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Thermal sensation, rate of temperature change, and the heat dissipation design for tablet computers

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ABSTRACT

Past research has shown that the rate of change of skin surface temperature can affect thermal sensation. This study investigated users' thermal responses to a tablet heating surface with different heat pads and different temperature change rates. The test conditions included: A. keeping the surface at a constant 42 °C, B. increasing the surface temperature from 38 °C to 42 °C at a rate of 0.02 °C/s in progressive intervals, C. increasing the temperature at 0.15 °C/s in progressive intervals, and D. Heating two left and right side pads alternately from 38 °C to 42 °C at 0.15 °C/s in progressive intervals. Overall results showed the lowest temperature change rate of 0.02 °C/s was most preferred in terms of thermal comfort. The findings suggest a potential to improve user thermal experience by dissipating tablet computer heat at a lower temperature change rate, or by alternating the dissipation areas.

1. Introduction

The computing power of central processing units (CPUs) have been developing rapidly in recent years, however, the thinner and smaller form factors of new ubiquitous computers, such as tablet and wearable computers have limited their applications. High-end CPUs can produce a large amount of heat with the burst activities, caused by user-related tasks such as graphic-intensive computing and gaming (Rotem et al., 2013). The form factor of the tablet has become thinner and lighter in recent years. The enclosure skin temperature (surface temperature) of a small form factor is sensitive to the power consumption, and even a small power consumption of 6 W for 100 s can increase the surface temperature up to a thermal limiting threshold of 45 °C (ISO 13732-1, 2006; Rotem et al., 2013; Deval et al., 2015). In addition, sustained computation requirements for a CPU, the need to sustain battery life, and the operational characteristics of the system can all lead to heat generation in the computer (Rotem et al., 2013). Although efforts have been made to design and implement software algorithms to optimize the power output of the CPU, sustained computing tasks such as multiprocessing have been limited with the restriction of heat dissipation (Deval et al., 2015; Getov et al., 2015). Therefore, optimizing heat dissipation is one of the major challenges for the next generation of tablet computers.

Currently, 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 °C (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 and Hedge (2014) found that the base surface temperature of a laptop can reach 45.4 °C under normal working conditions. Moreover, Tsang et al. (2011) surveyed normal working laptops and for some models the base temperature reached 55.4 °C. According to recent public media reports (Tapellini, 2012; Chattejee, 2014), the surface temperature of new tablets can reach up to 47 °C 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

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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, including humans and animal studies, suggests that heat thermoreceptors in the skin may react differently to thermal stimuli with various temperature change rates and contact durations, providing evidence for possible new heat dissipation designs by changing surface temperature at different temperature change rates. Studies on humans (Yarnitsky et al., 1992) and rats (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°C/sec (Yeomans and Proudfit, 1996). C-fibers are activated at a lower rate of 0.9 °C/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 °C (Yarnitsky et al., 1992). The rate of temperature rise was 0.3, 2.0 and 6.0 °C/s, but the discharge rate for C nociceptor increases significantly with an increase in stimulus temperature rates (Yarnitsky et al., 1992). Yet contradictory evidence exists from studies on humans and monkeys, 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 °C/s or 0.5 °C/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 °C and below 50 °C (Duclaux and Kenshalo, 1980). However, repetitive warm pulses lasting 10 s from 34 °C to 42 °C with less than 60-s 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.

Human's thermal sensation and thermal comfort are affected by the activation of warm fibers and cold fibers. In the scheme of temperature regulation illustrated by Hensel (1981), heat stimuli can activate external thermoreceptors, and temperature sensation and thermal comfort can influence each other. Hensel (1981) also suggested that thermoreception lead to the qualitative sensation of "warm" or "cold", instead of "physiology" or "physics" (Parsons, 2014). Different rates of temperature can activate external thermoreceptors differently, thus may lead to varied thermal sensation and comfort, evidenced by a series of studies (Molinari et al., 1977; Hensel, 1981; Yarnitsky et al., 1992; Yarnitsky and Ochoa, 1990; Pertovaara et al., 1996).

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. Hensel (1981) described that, as the rate of temperature change decreases from 0.08 °C/s to 0.02 °C/s, the threshold for warm sensations can increase up to 5 °C. Hensel's research provides a theoretical foundation for the current study. The mean heat pain threshold decreases from 46 °C to 42.7 °C as the temperature rise rate increases from 0.095 °C/s to 5.8 °C/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 °C/s to 6 °C/s, or from 3 to 10 °C/s (Molinari et al., 1977; Yarnitsky et al., 1992; Yarnitsky and Ochoa, 1990; Pertovaara et al., 1996). Heat pain thresholds were overestimated because of the artifact of reaction time (Croze et al., 1977; Pertovaara and Kojo, 1985; Yarnitsky and Ochoa, 1990). The warm sensation threshold (within 3 °C higher than skin temperature) was shown to be higher when the stimulus was at a rate of temperature change between 0.01 °C/s to 0.1 °C/s, but it remained relatively constant when the change rate was below 0.1 °C/s and above to 0.3 °C/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 °C/s to 6 °C/s, corresponding to the increase of C nociceptor discharge frequency (Yarnitsky et al., 1992). Similarly, the comfort level was lower for 3 °C/s warm stimuli than 1 °C/s when used for thermal feedback (Wilson et al., 2011). Therefore, it is possible to find a set of rates of temperature change that can lead to a relatively low thermal discomfort, at the same target surface temperature. With the optimization of the rate of surface temperature change, heat may be dissipated more efficiently while users can still feel comfortable thermally.

We explored what temperature change rate could allow for a higher user thermal comfort. A heating surface was developed to control the rate of temperature change to simulate a tablet undersurface. Currently, most tablet computers dissipate heat in a steady temperature, and the surface temperature is usually unevenly distributed (Wagner and Maltz, 2013). Previous research also showed that the upper limit of the surface temperature with which users can feel relatively comfortable was about 40–41 °C, for aluminum enclosure (Ray, 1984; Siekmann, 1989, 1990; Zhang et al., 2016; Berhe, 2007). Therefore, the tested conditions in this study include both steady temperature and varied rates of temperature change, as well as uneven heat distribution. The tested surface temperature also did not exceed the comfort threshold of 42 °C.

The main goal was to determine the rate of temperature change that led to the highest user thermal comfort. It was expected that 1) Repetitive heating leads to lower thermal discomfort than a constant temperature. 2) A slower rising temperature rate leads to less thermal discomfort than a relatively fast rising temperature.

2. Methods

2.1. 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. No significant difference existed in the age between genders.

2.2. Apparatus

A heating surface was developed to simulate the back surface of a tablet computer, as shown in Fig. 1. The surface is 24.4 × 18.5 cm (9.6 × 7.3 inches) in size. It comprised nine 5.1 × 2.5 cm rectangular heating pads connected with heaters (Kapton 28 V, 20 Watt) and thermal sensors controlled by National Instrument LabView (version 13.0.1f2, 32-bit) proportional-integral-derivative (PID) module. Resistance temperature detectors (RTD) were attached to the aluminum heating surface to measure the surface temperature. The accuracy of the RTD was 0.15 °C at 0 °C and was 0.35 °C at 100 °C. The frame was ABS plastic and the heating pads were aluminum. This system allows the control of surface temperatures at different levels and the rate of temperature change. The back surface was used in combination with an iPad Air (Model# A1566, Wi-Fi 16 GB, iOS 8.1.3). A Nature documentary "Parrots: Majestic Birds" was played on YouTube for the participants while they were holding the surface. All experimental sessions were conducted in a controlled environmental chamber. The indoor air temperature was maintained at 23 °C, while the humidity was controlled at 40% RH.