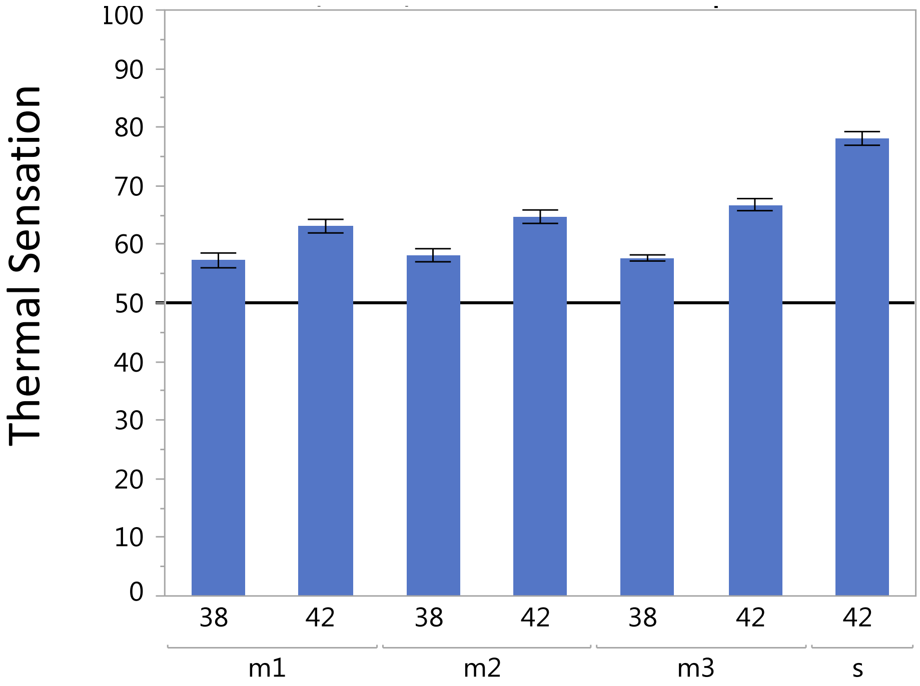


Figure 8.2 Thermal comfort ratings at fingers

(Error bar is constructed with 1 standard error from the mean)

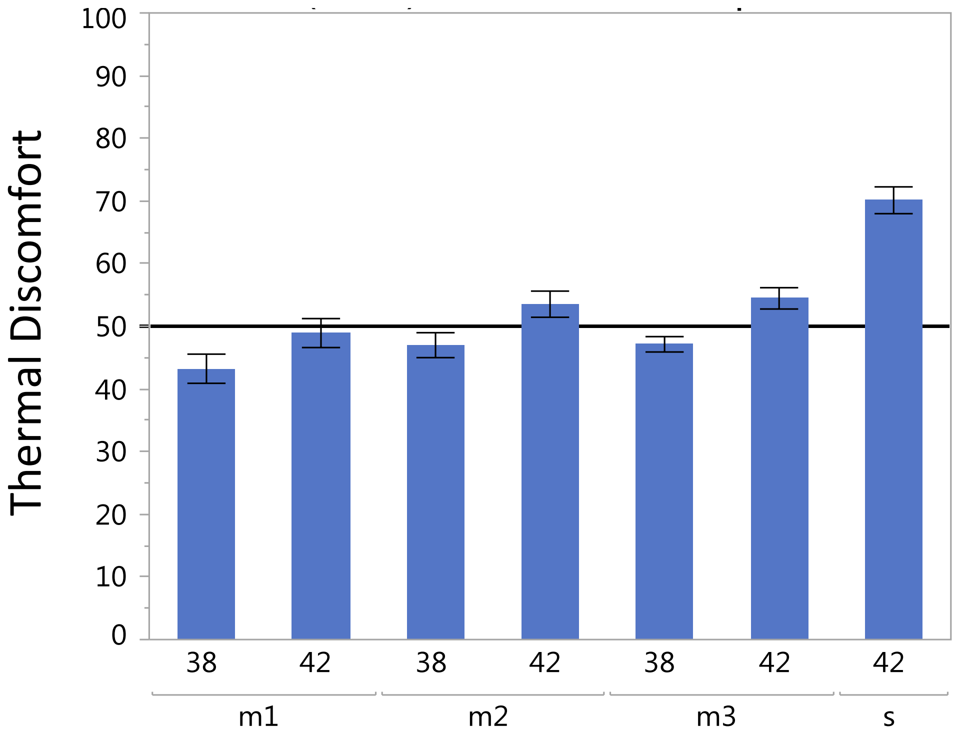


Figure 8.3. Thermal comfort ratings at fingers

(Error bar is constructed with 1 standard error from the mean)

At the surface temperature of 42 ℃, all three aluminum meshes received significantly lower finger thermal sensation and comfort ratings than the aluminum surface (F(6, 87)=42.15, p<0.0001; F(6, 87)=16.75, p<0.0001). However, no significant difference was found among the three aluminum meshes. All the scores are shown in Table 8.1.

At the surface temperature of 38 ℃, all three aluminum meshes received lower finger thermal sensation and comfort ratings than the smooth aluminum surface. The finger thermal sensation score for smooth aluminum was 66.0 from experiment 1 (Chapter 5), higher than all of the scores with the meshed surfaces in the current experiment. Similarly, no significant difference was found among the three aluminum meshes in the pairwise comparisons.

Between the surface temperature of 38 ℃ and 42 ℃, with the aluminum mesh m1, participants did not show a significant increase in finger thermal discomfort, while for m2 and m3 the difference in finger thermal discomfort was significant between 38 ℃ and 42 ℃.

Table 8.1 Finger and palm thermal sensation and comfort scores for different materials

		Finger sensation		**Finger comfort**		**Palm sensation**		**Palm comfort**	
Material	**Surface temperature**	Least Sq Mean	Std Error	Least Sq Mean	Std Error	Least Sq Mean	Std Error	Least Sq Mean	Std Error
M1	38	57.3	1.5	43.1	2.9	50.8	1.0	47.0	1.8
M1	42	63.1	1.5	48.8	2.9	50.4	1.0	46.5	1.8
M2	38	58.1	1.5	47.0	2.9	48.6	1.0	46.3	1.8
M2	42	64.7	1.5	53.5	2.9	51.9	1.0	49.2	1.8
M3	38	57.7	1.5	47.2	2.8	49.3	0.9	44.5	1.8
M3	42	66.8	1.5	54.6	2.8	51.4	0.9	47.9	1.8
Smooth	42	78.1	1.5	70.1	2.9	53.8	1.0	52.9	1.8

8.4.2 Duration effect

A significant duration effect was found on the thermal sensation scores (F(2, 211)=42.15, p=0.015). However the change is small in magnitude: the initial average thermal sensation score was 62.6, and the score was 63.9 at 90 seconds; and at 180s the score was 64.5. The score was significantly higher at 180s than 0s, yet no significant difference was found among the other pairs. On the other hand, no duration effect was found on the thermal discomfort scores (F(2, 211)=1.31, p=0.27).

8.4.3 Interaction effect of duration and the texture

The interaction effect of duration and the texture was found to be significant on thermal sensation (F(2, 211)=2.79, p=0.0015), and on thermal comfort (F(2, 211)=2.19, p=0.013). The interaction effect is shown in Figure 8.4. However, no significant difference was found between different time points for each mesh conditions, for either thermal sensation or discomfort scores. No significant effect of interaction was found on palm.

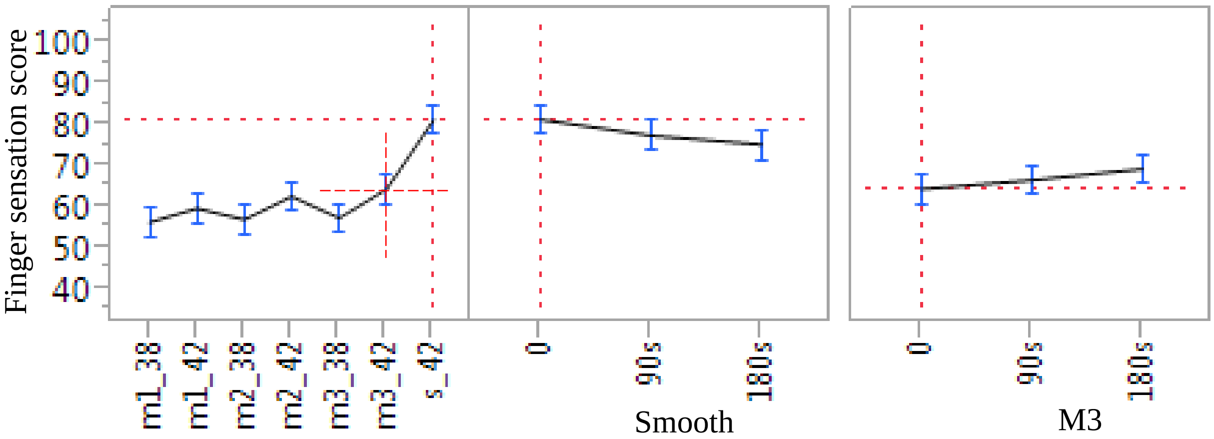


Figure 8.4 Interaction effect of mesh texture and time

8.4.4 Roughness and physical comfort of the texture

8.4.4.1 General roughness and physical comfort

Friedman test showed that not all the ratings on roughness were the same (Q=31.87, p<0.0001). Pairwise comparison showed that the smooth aluminum had the highest rating; the second highest was m1; the lowest rated were m2 and m3. No significant difference was found between m2 and m3.

In terms of texture physical comfort, smooth aluminum was rated as the most comfortable surface, while no significant difference was found between m1 and m3, or m2 and m3, yet m1 was found to be more comfortable than m2 (Figure 8.5). The average score for m1 was 4.1, for m2 was 3.5.

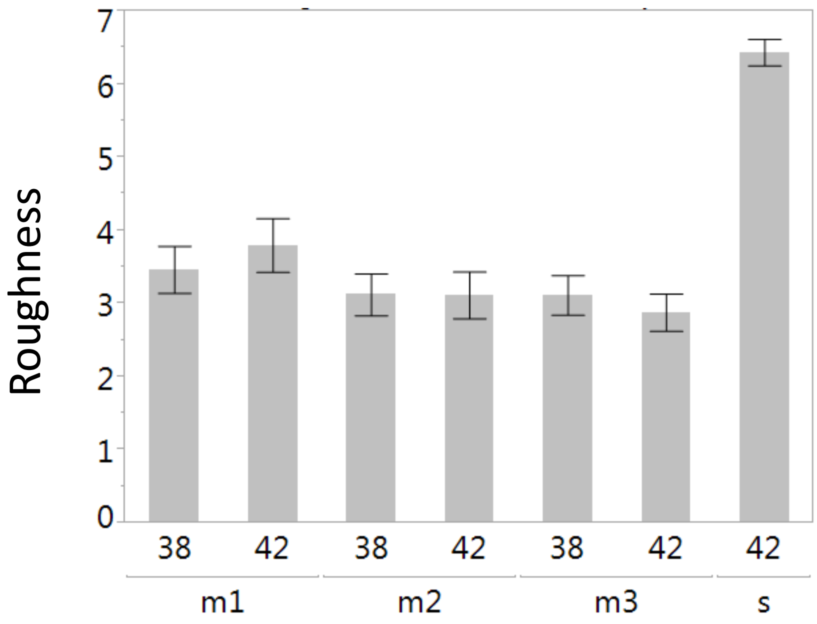


Figure 8.5 Roughness ratings on different mesh conditions

(1-rough, 7-smooth)

8.4.5 Comparison among the temperatures

8.4.5.1 Roughness

Smooth aluminum was perceived as significantly smoother than all the mesh nets at both 38 ℃ and 42 ℃ (Q=47.08, $p<0.0001$). With the same mesh, no significant difference was found between the temperature levels of 38 ℃ and 42 ℃. At 38 ℃, the roughness ratings of m1, m2, m3 were not significantly different from each other. However, at 42 ℃, m1 was rated smoother than m2, and m2 was smoother than m3.

8.4.5.2 Physical comfort

Physically, aluminum was perceived as significantly more comfortable than the mesh nets at 38 ℃ and 42 ℃ (Figure 8.6). No significant difference was found between the temperatures within the same mesh. At 38 ℃, the ratings of m1 and m3 were not significantly different, but m2 was rated lower than m1. On the contrary, at 42 ℃, no significant difference was found among the three meshes.

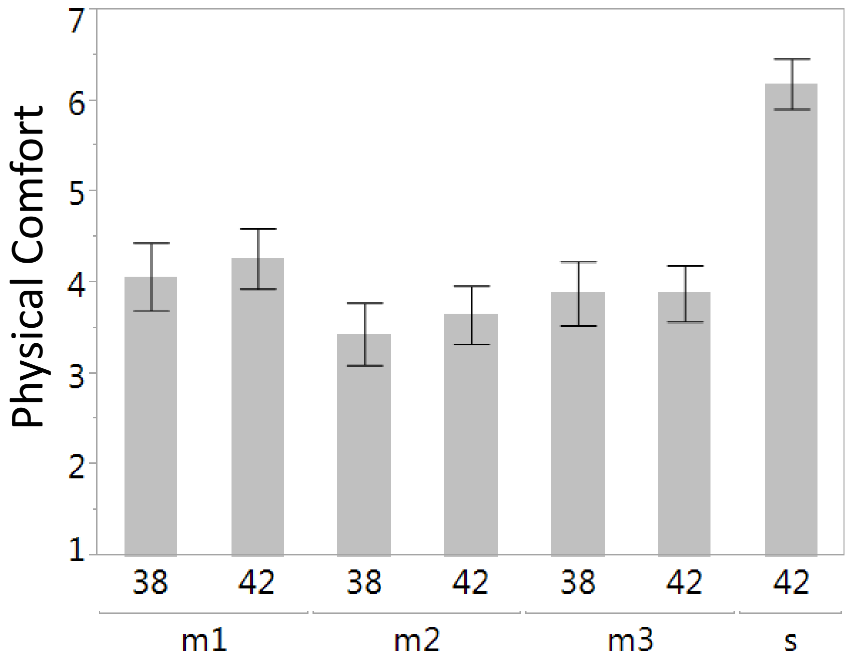


Figure 8.6 Physical comfort ratings on different mesh conditions

(1—comfortable, 7-uncomfortable)

8.5 Discussion

8.5.1 The texture's effect on thermal sensation and comfort

The surface texture had a significant effect on both finger thermal sensation and thermal comfort. At the same tested temperature, the thermal sensation and discomfort scores were the highest for the smooth aluminum condition in comparison to the other three mesh conditions. Therefore, H1 was supported. No significant difference was found among the three meshes. Therefore, H2 was not supported. As shown in Figure 8.2, 8.3 and Table 8.1, at 42 ℃ the mean thermal sensation scores at fingers for m1, m2, and m3 are 63.1, 64.7, and 66.8 respectively. The findings are consistent with the results by Galie et al. (2009), that there was a positive linear trend between the spatial period and the change of skin temperature. The range of the spatial period was between 0.8mm and 3mm in Galie et al. (2009), and was between 1.59mm and 6.53mm in the current study. Similar to the findings of the current experiment, the skin temperature change was also not significantly different from each other with pairwise comparisons in Galie et al.'s (2009) study. They also found that participants rated the rougher surface to be cooler, given that the tested surface in their experiments were kept in room temperature of 23 ℃. The air gaps between the skin and the rough texture may also help with heat dissipation (Hes and Araujo, 2010). The consistency of the findings illustrates that the roughness of the surface or the spatial period has an effect on the heat transfer between the skin and the material surface, thus an effect on the user thermal sensation and comfort. It was suggested that rougher surfaces allowed the skin to deform more around the textured surface to have more contact area with the stimuli (Galie et al., 2009). In addition, at the same surface temperature, the smooth surface in the current study received significantly higher thermal discomfort and thermal sensation ratings than all the meshed surfaces. The significant difference shows that rough surfaces have a potential to reduce heat transfer between the skin and the materials, improving the user thermal comfort.

8.5.2 The perception of the material roughness

Participants rated the roughness of the meshes differently at different temperatures. At a surface temperature of 38 ℃, no significant difference was found among the three conditions with meshes. However, at 42 ℃, significant difference was observed between the three levels: m1 with the largest spatial period of 6.53mm received the highest roughness rating, and m2 with 3.18mm was in between, while m3 with 1.59mm received the lowest rating. The trend was not consistent with previous findings that the magnitude of roughness was the highest at 3.0-3.2mm spacing of textures with dots (Connor et al., 1990; Galie et al., 2009). In Connor et al. (1990)'s study, the textures with 1mm, 2mm, and 6mm were rated lower in roughness magnitude than the texture with 3mm. The mean firing rates of mechanical cutaneous afferent fibers of tested monkeys were the highest at 2mm-2.2mm. Such inconsistency might be due to the different surface structure used and the test procedure applied. In the study by Connor et al. (1990), the stimulus surface texture was in dots spacing on a rotating motor, and the human subjects and the monkeys were tested with 70g/30g contact forces, and a scanning velocity of 50mm/s or 20mm/s. However, in the current experiment, the texture was meshes instead of dots, and the pressure on the fingers will be much higher since the weight of the iPad and the heating surface was 922g in total. In other words, the skin contact area, the skin deformation, and the presence of the stimuli were all different. As a result, the roughness of the tested surfaces could be perceived differently in the two experiments.

8.5.3 Temperature's moderation effect on *roughness*

It was shown in the current experiment that the surface temperature affected how participants rated the roughness of the surface. The result is consistent with previous research on the effect of heat on the perception of tactile stimuli (Green et al., 1979; Zhang et al., 2009). Zhang et al. (2009) tested vibrotactile stimulus at various skin temperatures, and found that the ability to detect a vibrotactile stimulus was improved at 43 ℃ than at room temperature. Similarly, Green et al. (1979) found when the skin temperature was increased; the perception of roughness was improved. On the other hand, in the same study, the researchers also found the perception of roughness was degraded if the skin was cooled below normal skin temperature. Aligned with their results, participants in the current study did not give significantly different roughness ratings among the three mesh surfaces at 38 ℃. However, at 42 ℃, participants rated the three meshes significantly different. Possible reasons were suggested by Green et al. (1979). The warming and cooling skin cause vasodilation and vasoconstriction, respectively, in turn, causing fluctuations in the mechanoreceptors' activity. Vasodilation increases the blood flow and hydrostatic pressure, increasing the sensitivity of the receptors' activity. In addition, vasomotion modulates the hydrostatic pressure, affecting the mechanical characteristics of the skin. In other words, cooling can stiffen the skin while warming can reduce the stiffness. Stiffer skin was shown to be less sensitive to respond to rough surface texture (Lederman, 1976; Green et al., 1979). This also helps to explain the inconsistent results of the current study and Connor et al. (2009)'s study. No heating element was designed in Connor et al. (2009)'s study, such that the surface temperature could be close to room temperature. This would, in turn, decrease the skin temperature, and could have affected the perception of the roughness by participants. While in the current study, both levels of the stimuli temperatures were above mean finger skin temperature, therefore, the mechanoreceptors’ sensitivity might be increased, to be more sensitive to mesh stimuli.

8.5.4 Physical comfort and thermal comfort

The mesh surfaces and the smooth surface received opposite ratings in thermal comfort and physical comfort. Therefore, the choice of the surface materials need to be a balance of material thermal comfort and physical comfort. It has been shown that mesh surfaces were more thermally comfortable than the smooth surface at both 38 ℃ and 42 ℃. Moreover, when the stimuli surface temperature increased from 38 ℃ to 42 ℃, m1 mesh did not lead to an increase of thermal discomfort scores. In contrast, m2 and m3 led to a significant increase. From previous results by Zhang, Hedge and Guo (2015) the increase of thermal discomfort score with a smooth aluminum surface was also significant, from 45.2 to 58.6. The contrast shows that the metal mesh with smaller spatial period of 1.59mm provides the most protection from thermal discomfort for users. Although the mesh aluminums surfaces can improve thermal comfort, participants still rated the mesh surfaces lower than the smooth surface in terms of physical comfort. Therefore, if a surface with meshed texture is selected to improver thermal comfort, its texture physical comfort should also be tested.

CHAPTER 9

DISCUSSION, LIMITATIONS AND CONCLUSION,

9.1 Discussion

9.1.1 Surface temperature and environmental temperature

The literature review identified a lack of information on thermal sensation/comfort for the hands at surface temperatures below the skin burn threshold that were being touched for relatively long duration. Experiment 1 filled this gap by testing thermal sensation and thermal comfort ratings for the prototype tablet surface in the range between normal skin temperature (34 ℃) and the lower limit of skin burn (44 ℃). . Results showed significant effects of both surface and ambient temperatures on participants' fingers' thermal sensation and comfort. The findings agreement with previous studies on thermal sensation for the hands when these were in contact with heated probes in similar temperature ranges (Fruhstorfer et al., 1976; Hirosawa, 1984; Meh and Denislic, 1994; Hagnder et al., 2000; Harju, 2002; Kiesa et al., 2005). In addition, experiment 1 showed the trend for changes in thermal sensation ratings over an extended duration of contact up to 180 seconds, which is longer than previous exposures.

Experiment 1 showed that cutaneous thermal sensation and comfort were also affected by the environmental temperature. The interaction effect of ambient and surface temperatures confirms previous findings by Strigo et al. (2000). The results from the two studies are the same for higher temperature of 44 ℃ and above, but different for lower temperatures such as 42 ℃ and below. The difference is because of the artificially controlled skin temperature in Strigo et al. (2000)'s study. In experiment 1 thermal responses changed with environmental temperature without controlling local skin temperature, and this also confirmed findings from other previous studies (Schoenfeld et al., 1985; Hirosawa et al., 1989).

9.1.2 Effect of rate of temperature change

Experiment 2 showed that a lower rate of temperature change of 0.02 ℃/s led to lower thermal sensation and thermal discomfort scores, than did a higher rate of 0.15 ℃/s. The results confirm the findings from multiple previous studies (Claus et al., 1987; Dyck et al., 1993; Wilson et al., 2012). However, it should also be noted that more heat was dissipated in the conditions of 0.02 ℃/s than the other conditions. The study also showed that an unbalanced repetitive heating does not result in any improvement in thermal comfort, comparing to a uniformly heated surface.

The study showed a potential to use a slow rate of temperature change when dissipating heat, to improve thermal comfort rather than a constant high temperature, or a higher rate of temperature change.

9.1.3 Hands' contact area when holding a tablet

In experiment 3, the tablet surface areas that were frequently in contact with skin when participants held the tablet to watch a movie, were identified. These areas are shown in Figure 7.7, for the conditions when participants held the tablet both horizontally and vertically. The identified areas are also consistent with the areas covered by the lengths of middle fingers of 5th percentile female and 95th percentile male from Pheasant and Haslegrave (2005). This provides designers with information for locating any heat sinks on tablet computers.

9.1.4 Spatial summation and the effect of duration

In the experiment 3, participants rated the conditions of smaller contact areas as being less uncomfortable and less hot. This finding confirms the effect of spatial summation, which was found in multiple previous literature (Kenshalo et al., 1967; Kojo and Pertovaara, 1987; Meh and Denislic, 1994; Hiltz et al., 1999; Hagander et al., 2000; Marchand and Arsenault, 2002; Kelly et al., 2005).

Experiment 2 also showed that the thermal sensation scores tended to decrease with increased duration of holding the device. At a surface temperature of 42 ℃, the initial rating was hot, while the rating at 600 seconds was warm. Such sensory adaptation effects to monotonous stimuli are a characteristic of the human sensory system (Kenshalo, 1970; Parsons, 2014). Similarly, Zhang, Hedge and Guo (2015) found a decrease in thermal sensation scores over a 60-second test condition, but the change was smaller in magnitude. The findings of experiment 2 extend the adaptation zone of 29 ℃ -37 ℃ (Kenshalo and Scott, 1966; Parsons, 2014) up to 42 ℃, confirming the adaptation temperature of a participant in the study by Kenshalo, Nafe and Brooks (1961). Repetitive thermal stimuli above 0.33Hz can lead to temporal summation and a more intense sensation of heat (Stevens, Okulicz and Marks, 1973; Kong et al., 2012). Since all the tested stimuli were under 0.33Hz in the experiment 2, no effect of temporal summation was found.

9.1.5 The effect of surface texture

Experiment 4 confirms that surface texture can significantly affect thermal sensation for surfaces at the same temperature. At the same surface temperature, a smooth surface was rated to be less comfortable and hotter than a mesh surface. However, no significant difference was found for thermal sensation scores between the different meshes tested in experiment 4. The finding is consistent with previous finding (Galie et al., 2009). Galie et al. (2009) found the change of skin temperature was not significantly different from each other, when the finger was in contact with surfaces with different sizes of spatial periods.

A moderating effect of surface temperature was found in experiment 4, showing that the ratings of surface roughness did not differ among the meshes at the lower temperature of 38 ℃; but the meshes with larger spacing were rated to be rougher at 42 ℃. The reasons may be because of an increase of receptor activity caused by vasodilation, and the change in mechanoreceptor activity because of differences in the deformation of the skin (Green et al., 1979). The findings are also consistent with the findings by Zhang et al. (2009), whose study found that the ability to detect a vibrotactile stimulus was improved when the skin was heated from room temperature to 43 ℃.

9.2 Limitation of studies

9.2.1 Limitations of experiment 1

In the study of the effect of the surface temperature and environmental temperature, the tested temperatures were static. However, the rate of temperature change may affect people's thermal sensation and comfort (Molinari et al., 1977). In future studies, the rate of temperature change can be a manipulated variable to understand people's thermal comfort when holding a tablet-size device. In addition, testing the thermal sensation for even longer holding durations can be useful as a reference for real-world tablet computer users.

9.2.2 Limitations of experiment 2

In the conditions tested of the second study, no plateau at 42 ℃ was tested. It is unknown whether other plateau lengths can have more thermally comfortable/uncomfortable effects. Additionally, it is unknown whether a slower rate of temperature (less than 0.02 ℃/s) increase may lead to higher thermal comfort ratings. It is also unknown whether the control of releasing heat at this rate of change at less than 0.02 ℃/s is feasible.

Another limitation is the amount of heat released in the tested conditions are different. Although the lower rate of temperature change of 0.02 ℃/s was rated more comfortable, the total amount of heat released were also lower than other conditions. In the future, it will be worthwhile to test conditions with a different upper limit of the surface temperature, with an equal total amount of heat of the condition at 0.02 ℃/s to make comparisons.

9.2.3 Limitations of experiment 3

In the study of the effect of heat spatial distribution, the participants were instructed to hold the device with two hands; however, the holding hand might shift among different areas when a user uses only one hand. Furthermore, the hand-device contact areas can change if the participants are not sitting in an office chair.

In addition, it would be useful to obtain the hand and grip measurement when the participants are holding the tablet. In the future studies, data on the range of motion of the fingers can be captured with the use of motion capture system. The range can better illustrate where participants' fingers are in contact with the tablet surface.

9.2.4 Limitations of experiment 4

In the study of the effect of the surface texture, the texture was tested with meshes over the heating pad. However, to achieve the same surface temperature of 42 ℃, the heating pad reached an average of 45.5 ℃. While participants held the surface, the skin may be deformed in contact with the heating pad, and this might lead to overrated thermal discomfort, especially for the mesh with the larger spacing. Therefore, to eliminate the possibility of the contact of overheated surface, etched surfaces can be used instead of meshes. Etched surface can be defined as a surface processed to have textures. It will help to avoid the overheating issue.

9.3 Future work

Future experiments should investigate the effects of users performing a greater variety of tasks. In the current experiments, the participants were asked to watch videos of different length while holding the tablet. However, the real-world use scenarios, users may take their hands off the tablet, or use one hand, when doing tasks such as web browsing, manual input, and video-watching. At the same time, when hands are in dynamic contact with the heated surface, the cutaneous thermal sensation can be affected (Green, 2009). Therefore, more tests should be conducted for the prediction of thermal sensation for alternative tasks.

All of the current experiments focused on thermal sensation and thermal comfort for the fingers and palm areas. Yet, thermal sensation varies among different body parts (Claus, 1987, Stevens and Choo, 1998, Hagander, 2000). Since wearable devices, such as smart watches or head-mounted displays are becoming more popular, future experiments should test the thermal responses at other body parts such as wrist and forearm for the watch, and facial and head areas for head-mounted displays.

9.4 Conclusion

Overall the preliminary survey explored the how user thermal comfort are affected by the normal-working laptops. The laptop surface temperature and a few factors that may affect user thermal comfort were identified. A heating surface was built for the experiments to test the variables that may affect thermal comfort. The experiments examined the effects of a few variables on thermal responses, including the surface temperature, the ambient temperature, the rate of temperature change, the contact areas, and the surface texture.

More specifically, the first experiment examined the effect of surface temperature and ambient temperature on tablet computer's user's thermal sensation and comfort with holding a simulated tablet heating surface. A significant interaction was found between surface temperature and ambient environment temperature and participants' thermal sensation and comfort for the fingers and palms. As the surface temperature increased from 34°C to 44°C, participants' thermal sensation and discomfort scores increased. The warmer surface temperature of 44 ℃ was perceived as less hot and less uncomfortable in a cool (13 ℃) or moderate (23 ℃) temperature than in a hot environment (33 ℃), and lower surface temperatures of 34 ℃ and 36 ℃ were perceived as less warm in the hot environment than in the cool environment. These results can be used as temperature limits for future tablet computer heat dissipation designs or hand held device surface temperature limits. Another application can be to use the device as a hand warmer. At a lower environmental temperature of 13 ℃, more heat can be dissipated with the upper limit of the surface temperature up to 42 ℃, while the participants would not feel uncomfortable.

The second experiment investigated the effect of temperature change rate on contact thermal sensation and thermal comfort. Participants found overall the lower rate of change at 0.02 ℃/s was more comfortable than a surface of constant 42 ℃. Heating two sides alternately from 38 ℃ to 42 ℃ at 0.15 ℃/s might lead to a more comfortable rating, yet more studies are needed to confirm the effect. The study implies a potential to improve thermal comfort for tablet computers by varying the surface temperature at a very low temperature change rate of 0.02 ℃/s or lower. However, it may be challenging to control the rate of temperature change while dissipating the heat. It may involve holding and releasing certain amount of heat during the heat dissipation process. The use of phase-chasing materials may help with the heat control.

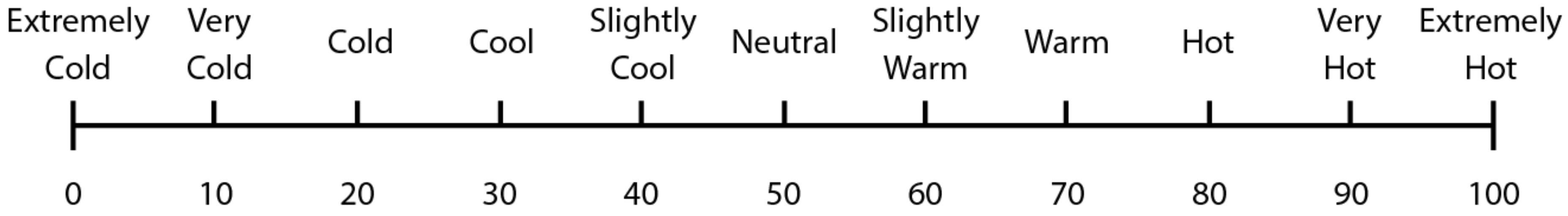
The third experiment investigated the contact areas when participants held the tablet horizontally and vertically, and the effect of heat distribution on thermal sensation and comfort. Larger contact areas led to a higher thermal discomfort. The areas that are not often contacted were identified: horizontally the central areas, and vertically the top areas. More heat can be dissipated at the identified areas that are less possible in contact with the fingers, to improve both the efficiency of heat dissipation, and to improve user thermal comfort. An example application can be to have a motion sensor attached to the computer to detect the orientation of the tablet. As a user moves the tablet, the areas that dissipate heat can be shifted to avoid the frequent touched locations. Again, to actually implement the design may be technically challenging. The use of phase-changing materials, and the layouts of the heat pipes, may lead to complexity.

The fourth experiment examined the effect of texture roughness. It was found the rougher texture can reduce thermal discomfort, and the perception of roughness is affected by the surface temperature. The material surfaces for tablet computers, laptop computers, or wearable computers that are in contact with users’ skin can be processed with a rough texture to improve thermal comfort. However, users' physical comfort on the texture should also be tested before adapting such rough texture.

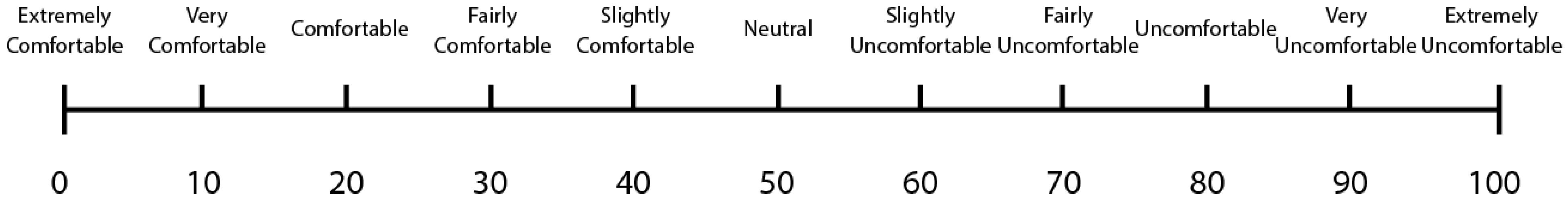
In summary, the findings in this study can be used as temperature limits for future tablet computer heat dissipation designs or hand held device surface temperature limits. Although previous research and standard has defined the threshold for the burn of skin, the threshold of pain, and the threshold of warm sensation, this study has more detailed found how thermal sensation magnitude have changed between 34 ℃-44 ℃. In addition, how thermal comfort change was moderated with the ambient temperature was also described. Furthermore, the findings have shown a few possibilities to improve user thermal comfort. The possible solutions can be: limiting the surface temperature, using slow temperature change rate, avoiding the hand contact areas for heat dissipation, and the use of rough texture. Further investigation is needed on a broader range of tested parameters in temperature change rate and surface texture to optimize the user thermal comfort.

APPENDIX I

Thermal sensation scale



Thermal comfort/discomfort scale



APPENDIX II

About the texture

Rough	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**Smooth**

Feeling about the texture

Feel uncomfortable	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**Feel Comfortable**

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