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Application and Analysis of Asymmetrical Hot and Cold Stimuli

Ahmad Manasrah
University of South Florida, manasrah@mail.usf.edu

Application and Analysis of Asymmetrical Hot and Cold Stimuli

by

Ahmad Manasrah

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of the requirements for the degree of
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Department of Mechanical Engineering
College of Engineering
University of South Florida

Co-Major Professor: Kyle B. Reed, Ph.D.
Co-Major Professor: Rasim Guldiken, Ph.D.
Nathan Crane, Ph.D.
Andres E. Tejada-Martinez, Ph.D.
Kristen Salomon, Ph.D.

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Abstract

The human body has a unique mechanism for perceiving surrounding temperatures. When an object is in contact with the skin, we do not feel its temperature. Instead, we feel the temperature change that is caused on our skin by that object. The faster the heat is transferred, the more intense the thermal sensation is. In this dissertation, a new dynamic thermal display method, where different rates of warm and cold are applied on the skin to generate a unique sensation, is presented. The new method can be related in a wide range of applications including thermal haptics and virtual reality.

To understand the perception of temperature and the general thermal state of the human body, the first aspect of this dissertation focuses on investigating the interaction between temperature change and perception on a large scale. Three field surveys were conducted inside air-conditioned buildings to investigate the change in the thermal state and temperature perception of occupants when the room temperature changes. The results showed that the participants' prediction of constant operating temperature was poor, however, their prediction was significantly improved when temperature changes were presented.

In order to more accurately investigate the perception of temperature on the skin, a new thermal display method using multiple-channel thermal actuators was developed. The principle of this method is to apply slow and fast rates of temperature change simultaneously on the skin. The slowly changing temperatures are below the perceptual threshold of the thermal receptors, therefore will not be detected whereas the quickly changing temperatures are above the perceptual threshold, hence, will be detected. The idea here is to keep the average surface temperature of the skin constant, however a person will perceive a sensation of continuous cooling. This method was tested through a series of experiments, and the results showed that it is capable of generating

a continuous cooling sensation without changing the average temperature of the stimulation area. Multiple variations of this method were tested including different heating and cooling rates of change, different skin locations and patterns of stimuli. Also, a continuous warming was generated using similar concept.

To further investigate the temperature distribution that is caused by this method and its effect on the skin, a computational simulation was conducted. An approximate model of the skin was used to monitor its surface temperature and record the temperatures in the stimulation area when the continuous cooling method is applied. The results of the simulation showed that the temperature under the surface of the stimulation area was affected by the continuous cooling method that was applied on the skin model, however this method did not affect the average surface temperature of the skin. These findings may later determine the efficiency and intensity of the method of continuous cooling, and allow us to investigate different technically challenging variations of this method.

Chapter 1: Introduction

The sensory system is responsible for perceiving all information in the environment surrounding the human body. It helps the body identify objects and detect changes in the environment. A person can recognize the shape and the texture of an object with his or her hands without looking at the object. A person's mood can even be recognized by listening to his or her voice on the phone. It is, through this system, that human beings can interpret information and interact with the world and with each other. The sensory system uses a set of sense organs and cells called receptors to detect any changes in the environment, convert it to signals, and send it to other organs to react upon it. Thermoreceptors are a type of receptor that allow humans to interact with the surrounding environment by perceiving the thermal characteristics of objects nearby or in physical contact with the skin. Some types of thermoreceptors are located in the dermal and epidermal skin layers and they are divided into hot and cold receptors. With the body core temperature between 36.5°C and 38.5°C [1], thermoreceptors play a part in regulating the body temperature by firing signals to the hypothalamus.

Thermal sensation, perceived by the thermoreceptors that are located in the skin, has the potential of virtually presenting information to a user as a type of haptic feedback. Much of the research into this area has focused on using thermal feedback in haptics applications to produce a more realistic feeling in teleoperation or virtual environment simulations [2]. Wilson [3] showed that thermal stimuli are identifiable within around 83% accuracy. Moreover, it was found that a thermal feedback can improve object recognition when visual cues are limited [4]. Other fields of research associated thermal sensation and temperature perception to thermal comfort and the physical and psychological response of the human body to different thermal environments even though thermal comfort is considered a very subjective condition.

Even though multiple studies have been conducted investigating the practical employment of thermal displays, there are still different areas in this field that are yet to be explored. All of these aspects inspire the investigation of temperature perception and its capabilities of conveying thermal information by studying the general temperature perception and thermal comfort of the body by examining how the skin can perceive and integrate multiple dynamic localized temperature changes. This dissertation contributes to the areas of temperature perception and thermal displays. The main contributions of this dissertation are:

- Introducing a novel technique in thermal display by generating a continuous sensation of cooling or heating on the skin.
- Increasing our fundamental understanding of thermal comfort and temperature prediction inside climate controlled spaces.
- Development of a finite element model that mimics the thermal properties of the human skin that provides insight into different thermal display techniques.

This dissertation is divided into five chapters. Chapter two introduces the idea of thermal comfort and temperature perception. It starts with a background that presents several examples of field surveys that have been conducted to test the level of comfort based on the American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE) standard 55 [5]. Some of the studies focused on creating adaptive thermal comfort models and testing the efficiency of mechanically and naturally ventilated buildings. This research, however, focused on the relationship between temperature change and thermal perception which is characterized by ASHRAE's thermal comfort scale. The chapter then explains the procedure that was followed to conduct three field studies in two different locations. All of these surveys were conducted inside air conditioned buildings investigating the general level of comfort of the occupants and their ability to predict the temperature inside the buildings. This chapter finally shows the results of the surveys and the impact of thermal perception on the level of comfort and the prediction of the ambient temperature as well as cultural and seasonal differences between the three surveys. This part of the dissertation allowed us to understand the fundamentals of temperature perception and the complexity and subjectiveness of thermal comfort.

Chapter three concentrates on the dynamic thermal perception over a large skin area in detail. It introduces the idea of a new thermal display that is localized on certain locations of the body. The chapter starts with introducing a hypothesis where a unique thermal display can be generated using multiple dynamic temperature inputs. Using thermal displays as a feedback in haptics applications and virtual environment simulations is challenging because this type of feedback is often sluggish [6] and confused with other types of tactile feedbacks. For instance, Weber showed that cold weights often feel heavier than warm ones [7] [8]. However, literature shows that the perception of temperature is highly dependent upon the rate of temperature change. A quickly-changing temperature will be perceived as a strong thermal sensation whilst a slowly-changing temperature will be perceived as a mild thermal sensation [9].

This nonlinearity that is associated with temperature perception inspired the creation of a new type of thermal display in which a person can perceive a continuous cooling sensation using multiple thermal actuators; this is the focal point of this dissertation. The continuous cooling is perceived when a few actuators are warmed up at a slow rate that is under the perceptual threshold of the warm receptors of the skin. Simultaneously, other actuators are cooled rapidly at a rate that is higher than the perceptual threshold, hence triggering the cooling sensation. If the applied temperature differences are equal, the average temperature from the warming and the cooling actuators will remain constant. In fact, when the average applied temperature equals the skin surface temperature, a person will perceive a continuous cooling sensation on the skin without changing the average temperature of the area of stimulation.

Chapter three is then expanded further to cover the influence of threshold and the rate of temperature change on thermal perception of the skin and to present the continuous heating that is conceptually similar to the continuous cooling sensation but has the opposite thermal effect. In order to investigate and test these concepts that were hypothesized, two thermal display devices were built and used in multiple sets of experiments. This part of the research provides new insights into the dynamic relationships between temperature perception, rates of temperature change, and spatial summation.

Chapter four introduces a computational analysis of continuous cooling perception. Simulations are often used to imitate and characterize the behavior of a system in the real physical world in order to analyze its results or outcomes. The previous investigations of this study showed that the perception of cooling can be generated using multiple thermal actuators. These findings allowed us to better understand the perception of temperature. Thus, the main focus of this chapter is a finite element model that simulates the thermal properties of the skin on the forearm. Previous studies have emphasized the use of thermal and psychological models of the human body and their capabilities of mimicking the thermoregulatory system [10] [11]. However, the goal of this chapter is to study the effects of temperature change on an approximate model of the skin. To validate the results obtained from the simulation, a physical model is designed and built for conducting continuous cooling experiments. This chapter presents a mathematical solution of the physical model showing the assumptions and the boundary conditions of the model. The chapter then discusses the assembly and experimental setup of the physical model used to validate the simulation. The finite element modeling is then discussed in detail showing the properties of the model. The chapter then represents the results of the experiments and the simulation as well as the differences between them.

Chapter five concludes the findings and contributions of this dissertation and suggests some of the future steps that can expand the use of the continuous cooling thermal display and the developed finite element model.

Chapter 2: Thermal Comfort and Temperature Perception

2.1 Note to Reader

This chapter, with the exclusion of section 2.6, has been accepted in the *AHSRAE Annual Conference 2016* and has been reproduced with permission from ASHRAE.

2.2 Introduction

The thermal comfort level inside closed areas has been studied for decades in various places in the world. According to the American Society of Heating, Refrigeration and Air-Conditioning Engineers, thermal comfort can be defined as "the condition of mind that expresses satisfaction with the thermal environment" [5]. Based on the definition, thermal comfort is a subjective sensation and it can differ from one person to another even if they are in the same environment. Thermal comfort is influenced by different factors that can be categorized as physical and psychological. The physical factors can be categorized by: air temperature, mean radiant temperature, relative humidity, air speed, clothing level, and metabolic rate [12]. The psychological factors are related to cultural differences, personal temperature expectations, and mood differences. Thermal comfort can be reached physically by maintaining a thermal equilibrium between the heat generated by the human body (represented in the metabolic rate) and the surroundings [13]. ASHRAE Standard 55 specified the comfort zone inside closed spaces where at least 80% of occupants feel thermally comfortable [5]. This specification is based on generalized theoretical and mathematical models that were developed from experiments and studies conducted by Fanger and others [14].

The purpose of this study is to investigate the temperature perception of humans inside air conditioned areas based on ASHRAE Standard 55 and to study whether or not these areas are within the acceptable level of thermal comfort. The study also investigates the influence of climate on temperature perception and thermal comfort.

2.3 Background

Most of the studies that were conducted on thermal comfort follow two different approaches. The first approach is conventional laboratory studies. Perhaps the most famous of them is Fanger's experiments in 1970 [15] [14]. This approach is based on conducting thermal experiments inside a well-controlled environment like chambers and cabins. Another approach is the field study approach where the experiments are conducted in real-life environments. The latter approach proved its effectiveness in studying the thermal comfort inside closed spaces like classrooms in schools and universities. Most of these studies were conducted using ASHRAE's seven point thermal scale [14]. Fanger developed a comfort equation and related it to ASHRAE's thermal scale to form a predicted mean vote (PMV) index. The predicted percentage of dissatisfaction (PPD) was also added to form Fanger's thermal model for indoor environments [15].

It was found that the outdoor climate is related to the indoor comfort temperature [16]. This relation is different between air conditioned and naturally ventilated buildings. It was also suggested that occupants of air conditioned buildings do not tolerate a wide range of temperatures [17]. Yamtraipat found that the recommended thermally acceptable indoor temperature is around 78.8°F (26°C) inside air conditioned buildings in Thailand [18]. However, the range of thermally comfortable conditions inside buildings depends on the physical factors of occupants and can be as narrow as 3.5°F (2°C) deviation above or below the comfort temperature [19]. Many studies have been conducted to test ASHRAE Standard 55 in different climates inside naturally ventilated and air conditioned buildings. It was shown that, in naturally ventilated buildings, the indoor temperature at which occupants feel comfortable increases during hot climate and decreases during cold climate [20]. Another study found that occupants' thermal preferences change gradually from the heating season to the mid and warm season in naturally ventilated classrooms in Italy [21]. However, de Dear showed that Fanger's PMV/PPD model is only applicable for air conditioned areas [17]. Huizenga studied air quality and thermal comfort inside air conditioned buildings and found that only 11% of the buildings had 80% or higher occupant satisfaction. The results showed the importance of field surveys in measuring the thermal performance of buildings [22].

Additionally, field surveys provide more reliable information about the thermal environments compared to laboratory studies [23]. By analyzing this information, researchers were able to study how occupants interact with their environment based on their thermal comfort level. Wong investigated the thermal comfort inside mechanically ventilated classrooms in Singapore and found that the classrooms did not fall within ASHRAE's comfort zone Standard. However, subjects felt thermally comfortable [24]. Humphreys conducted a study of thermal comfort and clothing in primary schools in England. The results showed that discomfort was related to the temperature variation in the classroom but not the temperature itself [16]. Another study in a Japanese school showed that most of the naturally ventilated classrooms did not fall within the Standard 55 comfort zone whereas the air conditioned classrooms complied with it. However, the mean thermal comfort vote reported by occupants of the air conditioned classrooms was "slightly cool" sensation on ASHRAE scale. Adaptive behaviors regarding clothing in the air-conditioned rooms where students brought sweaters and sweatshirts in the classrooms were also observed [25].

2.4 Method

Two field studies took place in Tampa, Fl during the summer of 2014 and fall of 2015. Both studies were conducted inside air conditioned buildings. The locations were inside classrooms at the university. Florida's climate is considered humid and subtropical where it is typically wet in the summer season, with average temperatures above 80°F (27°C) and dry from fall through spring with average daytime temperatures above 77°F (25°C) [26]. A survey was carried out in an air conditioned classroom at the University of South Florida in June 2014. The summer classroom has 11 inlet/outlet ducts and windows on its southern side. Due to the low representation of female subjects in the summer class and to test occupants' thermal comfort and temperature perception during a relatively colder weather, another survey was conducted in November 2015 in a different air conditioned classroom at the university. The fall classroom has 9 inlet/outlet ducts and no windows. Both surveys were conducted in a one-hour class session for four days in the summer classroom and three days in the fall classroom.

2.4.1 Survey Procedure

We studied the thermal perception of subjects in three different scenarios: A constant temperature, a gradually increasing temperature, and a gradually decreasing temperature. In the summer classroom, the room's thermostat was set to its original set point temperature of 68°F (20°C) in day 1 and day 2. On day 3, the temperature was increased from 68°F (20°C) at the beginning of the class session to 73°F (23°C) at the end of the class. On day 4, the temperature was decreased from 73°F (23°C) to 70°F (21°C) at the end of the class. A similar scenario was applied in the fall classroom where the temperature remained constant at 71.5°F (22°C) on day 1. On day 2, the room temperature was increased from 71.5°F (22°C) at the beginning of the class session to 75°F (24°C) at the end of the class. On day 3, the room temperature was decreased from 71.5°F (22°C) to 68°F (20°C). The temperature was also measured using a portable thermocouple in both of the classrooms during the surveys. The outside temperature was recorded in all survey days and it ranged between 87°F (30.5°C) and 89°F (31.6°C) during the summer class sessions and between 71°F (21.6°C) and 83°F (28.3°C) during the fall class sessions. The temperature was monitored during the class periods to ensure it was not fluctuating during the sessions where the temperature remained constant, and it was changing gradually during the sessions where the temperature was increasing or decreasing. The surveys were handed to subjects at the end of the class. The subjects were informed that the surveys were anonymous and participation was voluntary. The survey consisted of 14 multiple choice questions, which are shown in Figure 2.1.

1-How did you feel in the classroom?

Hot | Warm | Slightly warm | Comfortable | Slightly cool | Cool | Cold

2-How would you describe the weather today?

Sunny | Partly cloudy | Cloudy | Rainy

3-What do you think the outside temperature is?

70~75°F (21~24°C) | 75~80 (24~26.5°C) | 80~85 (26.5~29.5°C) | 85~90 (29.5~32°C) | 90~95 (32~35°C)

4-What did you think the room temperature was?

68 ~ 70 (20~21°C) | 70 ~ 72 (21~22°C) | 72 ~ 74 (22~23°C) | 74 ~ 76 (23~24.5°C) | 76 ~ 78 (24.5~25.5°C)

5-Five minutes prior from entering the class, were you...

Outside the building? | Inside the building?

6-Would you like the room temperature to be:

Warmer? | No change | Cooler?

7-Is the room temperature:

Increasing with time | Does not change | Decreasing with time

8-Are you within 3 ft range of an air duct?

Yes | No

9-Are you within 3 ft of a window?

Yes | No

10-Would you like...

More air movement? | No change | Less air movement?

11-Are you...

Male | Female

12-Please place a check sign by the pieces of clothing that you are wearing:

Top	Bottom	Footwear
Short sleeve shirt/ T-shirt	Trousers /Jeans	Socks and shoes
Long sleeve shirt/ Jacket	Shorts	Sandals
Sweater/ Sweatshirt	Ankle-length skirt/ skirt	Slippers

13-Are your clothes mainly...

Light colored? | Natural? | Dark colored?

14-Do you have a...

Cold drink? | Hot drink? | None

Figure 2.1: The survey used in the classrooms.

Table 2.1: Subjects distribution in summer and fall classrooms

class	Day	Number of subjects	Male/female
Summer class	1	29	26/3
	2	24	20/4
	3	26	23/3
	4	19	17/2
Fall class	1	44	7/37
	2	42	6/36
	3	45	9/36

2.4.2 Survey Subjects

A total of 98 surveys were collected in the summer class in four days. In the fall class, a total of 131 surveys were collected in three days. All subjects were healthy and between 18 and 55 year old. The subjects' numbers varied between the class sessions. Table 2.1 shows their distribution along the survey days. All the surveys were anonymous and no personal data were collected. The surveys followed a protocol approved by the university's Institutional Review Board.

2.5 Results and Discussion

2.5.1 Summer Class

An analysis of variance (ANOVA) with a dependent variable of the thermal scale (question 1) was conducted in the analysis of this study. In the summer class, the results showed statistically significant differences between genders ($F(1; 97) = 7.81$, $p < 0.01$) and between survey days ($F(3; 97) = 6.99$, $p < 0.005$). The analysis also showed a statistically significant difference between the answers of question 5. Subjects who were inside the building prior to class had a significantly "cooler" thermal perception (with an average thermal sensation of -0.6) than subjects who came from outside the building (with an average thermal sensation of 0) which suggests that the subjects who were inside the building prior to class may have had lower skin temperatures. Strigo showed that cool ambient temperatures can decrease the mean skin temperature significantly [27]. Also, there was a clear shift on the thermal sensation scale in day 3. However, the average thermal sensation for all four days was -0.18. Figure 2.2 shows the average thermal sensation between genders, and between the four days. The mean insulation value was also analyzed and was found to be 0.48 clo (the clothing insulation value) which is considered typical summer clothes [28].

According to the results of the summer class, the average thermal sensation for female subjects was -0.84 while for male subjects was -0.08. Previous studies found that females can feel uncomfortably cold more often than males [29]. However, the survey showed that more than 80% of subjects felt thermally comfortable during the four days of survey considering the range from -1 to 1 being thermally acceptable. Question 6 also showed similar results where 75.5% of

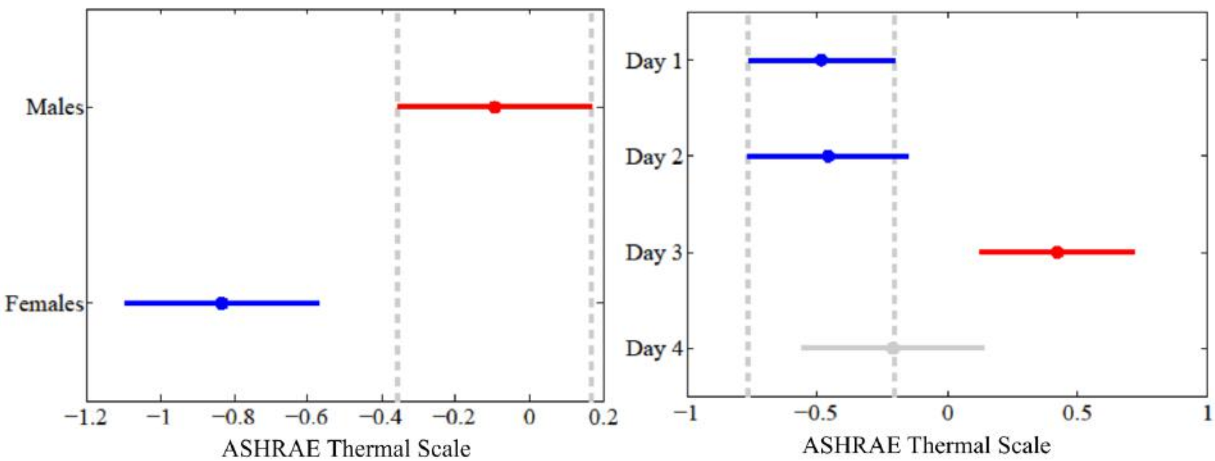

Figure 2.2: The summer classroom survey results. The thermal perception of females is statistically significantly different than males. The thermal perception in day 3 is statistically significantly different than the other days.

subjects voted for "no change" when answering whether they prefer the room temperature to be cooler or warmer. Figure 2.3(b) shows the average thermal sensation of subjects in the four days. Additionally, the majority of the subjects voted for "no change" in the air movement in day 3. Other studies indicated that higher air speeds may improve the occupants' comfort level [30] [31]. We also did not find a significant difference between the air ducts and window locations and the thermal perception of subjects (questions 8 and 9).

In addition to these results, the survey showed that the temperature prediction of the subjects improved in day 3 when the room temperature was gradually increasing, as shown in Figure 2.3(a). In day 1 and 2, subjects predicted the room temperature to be around 72°F (22°C) which is four degrees higher than the actual temperature. In day 3, their average prediction was 73.8°F (23°C) which was only 0.3°F (0.16°C) above the actual temperature. Moreover, only 7 out of 26 subjects were able to detect that the room temperature was increasing in day 3. This finding suggests that the indoor temperature can be raised to a higher temperature in order to reduce energy consumption without sacrificing the level of comfort or causing significant physiological changes to occupants (Chen 2011). A previous study showed that a 1.8°F (1°C) increase in a room temperature can significantly reduce energy consumption [32]. Other researchers have shown that occupants preferred indoor temperatures between 75.5°F (24.2°C) and 80°F (26.7°C) inside air conditioned areas in several hot-humid locations in the world [33] [23] [34].

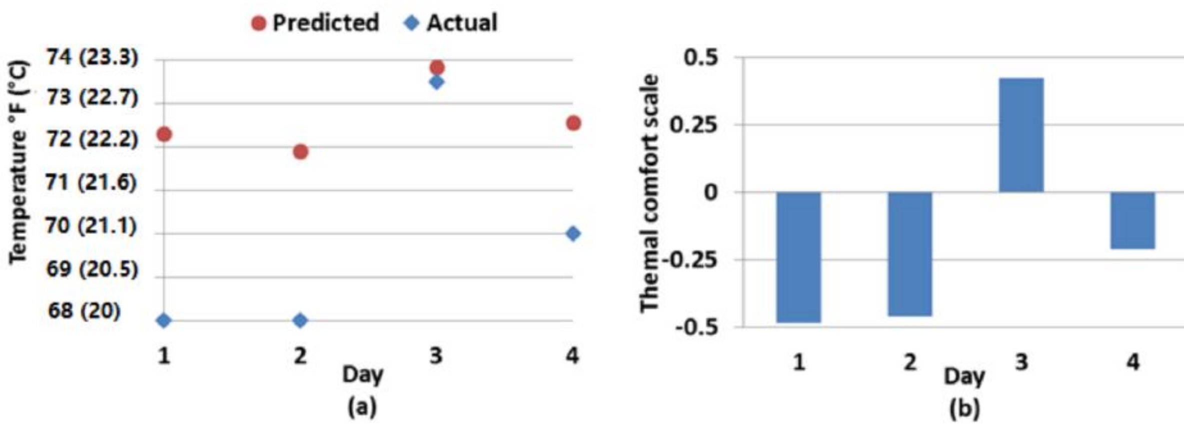

Figure 2.3: The summer classroom temperatures. (a) The actual temperature of the summer class versus the average predicted temperature from subjects. (b) The average thermal comfort level of subjects for four days during summer class.

2.5.2 Fall Class

In the fall class, the results showed statistically significant differences between the survey days ($F(2; 118) = 14.29$, $p < 0.005$). The results also showed that females were statistically significantly more accurate in predicting the room temperature ($F(1; 118) = 4.46$, $p < 0.$ 05). The average temperature prediction for female subjects was 73.5°F (23°C) while for male subjects was 74.6°F (32.7°C). This agrees with previous studies which suggest that female subjects are more sensitive to temperature deviation [15]. Figure 2.4 shows the average thermal sensation between the three days, and the temperature prediction between male and female subjects. The survey also showed that 87% of subjects felt thermally comfortable during the three days of survey considering the range from -1 to 1 being thermally acceptable. Figure 2.5(b) shows the average thermal sensation of subjects in the three days. Also, the mean insulation value of the fall class survey was 0.64 clo.

The results of the fall class surveys showed that the temperature prediction of the subjects improved when the room temperature increased as shown in Figure 2.5(a). In day 1, subjects predicted the room temperature to be 74.2°F (23.4°C) which was close to three degrees above the actual temperature. In day 2, subjects' prediction was 74°F (23.3°C) which was only one degree below the actual room temperature.

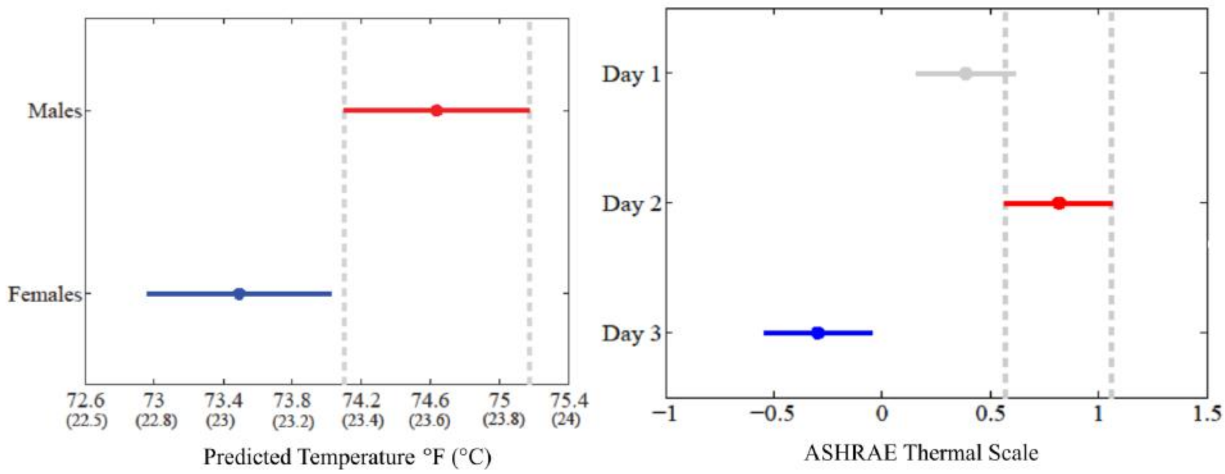

Figure 2.4: The fall classroom survey results. The thermal prediction of females is statistically significantly different than males. The thermal perception in day 3 is statistically significantly different than the other days.

Both surveys investigated the thermal perception and the comfort level inside air conditioned buildings. The results of both surveys showed that subjects were sensitive to temperature change in the classrooms. In the summer class, subjects were more sensitive to the increasing temperature while in the fall class subjects were more sensitive to the decreasing temperature. This contrast between the results may be related to the difference in the outside temperatures between the summer and fall classes. It can also be related to the percentage of female subjects in both of the classes. In the summer class, only 12% of the subjects were females, whilst in the fall class 83% of the subjects were females. Previous studies showed that females prefer higher room temperatures than males [29].

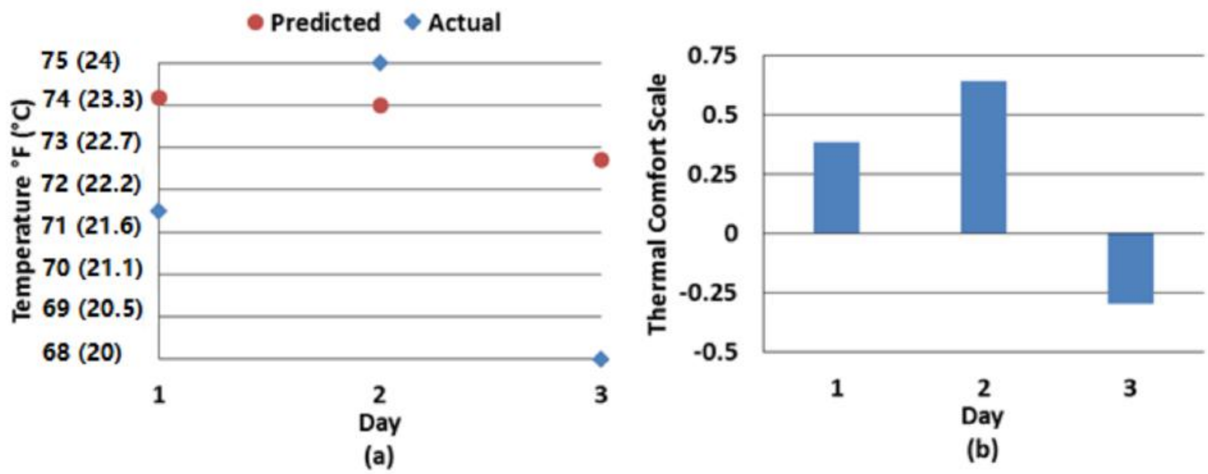

Figure 2.5: The fall classroom temperatures. (a) The actual temperature of the fall class versus the average predicted temperature from subjects. (b) The average thermal comfort level of subjects for three days during fall class.

The results of the temperature prediction were similar between the two classes. In the summer class, subjects expected the temperature to be 4°F (2°C) higher in a 68°F (20°C) room temperature. Their prediction became more accurate with a higher room temperature. We did not, however, find significant differences between male and female subjects. In the fall class, we noticed a significant difference between male and female subjects. The average prediction for male subjects was around 3°F (1.7°C) higher in a 71.5°F (22°C) room temperature whilst female subjects were significantly more accurate as was shown in Figure 2.4.

Additionally, subjects from both classrooms reported an average "neutral" level of comfort despite the difference in the room temperatures in both of the classes. The summer class subjects had a thermally "neutral" comfort level even when the room temperature was raised to 73.5°F (23°C) while the fall class subjects reported the same comfort level in a slightly higher temperature range even though they had the same metabolism rate. This difference may be linked to the clothing insulation level in the fall class which was noticeably higher than it is in the summer class. However, it did not affect the thermal comfort level or temperature prediction of subjects.

2.6 Cultural Differences

Thermal comfort has often been associated with studies that are related to the thermal perception of humans. A considerable amount of research has been done on thermal comfort in different climates and cultures. However, there is very little research that compares thermal perception in different cultures. The main goal of the surveys conducted in this section is to investigate the influence of culture and climate on temperature perception and thermal comfort.

A field survey was conducted in an air conditioned shopping mall in Amman, Jordan in July 2014. Jordan has a long dry summer season with an average temperature of 90°F (32°C) and a cool rainy winter season [35]. The surveys were conducted for three continuous days inside the shopping mall that consisted of four floors.

In this study we investigated the thermal perception of the mall shoppers for three days. Due to the difficulty of conducting an anonymous written questionnaire similar to the classroom survey, we approached random shoppers for two-minute interviews. The purpose of the survey was briefly explained to the subjects. After having their verbal acceptance to participate, they were asked two multiple choice questions:

1. How do you feel in the shopping mall?

(Hot Warm Slightly warm Comfortable Slightly cool Cool Cold)

2. What do you think the inside temperature is?

(68 – 70°F 70 – 72°F 72 – 74°F 74 – 76°F 76 – 78°F)

We used a portable thermostat to measure the temperature and humidity in random places inside the shopping mall and before asking each subject. Also, the outside temperature was recorded for all three days and it ranged between 86°F (30°C) and 91°F (33°C). Question 2 was asked to subjects in the Celsius scale since it is the most commonly used unit in Jordan. Even though choosing subjects was random, we did not approach subjects near entrances and exits to avoid thermally biased subjects and to follow the mall administration's policy. We also preferred subjects who were in a seated position or slowly walking to avoid high metabolism rate.

A total of 100 subjects participated in the survey, 63 males and 37 females all were above 18 years old. All the surveys were anonymous and no personal data were collected. The mall's approval was obtained before the survey. Also, the surveys followed a protocol approved by the University of South Florida's Institutional Review Board.

The results in this field study showed that the average ambient temperature inside the shopping mall ranged between 73.5°F (23°C) and 79°F (26°C) with an average of 75.7°F (24°C) during the three days of survey. The average thermal sensation for all subjects was 0.68 which is within the comfort zone. The results also showed a statistically significant difference in temperature prediction between genders ($F(1; 99) = 11.95$, $p < 0.05$), which is shown in Figure 2.6. This agrees with previous studies which suggest that female subjects are more sensitive to temperature deviation [15].

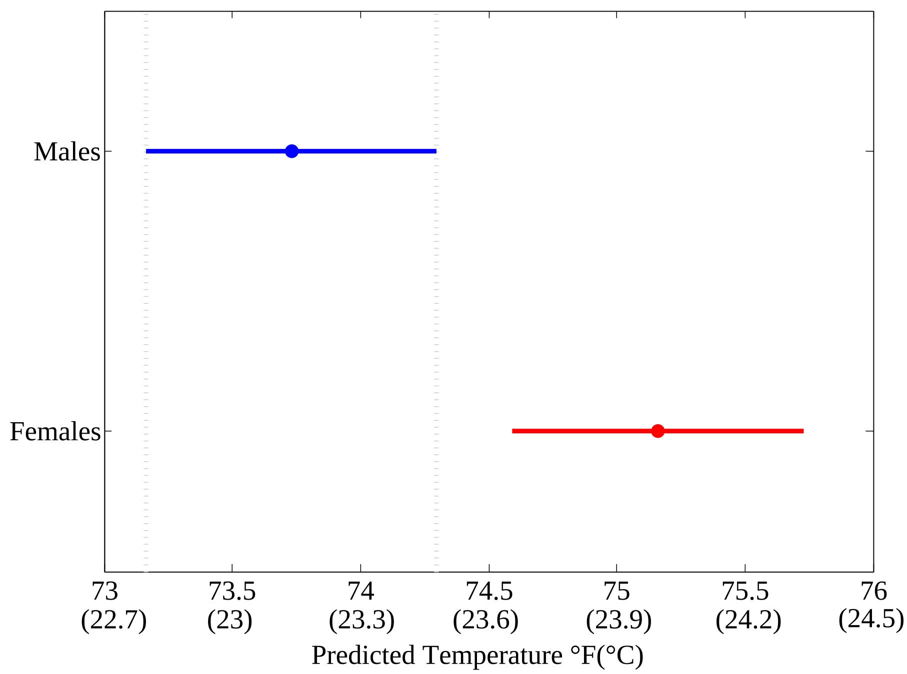

Figure 2.6: The shopping mall survey results. The temperature prediction in females is statistically significantly different than males.

Further analysis was performed on the comfort level inside the shopping mall using CBE thermal comfort tool [36] and it was found that the environment inside the building did not comply with ASHRAE standard 55. However, 83% of subjects felt thermally comfortable inside the shopping mall during the field study. Several thermal comfort studies were conducted inside naturally ventilated and air conditioned locations and it was found that 80% and more of occupants felt thermally comfortable in most of the studied locations even though they did not fall within the comfort zone of ASHRAE standard 55 [34].

In the shopping mall, we noticed a significant difference between male and female subjects. The average prediction for male subjects was around 2°F (1°C) lower than the ambient temperature whilst female subjects were significantly more accurate as was shown in Figure 2.6. This difference between male and female subjects may be related to the clothing insulation level. We noticed that the shopping mall's subjects had less exposed skin areas to the environment than the subjects from the classroom. Kwon and Choi had the same observation regarding Asian subjects when compared to other non-Asians [37]. Moreover, Kenz found that subjects living in different cultures had different thermal perception in different environments with similar thermal conditions [38].

The subjects also reported an average "neutral" level of comfort in a relatively higher temperature range even though they had a higher metabolism rate. This difference may be linked to the lack of air conditioners in most of Jordanian houses. Hence, they might have higher expectations for the environment inside an air conditioned building. Yamtraipat studied the acclimatization to using home air conditioners between subjects in Thailand and found that subjects who were acclimated to air conditioning have a lower "neutral" temperature perception than other subjects [18].

2.7 Conclusion

We presented two field surveys that studied thermal comfort and perception inside air conditioned areas. Both surveys were conducted inside two classrooms in Tampa, USA. In the summer class, a total of 98 surveys were conducted for four days. The results showed that subjects had a significantly more accurate temperature prediction at a slightly elevated room temperature. Also, there was a significant difference in thermal votes between male and female subjects. In the fall class, a total of 131 surveys were conducted for three days. The results showed that female subjects had a significantly more accurate temperature prediction than male subjects. In both surveys, subjects were thermally comfortable despite the difference in the operating temperature inside the two classrooms.

Chapter 3: Perceived Cooling Using Asymmetrically Applied Hot and Cold Stimuli

3.1 Note to Reader

This chapter, with the exclusion of section 3.6, has been accepted as a journal paper in *IEEE Transactions on Haptics*.DOI: 10.1109/TOH.2016.2578334 [39]

3.2 Introduction

Thermal sensation has the potential of virtually presenting information to a user and much of the research into this area has focused on using thermal feedback to increase the realism of teleoperation or virtual environment simulations by conveying the temperature of a remote or virtual object. For example, thermal cues can be used to discriminate between materials of different thermal properties [40]. However, the display of temperature in haptic and virtual environments is often excluded in practice because it is a relatively slow sense compared to tactile perception and also because the effects of temperature are confounded by many related tactile perceptions. But it is exactly these complex interactions that make it important to study. Skin temperature affects vibrotactile thresholds [41], calming music is associated with cooling skin [42], and body temperature can even affect the performance of athletes [43]. Yet, the ability to use a thermal actuator to generate a perception in a person lags behind the use of force and tactile feedback.

Skin contains different sensors that measure hot and cold, and the perception is highly dependent upon the rate of temperature change [44]. We hypothesize that multichannel dynamic temperature inputs will enable unique temperature display capabilities because a slower rate of temperature change causes a nonlinear increase in warm and cold thresholds [45]. By arranging a grid of independently controlled temperature actuators, one or more actuators can always be

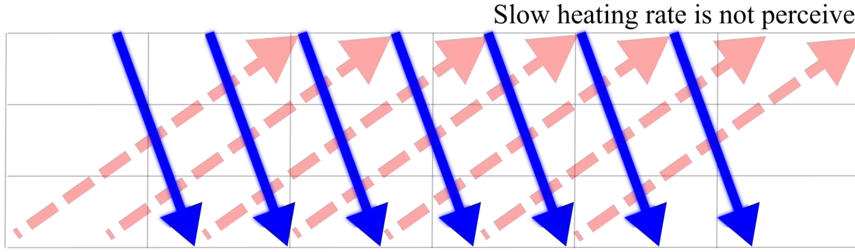

Figure 3.1: Slowly heating actuators mixed with quickly cooling actuators create the feeling of continuous cooling.

cooling quickly while the others are heating slowly as shown in Figure 3.1. Alternating which actuator/actuators are cooling quickly ensures that the average skin temperature never changes yet, the person will perceive that their skin is continuously cooling due to the nonlinear temperature perception. This method is conceptually similar to using an asymmetrically applied oscillating force that generates a perception of force applied in one direction, but without any net force applied [46]. To achieve this thermal pattern, we use thermoelectric devices (also known as peltier coolers). They work as heaters or coolers under an applied voltage with different polarities. Thermoelectric devices are well-suited to applying dynamic temperature inputs [47]. They can easily be scaled to small sizes because no moving parts are required. If one side is held at a relatively constant temperature, the other can be made cooler or hotter in proportion to the applied voltage.

The purpose of this work is to investigate our hypothesis that a perception of cooling can be conveyed without actually changing the average skin temperature, and to examine how the body can perceive and integrate multiple dynamic localized temperature changes (from peltier devices in these experiments). These results provide a new insight into the spatial summation process and could enable the rational design/development of thermal display systems for a wide range of applications.

3.3 Background on Thermal Perception

Human skin detects the changes in temperature by thermoreceptors located in the dermal and epidermal skin layers. There are two types of thermoreceptors: warm receptors, which are active for temperature increases from 30°C to 45°C, and cold receptors, which are active for temperature decreases from 30°C to 18°C. Cold receptors outnumber warm receptors in the skin by a ratio up to 30:1 [48] [6]. Additionally, cold receptors respond faster than warm receptors. Wilson [49] found that cold stimuli can be detected faster than warm stimuli. Between 30°C and 36°C, both warm and cold thermoreceptors are active, and no thermal sensation is observed at steady state [50]. Below 18°C and above 45°C, pain receptors, called nociceptors, are active [51].

According to Jones and Ho [52], temperature perception depends on the rate of temperature change, magnitude, baseline temperature of the body, and the stimulated location on the body. One typical metric of sensitivity is the threshold at which the stimulus is first perceptible. For example, a slow temperature change will not be noticed until the temperature has increased by over 3°C and temperature sensitivity increases up to 0.1°C/s, where the temperature change is noticed after about a 0.4°C change; further increasing the rate beyond 0.1°C/s has a small effect on the thermal threshold [53][9]. The relationship between the temperature threshold and the rate of temperature change is shown in Figure 3.2. The different sensations of cold and warm are usually associated with the conduction velocities of cold receptors, which respond much faster than warm receptors [50].

The area of the simulation is inversely related to the thermal threshold of the skin where the temperature change is first noticed. In fact, low spatial resolution of thermal stimuli occurs because the sensed temperature is based on the spatial average of stimuli over an area or feature of the body [55]. Spatial summation effects decrease the thermal threshold as the area of thermal stimuli increase. Smaller temperature differences can be detected by increasing the thermal stimuli area [56]. Increasing the area of warm stimulus has more effect on thermal threshold than increasing the area of cold stimulus [53]. Spatial summation implies that tests of perception should be performed on large areas of the skin. In order to apply thermal gradients to the skin

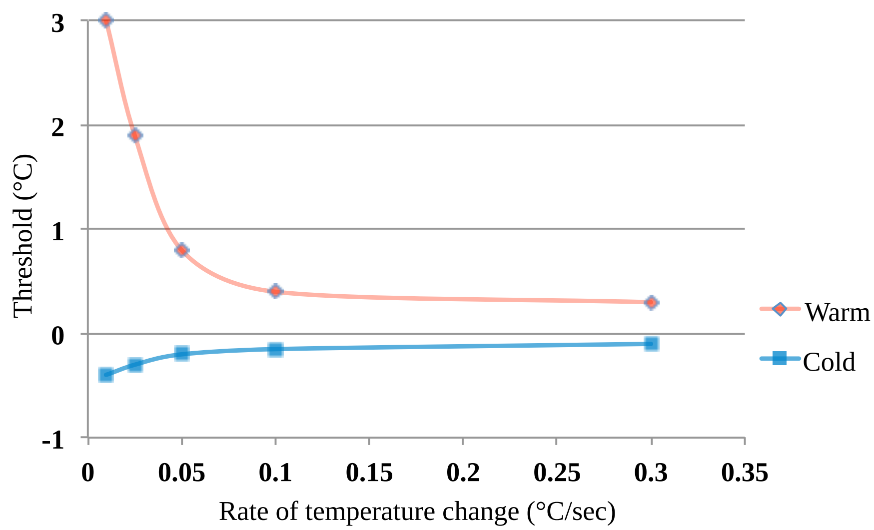

Figure 3.2: The rate of change affects the thresholds at which temperature changes are first noticed. Data adapted from [9] and [54].

without causing effects from the coverage, the area needs to be large enough so that there is not a significant size effect.

Studies have shown that large differences in nearby temperatures can confuse thermal perception [57]. Low temperature differences elicit a feeling referred to as synthetic heat [58]. Synthetic heat is generally perceived when adjacent hot and cold sensors perceive a discrepancy. Thunberg [59] first discovered this effect and called it the thermal grill illusion. Although synthetic heat and the thermal grill illusion terms are often used interchangeably because the resulting effect is the sensation of strong heat, synthetic heat usually refers to applying equal amounts of heating and cooling to the skin sequentially, whereas the thermal grill illusion typically refers to the heating and cooling of the skin in alternating rows. These effects often diminish after a short time [60]. The thermal grill illusion and synthetic heat are often related to the sensation of pain. However, it has been shown that synthetic heat can be perceived without pain by applying cool and mildly warm stimuli [61].

The method tested here is distinctly different than the thermal grill illusion and synthetic heat in that all of the actuators' temperatures are constantly changing and the application rates of heating and cooling are asymmetric. Furthermore, this method applies a 1°C temperature difference between heating and cooling stimuli unlike synthetic heat and thermal grill where the temperature difference can get up to 20°C between heating and cooling stimuli [62]. Also, in this method, the actuators are continuously changing directions between heating and cooling unlike the thermal grill illusion where each actuator has a constant temperature and does not change direction between heating and cooling.

3.4 Method

This study consisted of three sets of experiments evaluating different aspects of the continuous cooling perception. The first experimental set investigated the differences between the application of a four-channel dynamic thermal display with two patterns and constant skin temperature. The second experimental set employed a twelve-channel dynamic thermal display to investigate its effect on three locations by applying different heating/cooling rates. The third experimental set tested the effect of multiple thermal patterns on the perception of continuous cooling using the twelve-channel dynamic thermal display.

3.4.1 Thermal Stimuli

In experimental set 1, two patterns of stimuli, shown in Figure 3.3(a), were applied to the subjects to test how the pattern of thermal actuation affected the perception. The ordered pattern sequentially increased the temperature of the actuators in order across the forearm so that each location felt a delayed version of the adjacent actuator. The rearranged pattern mixed up this consistent pattern so the adjacent actuators were out of sync with each other. In these two dynamic patterns, four actuators were controlled such that three were slowly heating over 30 seconds out of phase with each other at a rate of 0.033°C/s and one was quickly cooling over 10 seconds at a rate of 0.1°C/s. Every ten seconds, the actuator that was cooling would start slowly heating up and another would start quickly cooling. This heating/cooling cycle will be referred to as 30/10, which corresponds to the pattern each actuator follows throughout the experiments. The third thermal stimulus in experimental set 1 applied a constant temperature as a neutral temperature reference point baseline for comparison. In this baseline, all actuators were maintained at 31°C for four minutes during this control stimulus, which is the same time duration and average temperature as the dynamic actuation.

Experimental set 2 investigated the same concept using twelve actuators so additional configurations could be evaluated. Nine actuators were slowly heating out of phase with each other and three were quickly cooling. Three different heating/cooling cycles were used with one diagonal pattern. The first cycle was the 21/7, where nine actuators were slowly heating over 21 seconds (at a rate of 0.047°C/s) and three were cooling over 7 seconds (at a rate of 0.14°C/s). The second cycle was the 45/15, where nine actuators were slowly heating over 45 seconds (at a rate of 0.022°C/s) and three were cooling over 15 seconds (at a rate of 0.067°C/s). The third cycle was the 30/10. Figure 3.3(b) shows the thermal pattern for experimental set 2 (with an example rate of 30/10).

Experimental set 3 was conceptually divided into two parts examining different aspects of the thermal perception, but was performed during the same subject session. In the first part, three different patterns were tested with the 30/10 heating/cooling time. The patterns were diagonal, horizontal, and arbitrary as shown in Figure 3.3(c). In the second part, two additional heating/cooling ratios were tested. The first ratio was 8:4 where eight actuators were slowly heating and four were quickly cooling in a vertical pattern. The second ratio was 10:2 where ten actuators were slowly heating and two were quickly cooling. Figures 3.3(c) and (d) illustrate all the patterns tested in experimental set 3.

All the heating/cooling rates from all three experimental sets were based on the data from Figure 3.2 and are selected so that the cooling will be above the perceptual threshold and the heating will be below the perceptual threshold. For instance, a rate of 0.033°C/s is large enough to raise the temperature of the actuator 1°C, but is small enough to not trigger the perception of warming. Table 3.1 summarizes the different heating/cooling time cycles and patterns used in all three experimental sets.

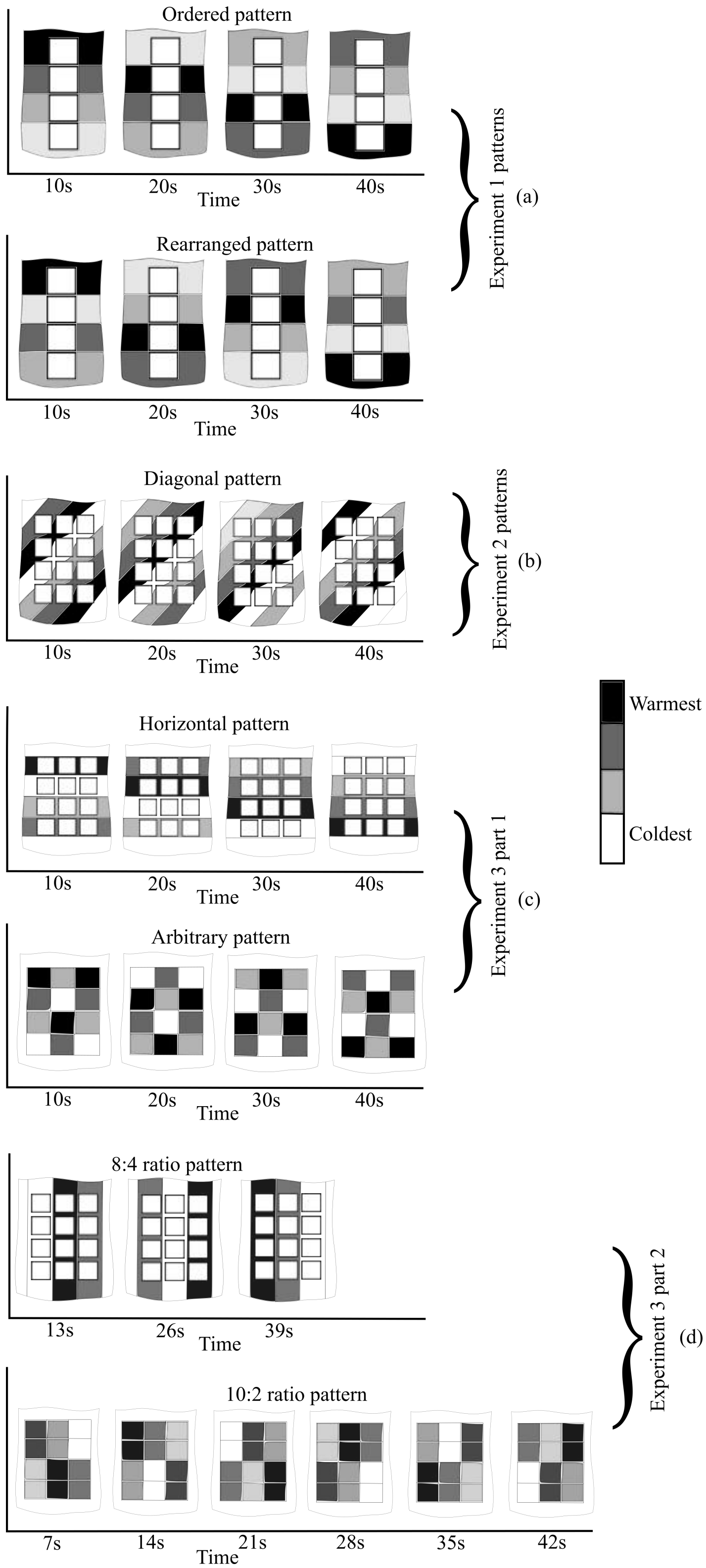

Figure 3.3: All experimental patterns with cycle time in seconds.

Table 3.1: Heating/cooling rates and patterns used in the experiments

	Warming/cooling time	**Pattern**	**Location**
Experiment 1	30/10	Ordered	Right anterior forearm
	30/10	Rearranged	
Experiment 2	21/7	Diagonal	Right/Left anterior/posterior forearm
	30/10		
	45/15		
Experiment 3 part 1	30/10	Horizontal	Right posterior forearm
	30/10	Diagonal	
	30/10	Arbitrary	
Experiment 3 part 2	26/13	Vertical	Right posterior forearm
	30/10	Diagonal	
	35/7	Diagonal	

The average surface temperature stayed constant in all trials during the experiments even though each actuator changed linearly between 30.5°C and 31.5°C in most cases. The actuators with increasing temperatures were under the rate threshold, whereas the actuators with decreasing temperature were above the threshold and, thus, noticeable. Before starting the patterns, all actuators were slowly warmed up to the normal skin temperature (which is approximately 31°C) [45].

3.4.2 Apparatus

In experimental set 1, four large thermal actuators were used. The actuators were peltier devices (40 mm x 40 mm x 3.8 mm) (Vktech TEC1-12706) mounted on an aluminum plate (80 mm x 200 mm x 4 mm). Two heat sinks (98 mm x 40 mm x 20 mm) were attached under the plate. Four surface-temperature thermistors (Mindray MR403) were attached to the surfaces of the peltier devices using double-coated thermal tape. A foam pad surrounded the peltier plates to ensure the heat transfer occurred through the peltier plates and not the surrounding portion of the plate or arm. Figure 3.4 shows the experimental setup.

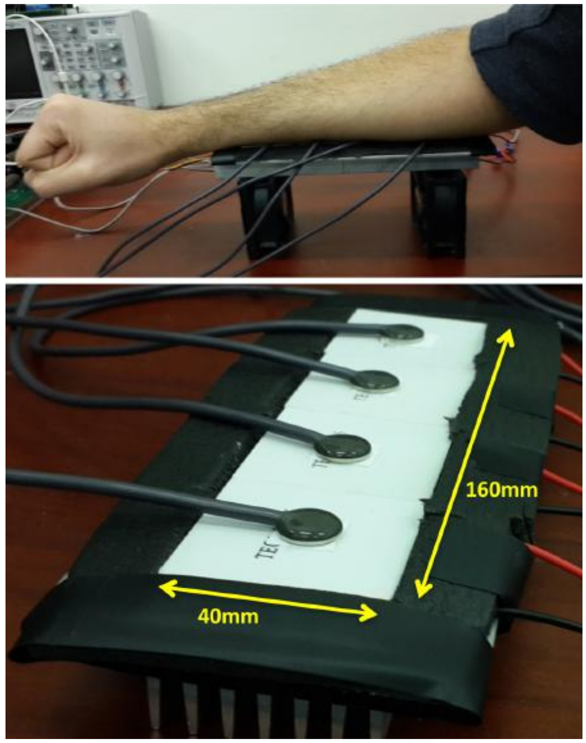

Figure 3.4: The device used in experimental set 1 to test the constantly changing thermal patterns on humans.

Twelve thermal actuators were used in experimental sets 2 and 3. The actuators were peltier devices (14.8 mm x 14.8 mm x 3.6 mm) (TE-31-1.0-1.3). The actuators formed a 3 x 4 thermoelectric matrix with a 7.5 mm space between the actuators. Twelve thermistors were used to control each actuator individually. To provide accuracy in temperature reading, each thermistor was inserted inside an aluminum plate (15 mm x 15 mm x 3 mm). The aluminum plates were attached to the surface of the peltier devices using thermal paste. Every four actuators were attached to a heat sink (98 mm x 20 mm). A simple voltage divider circuit was added to the apparatus to read the thermistors. The 3 x 4 matrix with the heat sinks, aluminum plates, thermistors, and the voltage divider circuit were built on a cellphone armband as shown in Figure 3.5 to add maneuverability to the apparatus. The total stimuli area was 48.53 cm^2.

The actuators were driven with a proportional feedback controller. After receiving the temperature readings from the thermistors, the controller calculated the required current for the

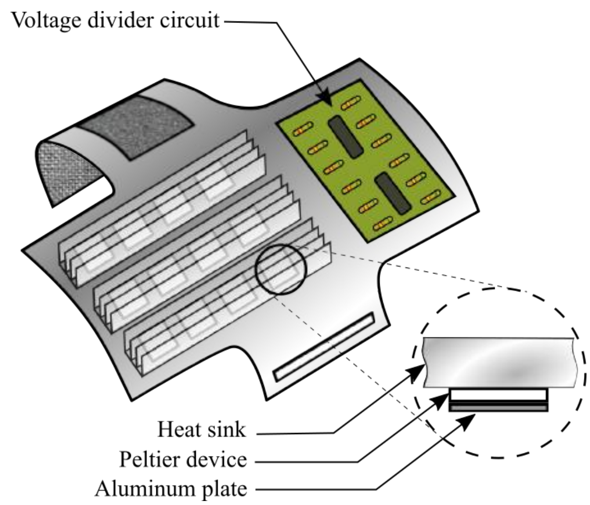

Figure 3.5: The device used in experimental sets 2 and 3 to test the constantly changing thermal patterns on humans.

peltier devices. The control signal was sent via serial port to an op amp in a voltage-controlled current source configuration. Figure 3.6 shows the proposed pattern against the actual temperature pattern applied on one of the subjects. The actual pattern ranged between 30.5°C to 31.5°C, which is slightly smaller than the proposed range, but sufficient for these tests.

The actuator board in experimental set 1 was designed in a way that allowed subjects to lift their arms at any time during the experiments in case they felt uncomfortable or in case of an emergency. We noted that some subjects moved their arms around during the experiments. Two subjects even lifted their arms completely off the actuators during experimental set 1 for none of these reasons. That motion caused some disturbance with the surface temperature of the actuators. However, the apparatus used in experimental sets 2 and 3 addressed the arm-movement issue by strapping the apparatus to the forearm to ensure full contact between the actuators and the skin. Because it was difficult to remove quickly, proper caution was taken to avoid any electrical contact or excessive temperatures. The amount of pressure applied from the actuators on the skin has been shown to not have significant effects on thermal thresholds or perception [63], hence, we did not consider it in our current investigation.

3.4.3 Experimental Procedure

In all three experimental sets, subjects were seated in a chair and were offered a brief explanation of the study followed by the consenting process. Following that, the temperatures of their anterior and posterior forearms were measured using a non-contact laser temperature gun.

Experimental set 1 was divided into three phases: the ordered pattern, the rearranged pattern, and the constant temperature. At the beginning of each phase, subjects were asked to press the anterior area of their dominant forearm against the actuators. Subjects were instructed to keep their forearms in continuous contact with the actuators for the entire four minutes of each phase. Each subject in experimental set 1 did a total of three randomly ordered experiments in an average of 30 minutes.

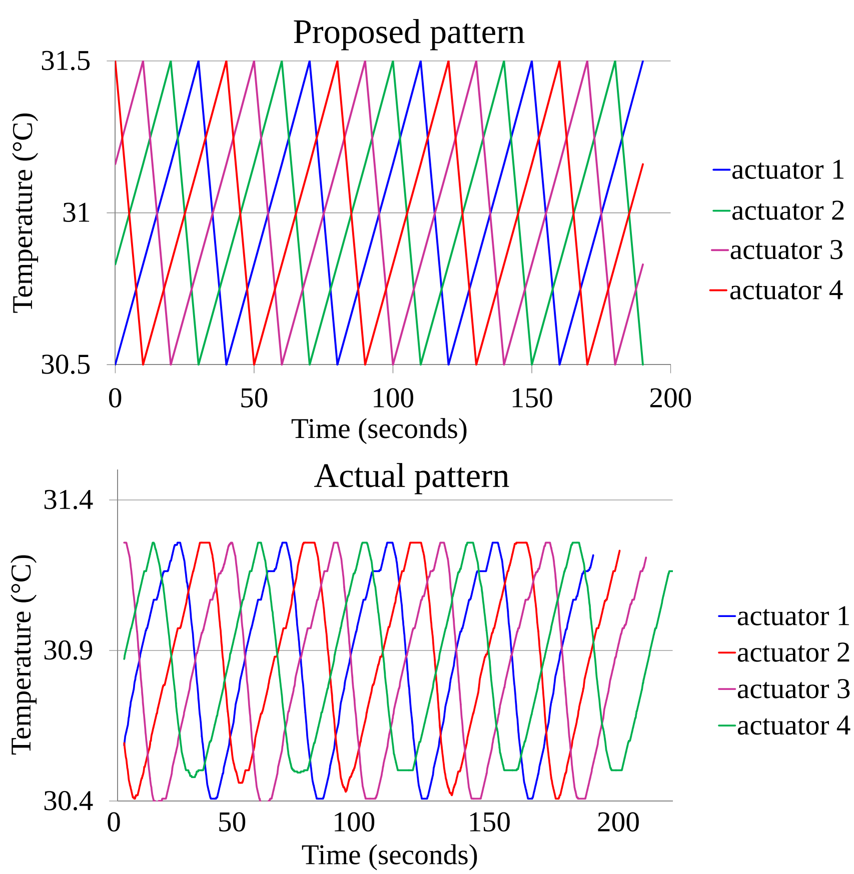

Figure 3.6: Proposed pattern (top) compared to the actual pattern applied on one of the subjects (bottom).

Experimental set 2 was also divided into three phases: 30/10, 21/7, and 45/15 heating/cooling time cycles, all in a diagonal pattern. Three different locations were tested: the posterior and anterior dominant forearm and the anterior non-dominant forearm. Subjects received assistance to wear the apparatus on their forearms. Each subject in experimental set 2 completed a total of nine randomly ordered experiments in an average of 1 hour.

To better describe experimental set 3, it was conceptually divided into two parts. The first part consisted of three phases: 30/10 diagonal, 30/10 horizontal, and 30/10 arbitrary. The second part consisted of two phases: 8:4 and 10:2 heating/cooling ratios. These two parts will be combined in the results section for analytical purposes. Subjects received assistance to wear the apparatus on their posterior dominant forearm. Each subject in experimental set 3 completed a total of five randomly ordered experiments in an average of 30 minutes.

To allow initial transients to settle, the first minute of each phase was not analyzed in all experiments and subjects were told to wait until after this warm-up phase before responding. Throughout the last three minutes of the experimental phases, subjects were asked to describe how they perceived the temperature of their arm. In experimental set 1, the participants were asked every 30 seconds, which corresponded to the point where two actuators are at the lowest and the highest temperatures. In experimental sets 2 and 3, different patterns and heating/cooling ratios were being implemented, hence, a question every 30 seconds would not coincide with similar peak points. Instead, a question every 22 seconds in experimental sets 2 and 3 was used to ensure the consistency of the effect between all three experimental sets. Subjects' responses were quantified using the scale shown in Table 3.2, which is a slightly altered form of the American Society of Heating, Refrigeration, Air-conditioning Engineering (ASHRAE) thermal sensation scale [64]. Subjects would take a five minute break between each experimental phase. During the break, subjects were asked to describe if they felt a temperature change and if there was any differences between the phases.

Table 3.2: Thermal sensation scale used in the experiments

Value	Thermal scale
+3	Hot
+2	Very warm
+1	Warm
0	Neutral
-1	Cool
-2	Very cool
-3	Cold

3.4.4 Subjects

All subjects were between 18 and 55 years old, healthy, right handed, and their average arm skin temperature generally ranged between 30°C and 32°C. All experiments were conducted in a room with a temperature of 22°C. Each participant read and signed a consent form before the experiment that followed a protocol approved by the University of South Florida's Institutional Review Board.

A total of 21 subjects participated, but a technical malfunction occurred during one experiment, so this subject's data was not analyzed. The subjects were distributed as follows: Ten subjects participated in experimental set 1, seven males and three females. Eight subjects participated in experimental set 2, seven males and one female. Three of them had participated in experimental set 1. Another eight subjects participated in experimental set 3, six males and two females. Two of them had participated in the previous experiments. Only one subject participated in all three experiments.

3.5 Results

A chi-square goodness-of-fit test was performed on all conditions of the experimental sets to determine whether the data were randomly sampled from a normal distribution. The results showed that the data were not normally distributed in any of the experimental sets. Therefore, a comparison of the repeated measures using Friedman's test was performed to analyze the data in each experimental set. When the Friedman test yielded significant results, a Wilcoxon Rank-Sum Test was used as the post-hoc test for individual comparisons. The results are illustrated using the means and standard errors of the factors in the experimental sets.

In experimental set 1, the non-parametric Friedman's test showed a statistically significant difference between the three experimental patterns ($X^2(2) = 37.98$, $p < 0.001$). A post-hoc test showed that the constant temperature control was statistically significantly different than the ordered pattern ($Z = -3.93$, $p < .0001$) and rearranged pattern ($Z = -3.27$, $p < .0001$), but there was no statistically significant difference between the ordered and rearranged patterns. Moreover, there was a clear perception of a continuous cooling effect in 9 out of the 10 subjects. The analysis did not show statistical significance between the answer timings. However, subjects reported that the location of cooling moved around the arm during the experiments. Only one subject perceived a sensation of heating during the ordered/rearranged patterns. The subject that did not perceive the continuous cooling was the only subject with a relatively low skin temperature ranging between 29°C (close to the wrist area) and 30°C. The thermal response results for all subjects are illustrated in Figure 3.7.

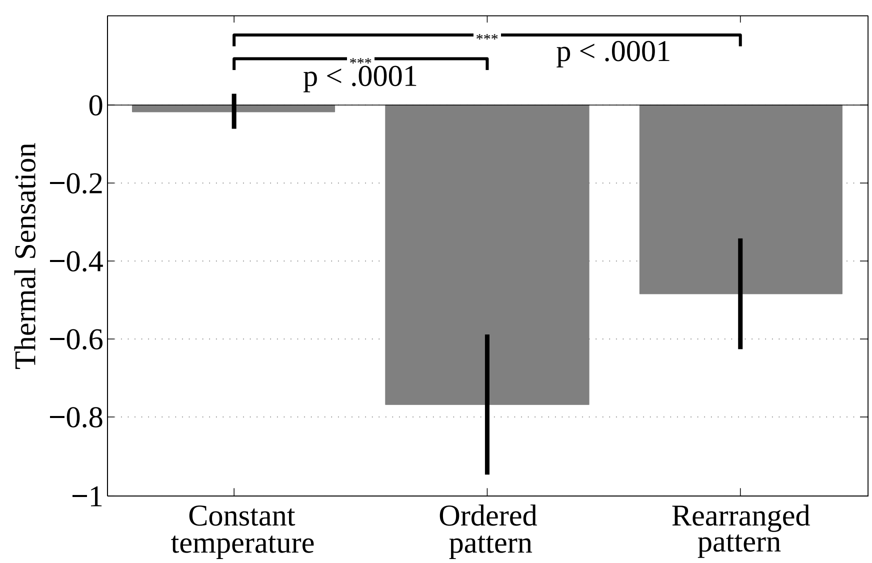

Figure 3.7: Experimental set 1 results showing means and standard errors for the different patterns. Ordered and rearranged patterns are statistically significantly different than the constant temperature condition.

All subjects in experimental set 1 reported that the temperature did not change during the constant temperature phase. Eight subjects reported that both the ordered and rearranged sequences were generally cool. Seven of them stated that the ordered pattern was colder than the rearranged pattern. Furthermore, two subjects performed the experiments on their posterior forearms in addition to the anterior side. However, we did not continue this version of the experiment because the subjects reported discomfort in positioning the dorsal area of their forearms horizontally on the actuators for four minutes.

In experimental set 2, Friedman's test yielded statistically significant results between the heating/cooling times ($X^2(2) = 15.72, p < 0.001$), and between locations ($X^2(2) = 17.74, p < 0.001$). The test did not show statistically significant differences between the answer timings. A post-hoc test showed that the 45/15 heating/cooling time is statistically significantly different than the 30/10 ($Z = -2.99$, $p = .003$) and 21/7 ($Z = -2.62$, $p = .009$) as illustrated in Figure 3.8. The perception of continuous cooling was reported from 7 out of the 8 subjects. Three subjects, who also participated in experimental set 1, reported that the cooling felt steadier and more spread out than it was in experimental set 1. One subject did not perceive a continuous cooling or heating sensation during the experiment. A post-hoc test, illustrated in Figure 3.9, shows that the dominant posterior forearm location was statistically significantly different than the nondominant anterior location ($Z = -4.24$, $p < .001$) and the dominant anterior location ($Z = -3.12$, $p = .002$). Subjects did not report any differences in the perception between the anterior locations of both forearms.

The analysis of experimental set 3 yielded statistically significant differences between the combinations of pattern/ratio stimuli ($X^2(4) = 10.36$, $p < 0.05$) and between the answer timings ($X^2(7) = 24.95$, $p < 0.001$). A post-hoc analysis showed that the diagonal 10:2 ratio was statistically significantly different than both the horizontal 9:3 ratio ($Z = -2.13$, $p = .033$) and the vertical 8:4 ratio ($Z = -2.50$, $p = .01$) as illustrated in Figure 3.10. Furthermore, time2 in the answer timings was statistically significantly different than time5 ($Z = -3.02$, $p = 0.003$)

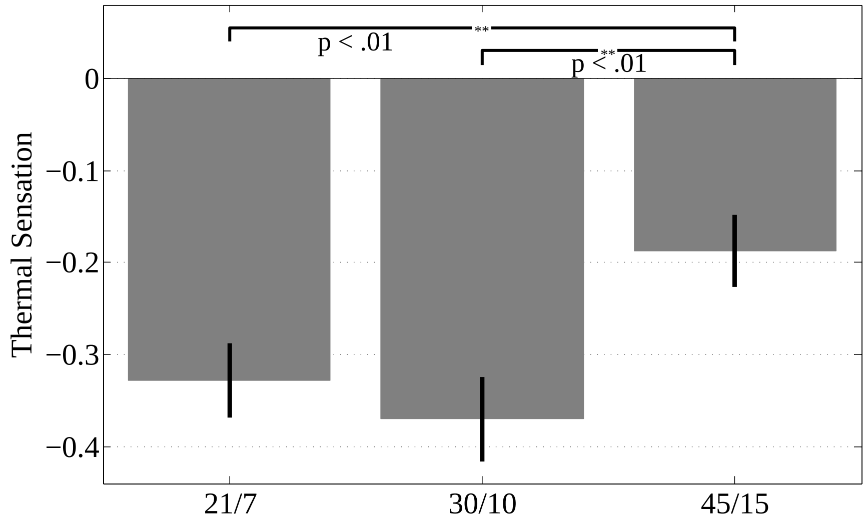

Figure 3.8: Experimental set 2 results showing means and standard errors for the different cooling rates. 45/15 heating/cooling time is statistically significantly different than 30/10 and 21/7 times.

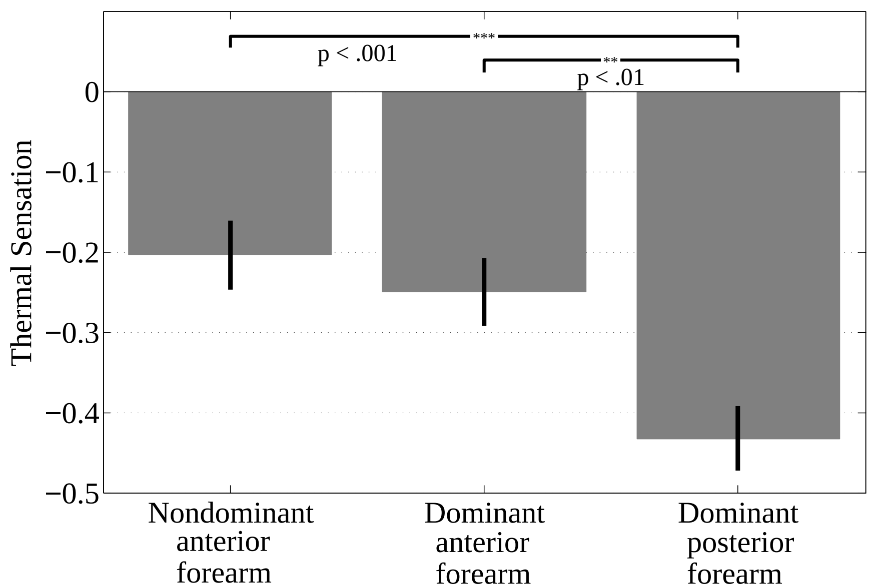

Figure 3.9: Experimental set 2 results showing means and standard errors for the location of thermal stimuli. The perception on the posterior forearm is statistically significantly different from the perception on the anterior forearms.

and time8 ($Z = -3.41$, $p = 0.001$). Time8 was also statistically significantly different than time3 ($Z = -2.84$, $p = 0.005$) and time4 ($Z = -2.6$, $p = 0.009$), as shown in Figure 3.11.

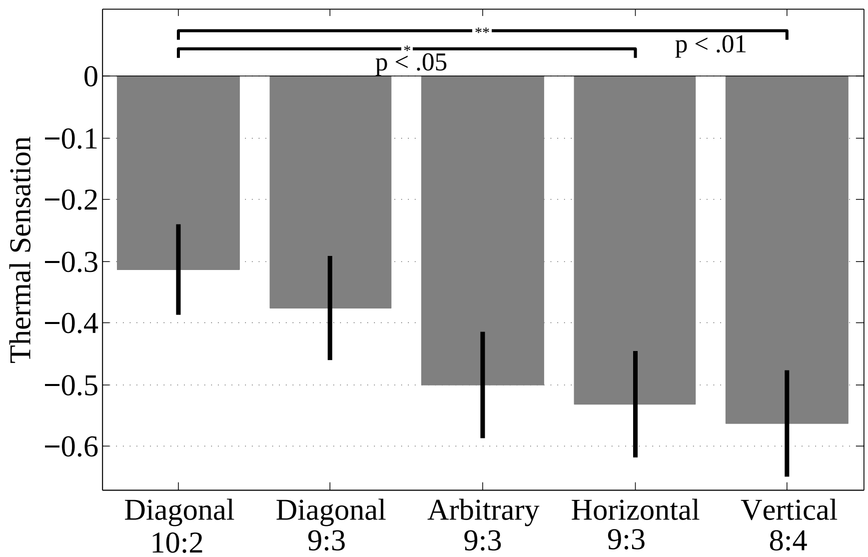

Figure 3.10: Experimental set 3 results showing means and standard errors of the patterns and ratios. The perceptions of the 8:4 and horizontal 9:3 heating/cooling ratios were statistically significantly different than the 10:2 ratio. Also, all results were statistically significantly different than zero.

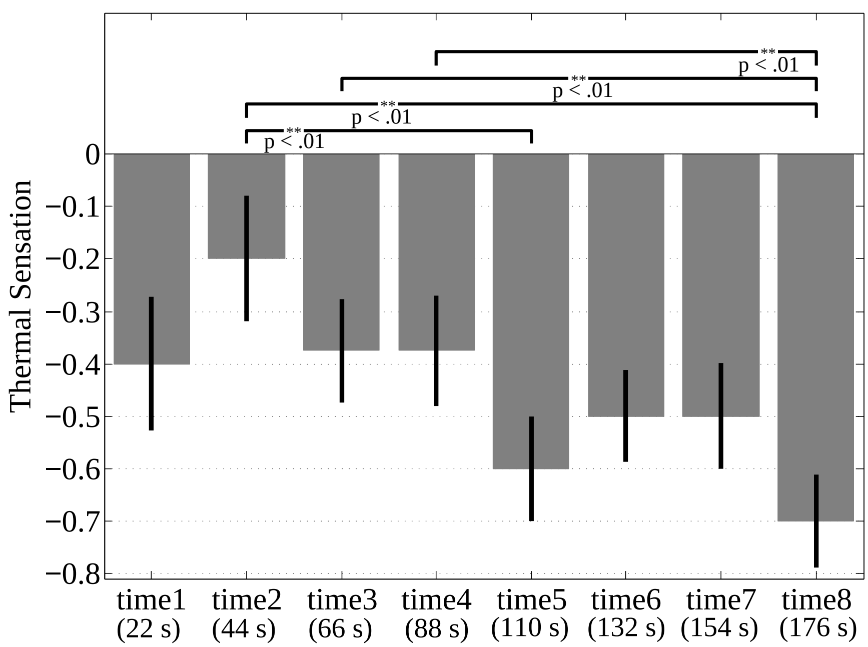

Figure 3.11: Experimental set 3 results showing means and standard errors of the answer timings. The horizontal axis shows the time at which subjects were asked in seconds. Time8 was statistically significantly different than time2, time3, and time4. Time2 was statistically significantly different than time5. All results were statistically significantly different than zero.

3.6 Continuous Heating Stimulation

The previous results showed that a continuous cooling sensation can be generated using asymmetrically applied heating and cooling stimuli. In this section, continuous heating is investigated using the same stimulation principle. The new method applies a combination of fast heating and slow cooling rates using the same thermal actuators. The slow cooling rate is under the perceptual threshold level, hence it is not perceived. The fast heating rate, however, is perceived creating the feeling that the temperature is warmer than it actually is. The goal here is to generate a continuous warm sensation using multiple dynamic localized thermal inputs. To achieve this goal, the thresholds of hot and cold receptors has to be tested using different heating and cooling rates of change and baseline skin temperatures. The results will provide new information about temperature thresholds of relatively slow rates of change and will increase our understanding of thermal perception.

It has been shown that large temperature differences between a stimulus and nearby skin areas can create confusion in thermal perception [57], and it often happens when adjacent hot and cold sensors perceive a discrepancy. This phenomenon is referred to as synthetic heat [58] and was first discovered by Thunberg [59] [62] who called it the thermal grill illusion. Although the outcome of both terms perceives excessive heat sensation, synthetic heat usually refers to applying equal amounts of heating and cooling on two locations on the skin, whereas thermal grill refers to heating and cooling in an alternating sequence. The effects of synthetic heat and thermal grill illusion are often accompanied with the momentary sensation of pain.

The method presented here is distinctly different than the synthetic heat and thermal grill illusion. In this method, the temperatures of the actuators are constantly changing with two different rates for cooling and heating unlike the thermal grill illusion where each actuator has a constant temperature and does not change direction between heating and cooling. Additionally, only 1°C temperature difference is applied between the heating and cooling stimuli in this method whereas the temperature difference can get up to 20°C between the heating and cooling stimuli in the thermal grill illusion [62].

The study in this section was divided into two parts examining the characteristics of thermal threshold and constant heating perception. The first part investigated the perceptual threshold of a decreasing temperature from three baseline starting temperatures using three rates of change. The second part studied the effect of applying asymmetric hot and cold stimuli using three average operating temperatures. The two parts of the study were conducted on the dorsal area of the dominant forearm using the same apparatus.

3.6.1 Thermal Threshold

In the first part of the study, three rates of cooling (0.05°C/s, 0.033°C/s, and 0.022°C/s) were applied to the participants. These rates were chosen to test our hypothesis of creating a unique thermal display and to examine how participants will react to the temperature change. Also, there is very little research that has been done studying thermal thresholds on such low rates of temperature change. Three baseline starting temperatures were used (29°C, 31°C, and 33°C) with the rates of temperature change making a total of nine experiments. Only three actuators out of 12 were cooling while the other nine remained at the baseline temperature to be comparable to our method of continuous heating. Figure 3.12(a) shows the layout of the actuators where three are cooling diagonally and the rest are at a constant temperature. The total surface area of thermal stimulation was approximately 7 cm^2. Figure 3.12(b) illustrates the difference between the three rates of temperature change over a 60 second period.

3.6.2 Multiple Thermal Stimuli

The second part of the study investigated the concept of constant heating using twelve actuators. Nine actuators were slowly cooling over 30 seconds out of phase from each other at a rate of 0.033°C/s while three actuators were quickly heating over 10 seconds at a rate of 0.1°C/s. Every ten seconds, the actuator that was heating would start slowly cooling down and another would start quickly heating. Three different average temperatures (29°C, 31°C, and 33°C) were used with one diagonal pattern applied on the forearm. Figure 3.13 shows the thermal pattern of

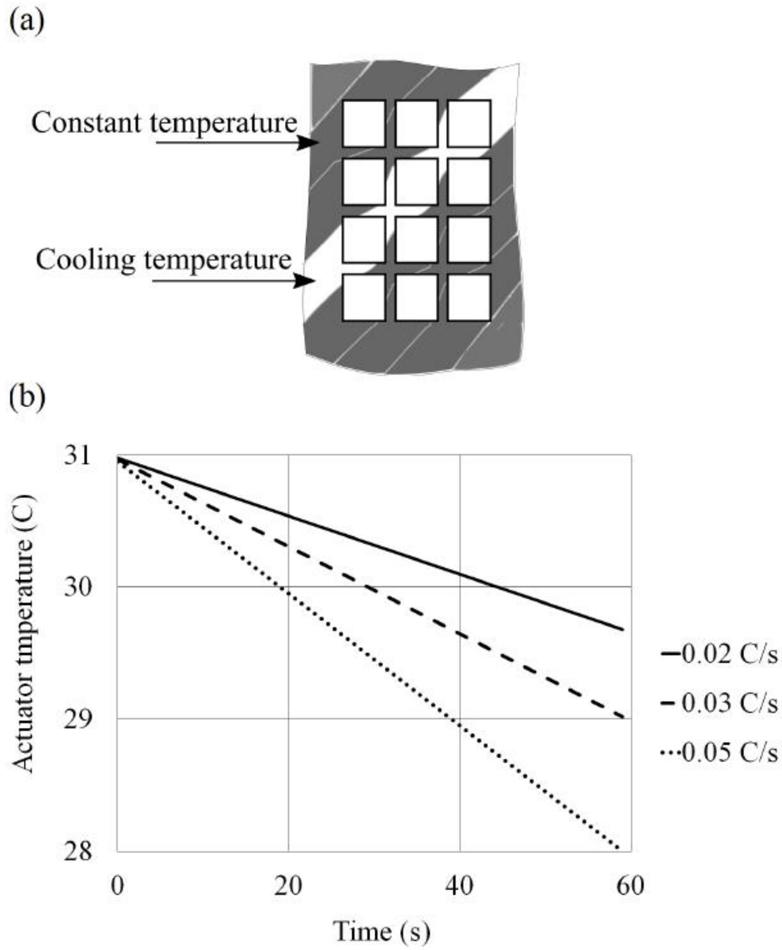

Figure 3.12: (a) The layout of the activated actuators, (b) The rates of change that are used in the first experimental set for a 31°C baseline temperature.

the continuous heating method. Two more experiments were added to this part where two constant temperatures of 31°C and 33°C were applied on the skin as a neutral temperature reference point for comparison.

Before generating the pattern, as shown in Figure 3.13, all actuators were slowly warmed up to match their corresponding average temperatures of thermal stimuli. Even though the temperature linearly changed within 1°C difference, the average surface temperature of the skin did not change during the experiments.

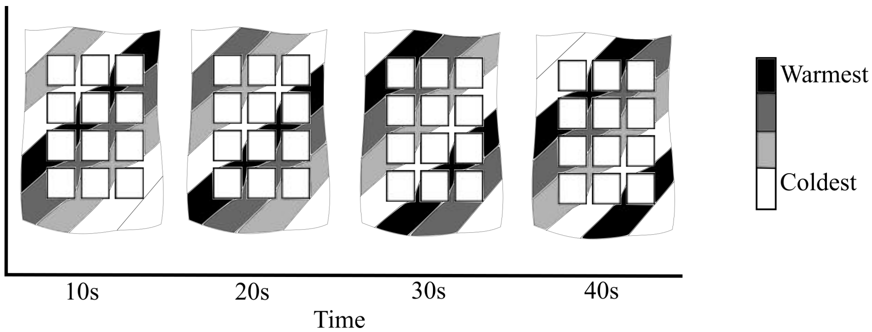

Figure 3.13: The heating and cooling patterns used in the second experimental set.

3.6.3 Procedure and Participants

Participants were seated in a chair inside a temperature-controlled room with an ambient temperature of 23°C. After the participants were given a brief explanation of the experiments, their forearm temperature was measured.

In the first part of the experiment, the cold threshold of different rates of change and baseline starting temperatures was studied (section 3.6.1). After one minute of transition time, to allow the actuators to reach the baseline temperature, three actuators started to cool down according to the assigned rate of change for one minute. Participants were instructed to report when they perceived a clear sensation of cold. Each participant completed nine randomly ordered experiments in this part over an average of 15 minutes.

The second part of the experiment tested the concept of constant heating using twelve actuators (section 3.6.2). Three trials were conducted using three average temperatures (29°C, 31°C, and 33°C) with a cooling rate of 0.033°C/s over 30 seconds and a heating rate of 0.1°C/s over 10 seconds. The fourth trial applied a constant temperature of 31°C throughout the actuators as a neutral reference for comparison. A fifth trial, added for later subjects, applied a constant temperature of 33°C as another reference for comparison. Only five participants took the 33°C constant temperature experiment. At the beginning of each experiment, the actuators were given one minute to warm up and settle on the starting temperature. After that, participants were asked to describe their thermal sensation on the forearm every 30 seconds using the American Society of Heating, Refrigeration, Air-conditioning Engineering (ASHRAE) thermal sensation scale [64]. The scale consists of seven thermal levels: hot, warm, slightly warm, neutral, slightly cool, cool, and cold, or from $+3$ to -3 respectively. A two-minute break was given to participants between each experiment.

Ten participants (eight males and two females) participated in this study. They were all healthy and between 18 and 55 years old. Nine of the participants were right handed, and their skin temperature ranged between 30°C, and 32°C on the dorsal area of the dominant forearm. Each participant read and signed a consent form before the experiment that followed a protocol approved by the University of South Florida's Institutional Review Board.

3.6.4 Results

In the first part of the study, the obtained data was analyzed using an ANOVA with a dependent variable of response time and three independent variables of baseline starting temperature, rate of change, and participant. Another ANOVA with a dependent variable of subjective rating and two independent variables of average temperature and participant was used in the analysis of the second part. All statistical tests were based on an alpha value of 0.05.

The results of the first part showed the response time to cooling at 29°C baseline temperature was statistically significantly faster ($F(2,76) = 17.84$, $p < 0.001$) than 31°C and 33°C. However, there was no statistical significance between the other two cooling rates. Figure 3.14 shows the response time of cooling for the three baseline starting temperatures.

The mean response time for all rates of change was longer than 40 seconds which accounts for a threshold above 1°C with the 0.033°C/s and 0.05°C/s rates of change. Figure 3.15 represents the response time to cooling at the three rates of change.

In the second part, the results showed a statistically significant difference between the average temperatures of stimuli and the constant temperature($F(3,267) = 223.71$, $p < 0.001$). The perception of continuous heating was distinctly noticeable at 31°C average temperature stimulus compared to the constant stimulation at the same temperature where participants reported

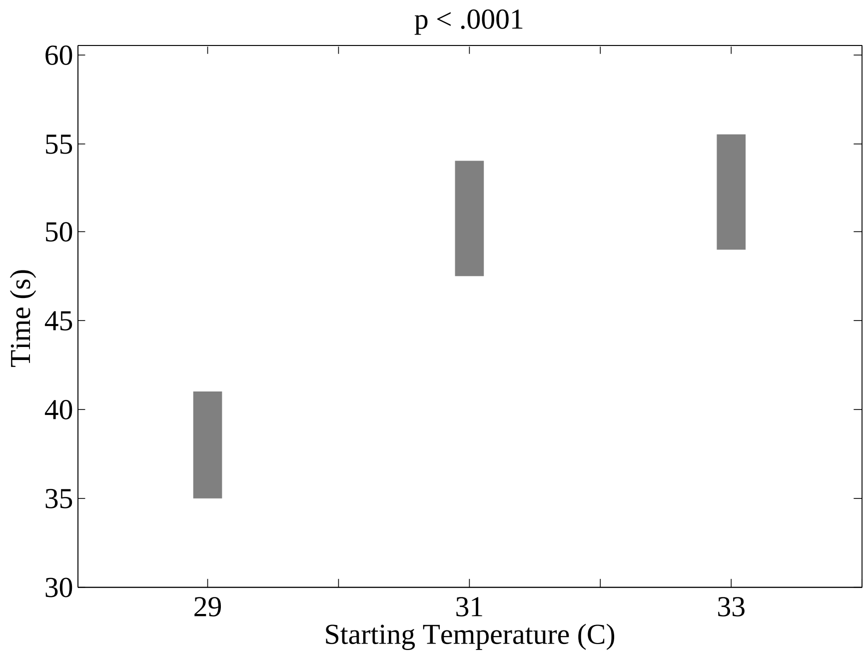

Figure 3.14: The results of the response times regarding the baseline starting temperature. The response time to cooling at 29°C is statistically significantly shorter than the response at 31°C and 33°C.

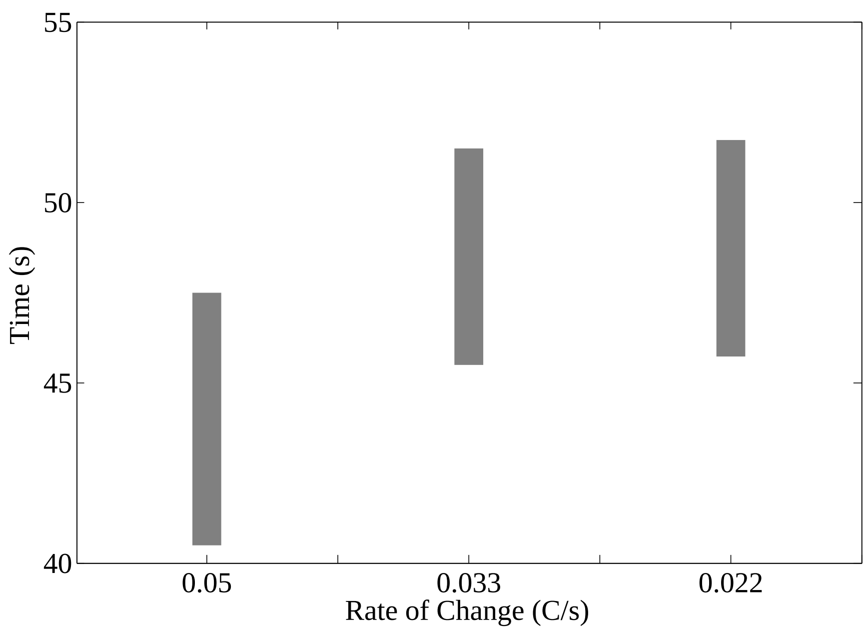

Figure 3.15: The results of the response times regarding the rate of temperature change. No significant results were found between the three rates of change.

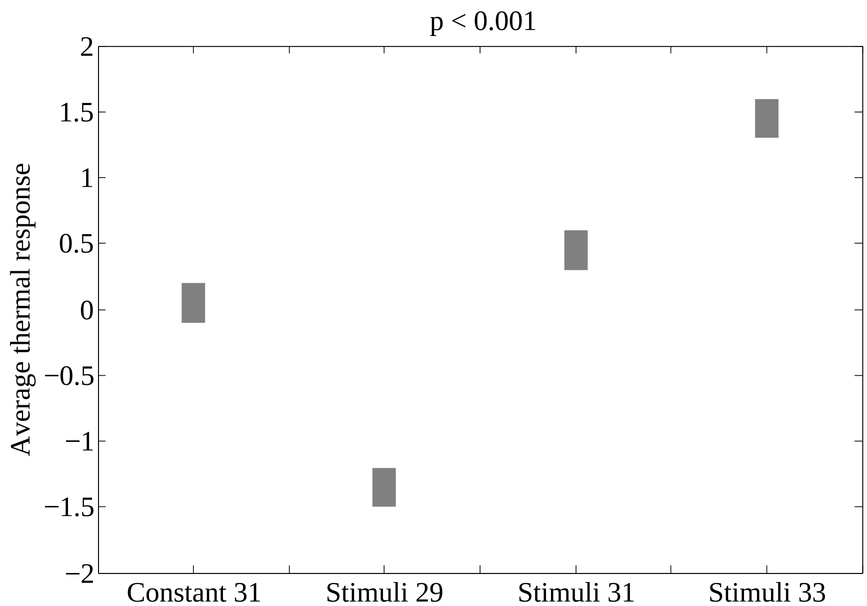

Figure 3.16: The results of applying three asymmetric hot and cold stimuli and a constant temperature at 31°C on ten subjects. Statistically significant differences were found between thermal stimuli.

a "neutral" sensation. Continuous heating was also perceivable at 33°C average temperature stimulus. Participants did not report any sensation of temporary cooling during thermal stimulation at 31°C or 33°C. However, the continuous heating sensation completely vanished at 29°C average temperature stimulus where participants reported a continuous cooling instead. Figure 3.16 shows the results of the second part of the experiment.

For the last five participants, who had an additional comparison of the constant temperature at 33°C, the results did not show a statistically significant difference between the constant temperature experiments at 33°C and the stimulus at the same temperature as shown in Figure 3.17.

The study represented here tested thermal thresholds of cold receptors in ten participants at three baseline starting temperatures and three rates of change to identify if they would have a chance to perceive the slowly decreasing temperatures. The results showed that participants' response time to cooling from 29°C was statistically significantly shorter than the response of the same cooling rates at 31°C and 33°C. Kenshalo [45] investigated warm and cold thresholds as a function of rate of temperature change and showed that slower rates of change caused a noticeable

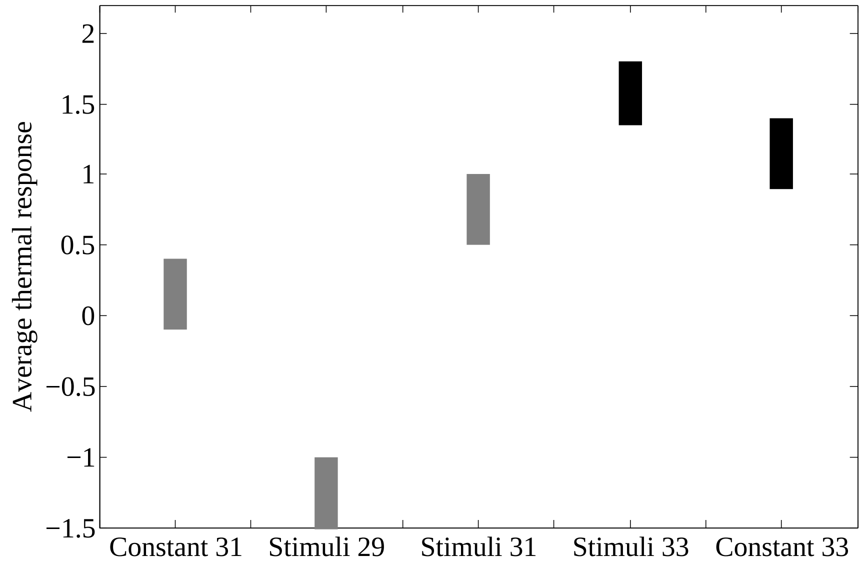

Figure 3.17: The results of applying three asymmetric hot and cold stimuli and two constant temperatures at 31°C and 33°C on the last five subjects. No significant results were found between the constant experiments at 33°C and thermal stimulus at the same temperature, highlighted in black.

increase in warm and cold thresholds as shown in Figure 3.2. Kenshalo's study, however, was conducted using one baseline temperature at 31.5°C and a 14.44 cm^2 thermal stimulator which is approximately twice as large as the stimulation used in this study. This suggests that the slowly cooling actuators would be more likely to be perceived during the constant heating experiments, however the average response time is still longer than that used in the constant heating experiments.

The second part of this study investigated the possibility of creating a continuous warm sensation without changing the net temperature on the skin using slowly cooling and quickly heating actuators. The results showed that participants clearly perceived continuous heating using thermal stimulation at an average temperature of 31°C. This sensation appeared to taper off as the average temperature deviated from the normal skin temperature. For instance, thermal stimulation at 33°C average temperature generated a continuous feeling of heating, yet the application of constant 33°C temperature also generated a similar effect. Participants reported that both experiments had a thermal sensation between "slightly warm" and "warm" on ASHRAE's thermal scale. However, the lack of the cold perception within the time frames of the 33°C and 31°C average temperature stimuli is in agreement with the hypothesis that is presented here, but within limits. This may be related to the response functions of hot and cold receptors. Previous studies showed that the static discharge of warm receptors starts at 30°C [65], whilst cold receptors' static discharge reaches its peak between 25°C and 30°C [66].

Based on the results represented in this study, it appears that there is a range at which the asymmetrically applied hot and cold stimuli are most active. To further investigate this range, these stimuli can be tested using temperatures between 25°C and 35°C and can be later compared to their peers of constantly applied stimuli in the same range. The results of these comparisons will create a map of thermal responses at which these stimuli are most and least active. Furthermore, the size of the thermal stimulus also affect thresholds [67] [68] [69]. To study the effect of area, the asymmetrically applied hot and cold stimuli can be tested in 2 x 2, 2 x 3, and 3 x 3 thermal matrices using the same thermal display device.

3.7 Discussion

The experiments showed that subjects were generally able to perceive a sensation of continuous cooling. However, most of the subjects reported that the location of the cooling moved around the arm throughout experimental set 1. The large surface area of each actuator and lack of interspersing of the channels likely caused this perception of moving. Lee et al, showed that cooling stimuli are localized significantly better than warming stimuli [70]. It was also shown that, for warm thermal stimuli, spatial localization is usually very poor on the forearm [71], which may account for this moving perception of cooling.

Interspersing the thermal actuators increases the effectiveness of the continuous cooling sensation. Experimental set 2 offered a further study of this observation by increasing the number of the actuators from four to twelve while decreasing the size of each actuator from $16\,cm^2$ to $2.25\,cm^2$. By decreasing the surface area of each actuator and interspersing them, the nine out of ten subjects that perceived cooling in experimental set 2 reported a locally fixed feeling of cooling. Sato [72] studied a thermal display on relatively small, spatially divided peltier devices and the results showed that small skin areas can perceive thermal stimulations effectively. Also, decreasing the area of stimulation may have a slight effect on the cooling intensity, however, cold thresholds are less dependent on the area compared to warm thresholds [53] [73].

The patterns of stimulation also showed a slight effect on thermal perception in experimental set 1. Seven out of ten subjects reported that the ordered pattern was cooler than the rearranged pattern. This can be explained by the locations of the coolest and warmest actuators during the patterns shown in Figure 3.3. In the ordered pattern, the actuator with the lowest temperature was next to the one with the highest temperature for 30 uninterrupted seconds out of each 40 second cycle, which created a relatively high temperature difference applied on a relatively small surface area. In the rearranged pattern, the lowest and the highest actuator temperature were next to each other for only 20 seconds divided on two separate intervals of 10 seconds each. This implies that the local temperature gradient has a significant effect on the consistency of the continuous cooling perception.

Previous studies showed that warm thresholds decrease with faster rates of temperature change [45]. However, experimental set 2 showed that 30/10 and 21/7 heating/cooling rates were perceived as significantly colder than 45/15, even though it had the slowest rate of change at 0.022°C/s. Moreover, subjects reported a better cooling perception in the 21/7 rate even though the heating rate of change was the fastest at 0.047°C/s. Harding and Loescher [69] tested different rates of stimulus change up to 1°C/s with a 16 x 16 mm peltier device and indicated that a faster rate of stimulus change can invoke a thermal adaptation to the warming stimulus. However, they did not find adaptation in cooling stimulus with the different rates of stimulus change. Thus, subjects may have adapted to the warming stimulus during the 21/7 and 30/10 rates.

This study found a difference in the perception based on the location of applied stimulus. In experimental set 1, two subjects performed the experiments on their posterior forearms in addition to the anterior side. However, both subjects reported discomfort in positioning the dorsal area of their forearms horizontally on the actuators for four minutes. Additionally, their forearms were not in full contact with the actuators due to the unusual angle, thus, we did not continue this version of experimental set 1 and their data were discarded. The apparatus used in experimental sets 2 and 3 helped us perform additional tests on the posterior area of both left and right forearms of the subjects. The results showed a significantly colder sensation on the posterior forearms. Stevens [74] found that thermal sensitivity varies 100-fold between body parts. Other studies have shown that dorsal and ventral areas on the hand and the forearm have different thermal sensitivities [75].

The results from experimental set 3 showed significant differences between different answer times. Such differences were not found in experimental sets 1 and 2 since they were conducted using the same heating/cooling ratio but with different patterns, locations, and heating/cooling times. However, different heating/cooling ratios were used in experimental set 3 which means that, at a certain time period, subjects reported an answer while perceiving cold from two, three, or four actuators based on the experiment's ratio. Figure 3.11 shows that the perception of cold may not be as consistent during the transient periods of the experiments, however, the perception becomes relatively more consistent and intense after that. To better address the effect of timing, more question timings should be tested to verify that the perception of cold is not consistent during a time period. This inconsistency in perception can also be avoided by overlapping the cooling periods of the actuators such that the next actuator reaches the perception threshold of cold about the same time that the first one is switching to heating without causing a change in the average temperature on the area of stimulation.

To compensate for the difference between heating/cooling ratios in experimental set 3, the heating/cooling times for the 8:4 and the 10:2 ratios had to be modified from the original 30 second heating and 10 second cooling. Instead of keeping the warming time constant and changing the cooling time (for instance 30 second warming and 15 second cooling for the 8:4 ratio), we chose to change both warming and cooling times in a way that keeps both times (26 second heating, 13 second cooling) close to the original 30 second heating and 10 second cooling. The same concept was used to determine the heating/cooling times for the 10:2 ratio where the time cycles were set as 35 second heating and 7 second cooling. Investigating different heating/cooling ratios with a constant warming or cooling time may determine whether the driving factor of the localized thermal perception is governed by warm or cold stimulus. Melzack [76] found that a continuous cold stimulus reduces the skin sensitivity to cold while warm stimulus increases it, which suggests the maximum time for cooling should be limited.

Based on the data shown in Figure 3.2, relatively slow temperature rates of change should not trigger the warm thermoreceptors. However, during experimental set 1, we found that a 1°C increase can sometimes be sensed even with a low rate of change like 0.033°C/s. We also investigated different rates of temperature change in experimental sets 2 and 3 ranging from 0.022°C/s to 0.047°C/s and found that a 1°C increase was not sensed. This is likely related to the dependence of temperature perception on the heat flux transferred between the actuators and the skin [77] and to the area of stimulation [53]. This is, however, challenging to control since heat flux is based on the temperature differential between the lower layers of skin and the thermal actuator. A better option to relate the applied heat to the perception in dynamic environments is a flux meter that could be constructed by placing two resistance temperature detectors (RTD) on either side of a thin film of material of known thermal conductivity. The temperature sensor pair would measure the thermal flux entering the skin to test how absolute temperature and heat flux affect thermal perception. There would be some delay associated with this measurement because the thermal receptors measure the heat flux at a distance below the skin, but this difference should be negligible over the time scales that would be studied.

Most thermal display applications provided a thermal feedback using hot or cold stimuli. These stimuli often apply relatively large temperature differences on the skin. Salminen [78] found that a 6°C change on the skin temperature was unpleasant, arousing, and dominant. In other cases, a combination of hot and cold stimuli, like the thermal grill illusion and synthetic heat, were used to convey thermal information. These combinations also apply large temperature differences on the skin and often diminish after a short time, typically around 10 seconds [60]. The method presented here can apply a continuous cooling sensation without changing the average temperature of the area of stimulation for substantially long periods as illustrated in Figure 3.11.

Peltier devices were very effective and efficient to use as actuators in this study. However, with continuous use, the heat build-up in the devices caused difficulties when cooling the actuators after prolonged periods of time. Small differences can be observed between the different actuators in Figure 3.6 even though the same controller properties were used. As an alternative, small hot and cold liquid channels with controlled valves could replace the thermoelecric device system. Hot and cold water would be mixed to the desired temperature and run through small tubes that are in contact with the skin. The system could easily cover relatively larger skin areas and its temperature could be controlled precisely. There will however be some difficulties in routing all of the water tubes since they are typically less flexible than electrical cables.

3.8 Conclusion

We presented four-channel and twelve-channel dynamic thermal displays that were used to create the sensation of continuous cooling without a change in the average temperature of the area of stimulation. We focused on the interaction of a relatively large area of skin with multiple nonlinear localized temperature changes. The study consisted of three different sets of experiments. Twenty one subjects participated in a total of 142 sessions. The results showed that subjects were generally able to perceive continuous cooling. The study demonstrated the possibility of testing thermal perception without causing a net change in the actual thermal state of the skin.

There are several planned future works and improvements that could be pursued for this study including measuring the heat flux instead of the surface temperature to control the actuators. These changes will likely lead to an improved and more robust perception.

Chapter 4: Computational Analysis of Cooling Perception

4.1 Introduction

Computer simulations have been widely used in the past few decades by modeling systems and processes to study their characteristics and reactions in the physical world. They can provide information and conclusions about the studied system or process. For instance, Murakami [79] used a simulation of airflow, moisture transport, and thermal radiation to predict the amount of heat released from the human body. Ho and Jones [80] conducted a simulation study based on a thermal model to predict the temperature response of the skin.

The method, previously discussed in chapter three, takes advantage of the nonlinear nature of temperature perception of the skin to generate a continuous sensation of cooling. A few thermal actuators were quickly cooled while others were slowly heated simultaneously on the skin. The heating actuators were below the perception threshold so they were not detected but cooling actuators were above the threshold, hence, they were detected. The results of this method, discussed in chapter three, showed that a cooling sensation can be generated using asymmetrically applied hot and cold stimuli. However, more information is needed to understand the temperature distribution within the skin and how the skin reacts to the thermal stimuli. We hypothesize that a simulation of a model that mimics the physical and thermal properties of the skin on the human forearm can provide the capability to investigate more complex and technically challenging variations of the same type of thermal display. In order to validate the results of the simulation, a physical structure of the forearm was built using a copper tube covered with a thin layer of polyurethane rubber serving as the skin of the forearm as illustrated in Figure 4.1. The copper was heated so that the surface temperature of the polyurethane reaches the desired temperature of

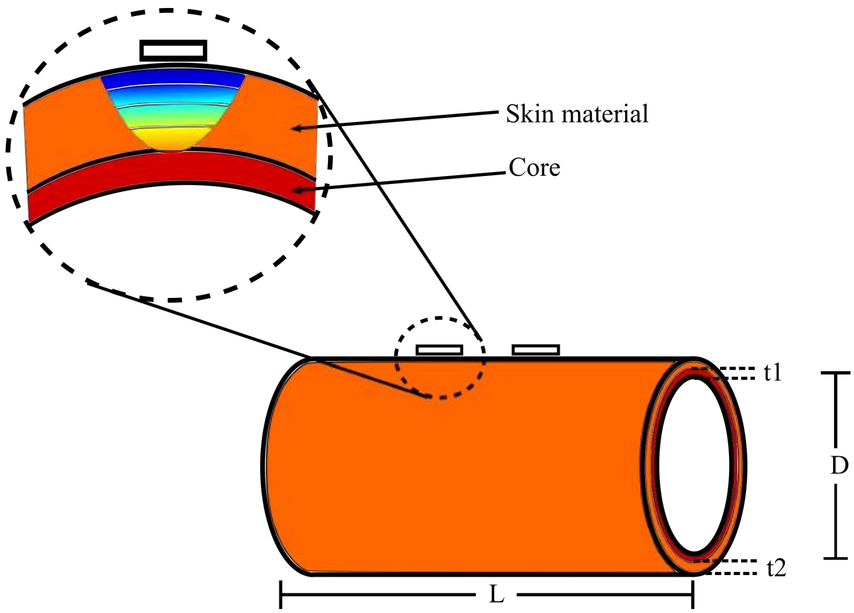

Figure 4.1: Schematic representation of the copper cylinder with thermal actuators.

the human skin which is the same average skin temperature that was measured in the subjects that participated in the previous set of experiments.

The purpose of this study is to present an approximate model of the skin that can provide information about its temperature distribution and the thermal behavior when asymmetrical hot and cold thermal stimuli are applied on it. The results of this study can help us have a better understanding of the effects of temperature change on the skin at different depths. The results will also help us perform more challenging thermal display experiments and predict their outcomes.

4.2 Background

It is known that thermal receptors that are located in the skin can thermally identify and discriminate between different objects by detecting the temperature differences that occur on the skin. Perceiving temperature differences depends on many factors such as the rate of temperature change and temperature of the surface of the skin [52]. These receptors are also important for regulating the temperature of the body.

Most of the mathematical and computational models were developed to study the thermoregulation system and the general thermal comfort of humans [5]. For example, Rugh and Bharathan [81] [82] simulated a human model based on a manikin where the human physiological response and skin temperatures were studied to investigate the thermal effect of a climate control system of an automobile. Other studies have developed mathematical models to predict the human thermal response in different environments [83] [84]. Computer models were also used to study the performance and characteristics of different devices. Boetcher et al. [85] performed numerical simulations to test skin-surface temperature measurement devices. Numerical models were also used to investigate the effect of airflow and thermal noise in detecting tumors [86]. Moreover, McKnight [87] studied the effects of thermoelectric devices on thermal receptors inside the skin.

The simulation performed in this study aims to investigate the thermal perception of the skin when asymmetrical hot and cold stimuli are applied. The simulations also aim to test the performance of the thermal display device discussed in chapter three.

4.3 Approach

For this model, a simple cylindrical structure is considered to approximate the shape of the forearm. The structure consists of a core, which represents the forearm, and a thin layer that covers the core, which represents the skin. Based on Figure 4.1, a copper tube with an outer diameter $D = 7.6\,\text{cm}$, a length $L = 30.5\,\text{cm}$, and a wall thickness $t1 = 0.23\,\text{cm}$ is chosen to represent the forearm. A polyurethane layer with a thickness of $t2 = 2\,\text{mm}$ is chosen to approximate the skin of the forearm. The thermal conductivity of polyurethane ranges from 0.2 W/mK to 0.3 W/mK in its rubber form which is similar to the thermal conductivities of the dermis and epidermis layers combined in the human skin where the thermoreceptors are located [88].

The air that is in contact with the model is considered to be stagnant with a convective heat transfer coefficient of $10\,W/mK$ at 23°C ambient temperature. Further, warm water is chosen to generate heat in the cylindrical structure. The water runs through the copper tube to warm up the structure so that the surface temperature of the skin reaches 31.5°C.

4.3.1 Analytical Solution

The temperature at the core of the cylindrical structure can be calculated using the concept of thermal resistance. The total resistance of the two layer cylindrical system shown in Figure 4.2, is calculated as follows [89] :

$$R_{total} = R_1 + R_2 + R_3 + R_4 \tag{4.1}$$

$$R_{total} = \frac{1}{h_1 2\pi r_1 L} + \frac{\ln \frac{r_2}{r_1}}{2\pi k_1 L} + \frac{\ln \frac{r_3}{r_2}}{2\pi k_2 L} + \frac{1}{h_2 2\pi r_3 L} \tag{4.2}$$

where

r_1 = Inner radius of copper.

r_2 = Outer radius of copper.

r_3 = Outer radius of polyurethane.

h_1 = Convective heat transfer coefficient of water flowing in a pipe.

h_2 = Convective heat transfer coefficient of stagnant air.

k_1 = Thermal conductivity of copper.

k_2 = Thermal conductivity of rubber polyurethane.

On the surface of the polyurethane material, the rate of heat flow is represented as follows [89] :

$$q_{convection} = h_1 A(T_{surface} - T_\infty) \tag{4.3}$$

Equation (4.3) can also be written as the ratio of the temperature gradient to the corresponding thermal resistance [89] :

$$q_{convection} = \frac{T_{s2} - T_{surface}}{R_3} = \frac{T_{water} - T_{s2}}{R_1 + R_2} \tag{4.4}$$

The result of Equation (4.4) shows that T_{water} = 32.15°C. This result was later used to set the temperature of the water inside the copper pipe to generate the desired skin surface temperature of 31.5°C.

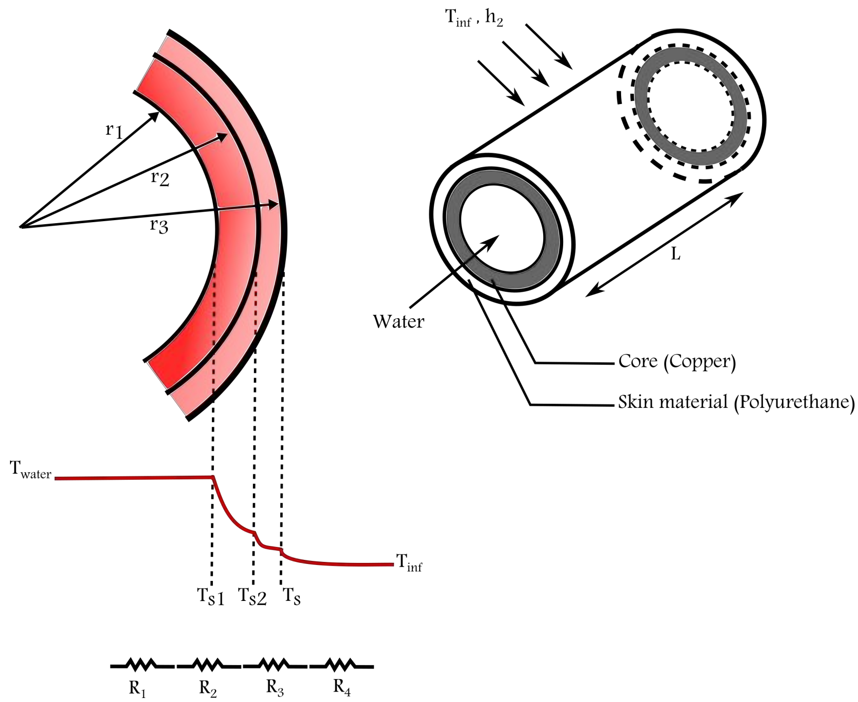

Figure 4.2: Temperature distribution of a copper cylinder covered with a polyurethane layer at transient state. The electrical resistances represent thermal resistance associated with the conduction and convection of heat.

4.3.2 Finite Element Modeling

The modeled forearm and thermal display system, shown in Figure 4.3, were created using SOLIDWORKS, whereas the simulation was conducted using ANSYS v15.0. The model was set up using transient thermal analysis and had dimensions of 30.5 cm 7.8 cm, 8.2 cm, a volume of 340.72 cm^3, and weighed 1.76 kg. The geometry of the model was sliced in four places in the *x* and the *y* axes using ANSYS Design Modeler in order to better control the mesh size in the stimulation area, which is the area underneath the thermal actuators. This procedure resulted in 24 bodies and 62 bonded contact regions. Furthermore, aluminum plates (15 mm x 15 mm x 3.8 mm) were chosen to represent the thermal actuators in the model instead of using ceramic peltier devices that were used in the twelve-channel thermal display device. The reason of this substitution was to simplify the thermal display apparatus in the model. Initially, the main purpose of using peltier devices in the experiments was to apply temperature differences on the forearm, therefore, an aluminum plate that applies the same temperature difference on the modeled arm is sufficient. Moreover, the thermal actuators in the apparatus were also covered with aluminum plates that were directly in contact with the skin.

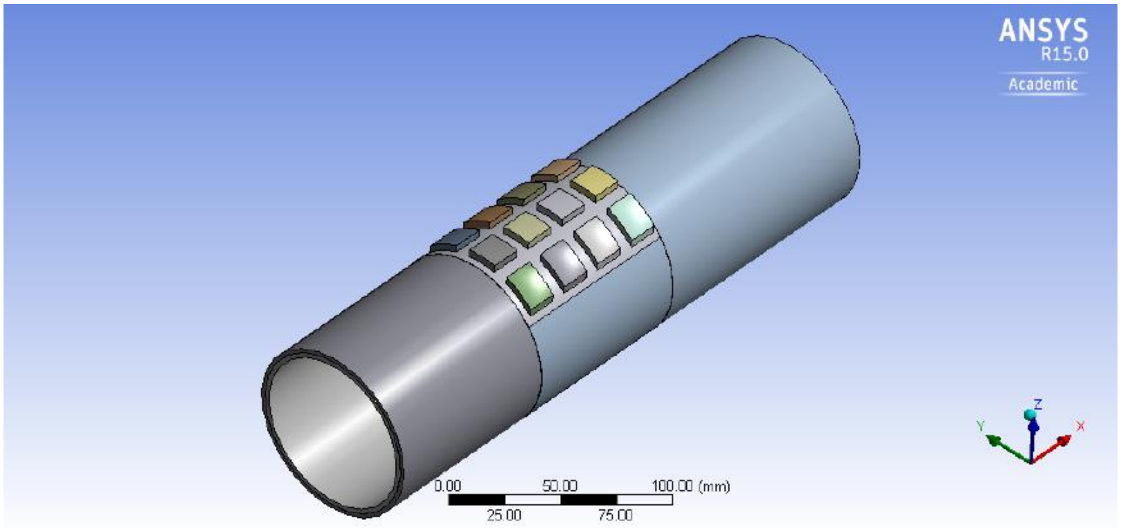

Figure 4.3: ANSYS model of the copper cylinder with thermal actuators.

For the cylindrical structure, the governing differential equation of the polyurethane layer in the radial direction is represented as follows:

$$\frac{1}{r_2}\left(\frac{\partial}{\partial r}\right)\left(r_2\frac{\partial T}{\partial r}\right) = \frac{k_2}{\rho_2 c}\left(\frac{\partial T}{\partial t}\right) \tag{4.5}$$

where:

ρ_2 = Density of polyurethane.

c = Specific heat of polyurethane.

The boundary conditions of the polyurethane layer are:

$T(r_2) = 32.15°\text{C}$

$-k\frac{dT}{dr}_{r=r_3} = h_2(T(r_3) - T_\infty)$

$T(r)_{t=0} = 31.5°\text{C}$

The model was meshed using four sizing modules in four main geometries: the copper tube, the stimulation area, the twelve actuators, and the rest of the polyurethane layer. The copper tube and the polyurethane layer were meshed using an element size of 1 cm while the actuators were

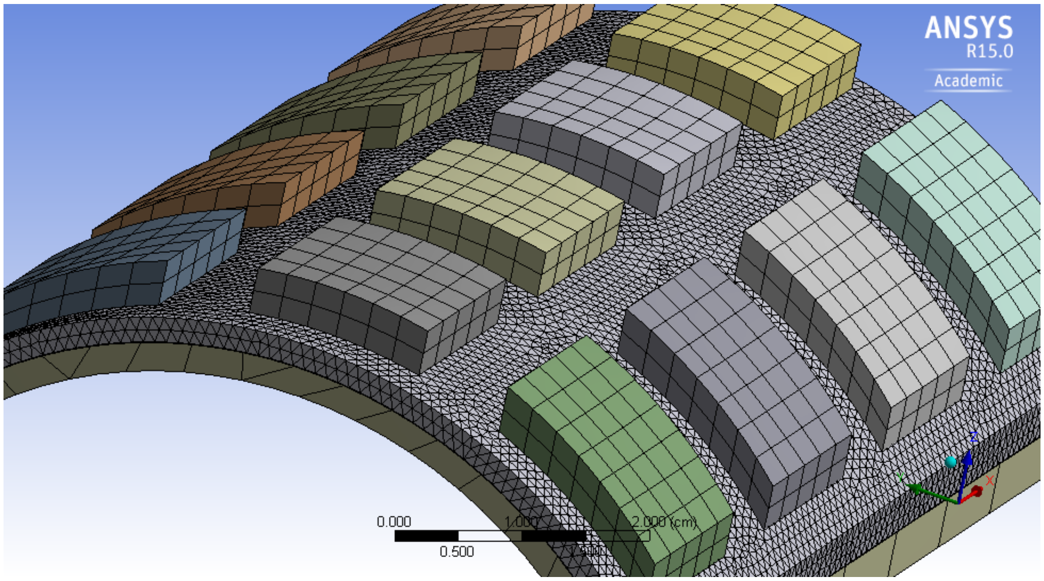

Figure 4.4: Meshing of the stimulation area.

meshed using an element size of 0.3 cm. The main focus in this simulation was to approximate the skin on the area of stimulation hence, these geometries were coarsely meshed in order to save processing time since two of which only act as temperature sources. Moreover, finer element sizes were tested on these geometries, however, they did not have a significant impact on the results. On the other hand, several element size trials were attempted on the area of stimulation ranging from 1 cm to 0.1 cm. The goal was to create fine-enough nodes inside the stimulation area and on its surfaces. Using an element size of 0.2 cm generated three nodal layers in the stimulation area, as illustrated in Figure 4.4, and resulted in 56,174 nodes in the model, hence, a 0.2 cm element size was implemented. A 0.1 cm element size was also tested and resulted in 221,360 nodes, however, it did not add a significant change on the final results. Also, the finer mesh increased the processing time significantly. The generated mesh of the model has a fine relevance center, high smoothing factor, and slow transition between the nodes. Appendix C shows the effect of the number of nodes on the temperature readings under one of the actuators, as well as the element quality in the model.

Five temperature modules, one convection module, and one insulation module were applied to govern the boundary conditions of the simulation. The initial temperature was set at 31.5°C which represents the surface temperature of the skin. The first temperature module was applied on the copper tube, keeping its operating temperature at 32.15°C which is the calculated temperature at the core the cylindrical structure. Because of the good thermal conductivity of copper, the temperature differences across the tube wall were neglected. The other four temperature modules were used to apply the continuous cooling sequence on the twelve actuators. The heating/cooling pattern was applied diagonally in the actuators as illustrated in Figure 3.3(b), using the 30/10, 12/7 and 45/15 heating/cooling rates. The convection module was applied on the surface of the skin simulating the environment around the forearm. The convective heat transfer coefficient was set to $10\,W/mK$ at 23°C ambient temperature. The insulation module was applied on surfaces of both ends of the model forcing the heat to be dissipated radially across the copper and the skin. The transient thermal analysis of the model had 24 steps and 240 seconds end time for the 30/10 heating/cooling rate resulting in a step size of 10 seconds. Each step was divided into 20 substeps. Different substep sizes were also tested to investigate the effect of time discretization on the temperature readings. The results did not show a difference in temperature readings when substeps were changed.

Four temperature probes were added in the stimulation area to record the temperatures under, and between, the actuators. The probes were initially placed 0.05 cm under the surface of the stimulation area. However, the temperatures were recorded at different depths from 0 cm to 0.2 cm. These temperature recordings were later compared to the actual thermistor readings from the physical experiment.

4.3.3 Physical Validation

In order to validate the results of the simulation, where the twelve-channel dynamic thermal display was used on an approximate model of the skin, a physical experimental model of the simulation was built. The physical model of the forearm was constructed using a 30.5 cm long copper tube. The skin was approximated using a 30 cm x 48 cm polyurethane sheet. A water bath and a pump were used to run 32.2°C warm water in the copper tube to generate heat in the physical model based on the results of the analytical solution. The relatively high thermal conductivity of copper decreased the transient time that took the physical model to warm up to the desired temperature.

4.3.3.1 Assembly

The copper tube was connected to the water bath and pump using hoses, rubber couplings, and plastic fittings on both ends. The polyurethane sheet was tightly applied on the tube as shown in Figure 4.5. The four thermistors are immersed in the 0.2 cm thick polyurethane to record the temperature of the material at four different locations. Similar to the temperature probes in the simulation, the thermistors were placed so that two would read the temperature of the skin directly under two different actuators while the other two thermistors were placed in between the actuators. Because of the nature of the preparation procedure, the depth of each thermistor was not known during the experiments. The depths were determined after the experiments by cutting the polyurethane sheet using a stencil knife. Comparisons of the depths and temperature readings were later conducted with the results of the simulation.

The thermal display apparatus was placed on top of the skin and fixed around the copper tube. The apparatus was aligned with the skin's thermistors to ensure that two thermistors are placed under two actuators and another two are placed between the actuators. The whole system was then elevated 10 cm and was placed horizontally on a wooden structure for the ease of access.

4.3.3.2 Experimental Procedure

At the beginning of each experiment, the water bath pumped 32.2°C warm water through the copper tube that is covered with a 0.2 cm thick sheet of polyurethane. The water bath operating temperature fluctuated between 32°C and 32.2°C however, the surface temperature of the model was not affected by the fluctuation. Moreover, the surface temperature was tested at the beginning and end of each experiment using a non-contact laser temperature gun. When the surface temperature settled on 31.5°C, the thermal display apparatus was applied on the physical model.

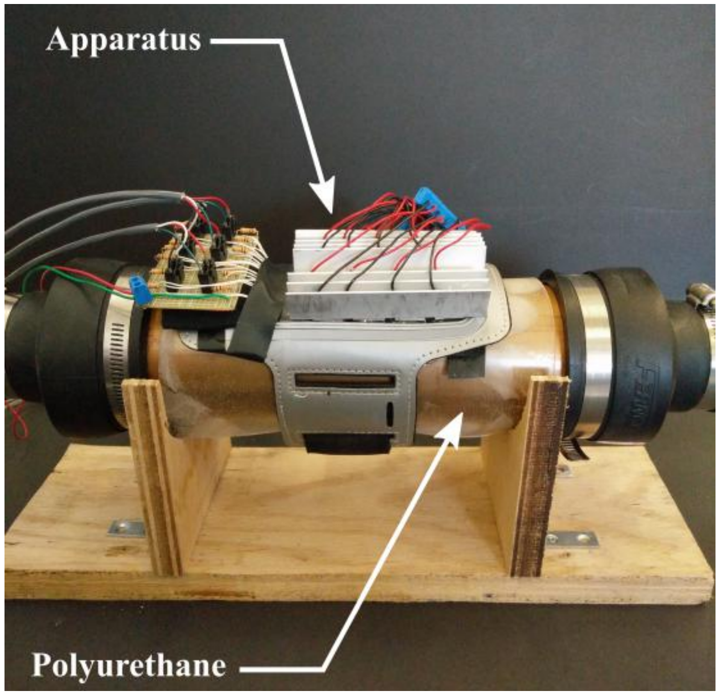

Figure 4.5: The setup used for the experiments.

The experimental set was divided into ten phases using a 30/10 diagonal heating/cooling time rate at ten different average temperatures from 25.5°C to 33.5°C. Each phase of the experimental set lasted four minutes. The first minute of each phase was not analyzed in order to allow the thermal stimulation to settle on consistent heating/cooling cycles. The temperature readings of the four thermistors in polyurethane were then recorded every 100 ms throughout the last three minutes. The surface temperature of the polyurethane was measured at the end of each experiment to ensure no temperature build-ups occurred in the skin.

4.4 Results

4.4.1 Finite Element Model

In this model, the simulation predicted the temperature of the polyurethane layer in the area under the thermal stimuli. The results showed that the average surface temperature of the polyurethane layer was 31.5°C which was the desired skin temperature. Figure 4.6 shows the temperature readings of the probes in the area under the actuators at 0.2 mm, 1 mm, and 1.8 mm

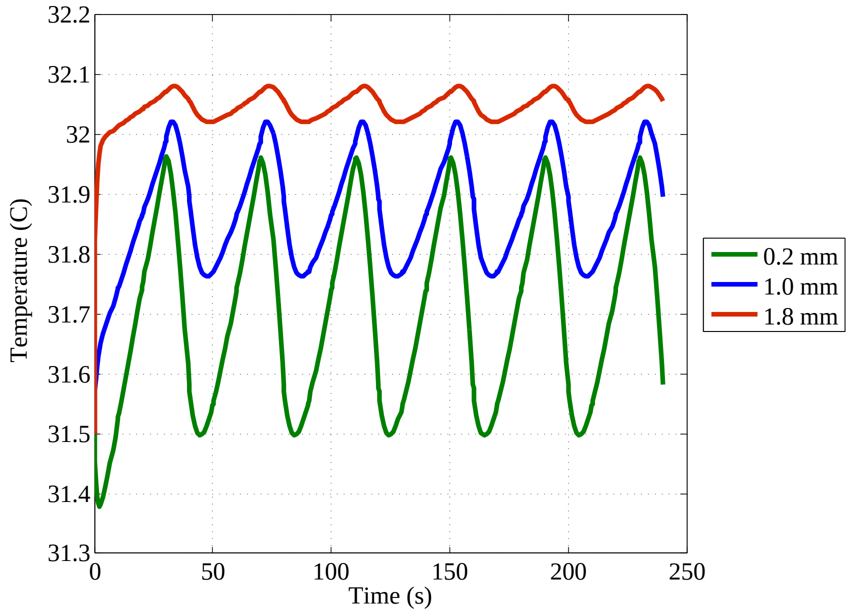

Figure 4.6: Temperature inside the polyurethane layer under one of the actuators at three different depths.

under the surface of the polyurethane layer using 30/10 heating/cooling rate. The oscillation of the temperature decreases with the depth of the approximated skin layer, however the average temperature increases as the probes get closer to the surface of the copper tube. Similarly, the temperature readings of the area between the actuators increase with the depth of the skin layer, as illustrated in Figure 4.7. Appendix D contains temperature graphs showing the relationship between temperature and depth for areas under the actuators.

Different patterns, as illustrated in Figure 3.3 (b) (c) were also simulated using 9:3 heating/cooling ratio. The results did not show any noticeable difference in the temperature readings between the ratios. Furthermore, the 21/7 and 45/15 heating/cooling rates were investigated. Figure 4.8 illustrates the difference between the temperature readings under an actuator among the three heating/cooling rates.

4.4.2 Physical Experiments

Four thermistors were used to validate the results of the simulation. Figure 4.9 shows the temperature readings of a thermistor under one of the actuators using diagonal 30/10

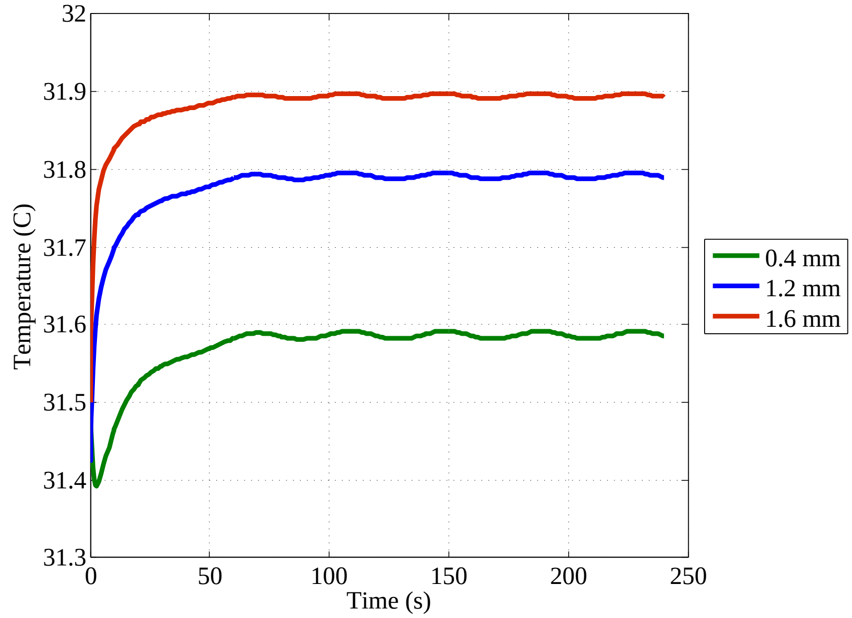

Figure 4.7: Temperature readings inside the polyurethane layer between the actuators at four different average temperatures of thermal stimuli.

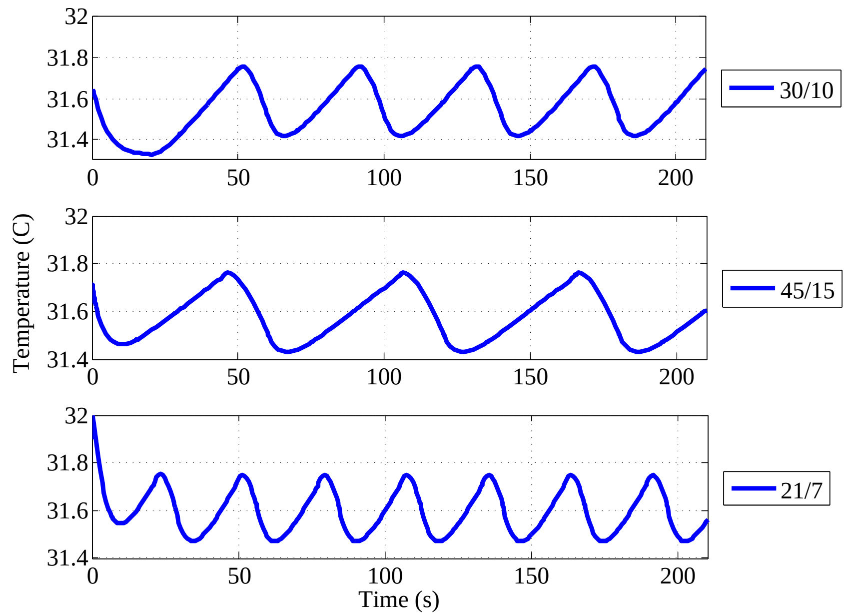

Figure 4.8: Temperature readings at different heating/cooling rates.

heating/cooling rate at different average temperatures of thermal stimuli. The readings show that the temperature of the skin fluctuated within 0.2°C under the actuators. The readings also reveal that the temperature under the actuators increases as the average temperature of thermal stimuli increases. Furthermore, the temperature readings of the thermistors located between the actuators also increase as the average stimuli temperature increases, however, the fluctuations in the readings are more subtle as illustrated in Figure 4.10.

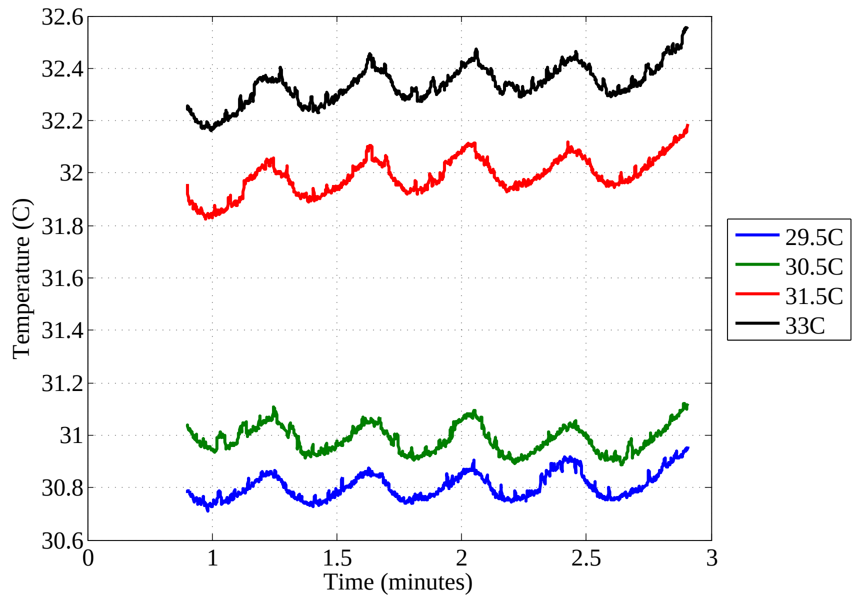

Figure 4.9: Temperature readings inside the polyurethane layer under one of the actuators at four different average temperatures of thermal stimuli.

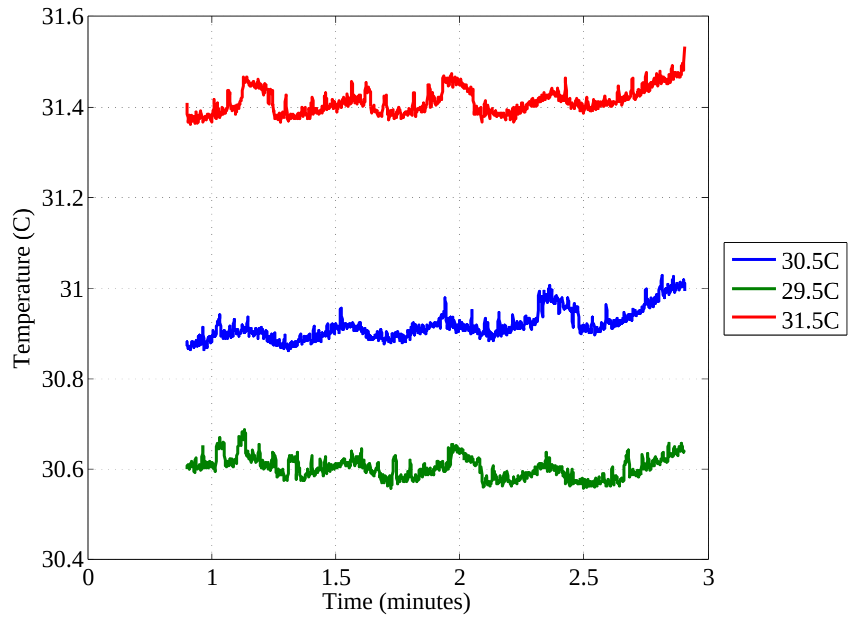

Figure 4.10: Temperature readings inside the polyurethane layer between the actuators at three different average temperatures of thermal stimuli.

4.4.3 Comparison

The experimental setup served as a physical validation for the simulation, therefore, a comparison was conducted between the temperature readings of the experiment and the results of the simulation. A stencil knife was used to cut the polyurethane layer near the thermistors to measure their depths in the material. The results showed that all four thermistors were between 1.6 and 1.8 mm below the surface of polyurethane layer. Figure 4.11 shows that the temperatures of the physical experiment and the simulation model at 1.6 mm under an actuator had similar readings but were out of phase. Figure 4.12 represents the temperature readings in the physical experiment and the simulation between the actuators. The comparison shows that both temperatures were constant in that area, however, there was a 0.5°C difference between them.

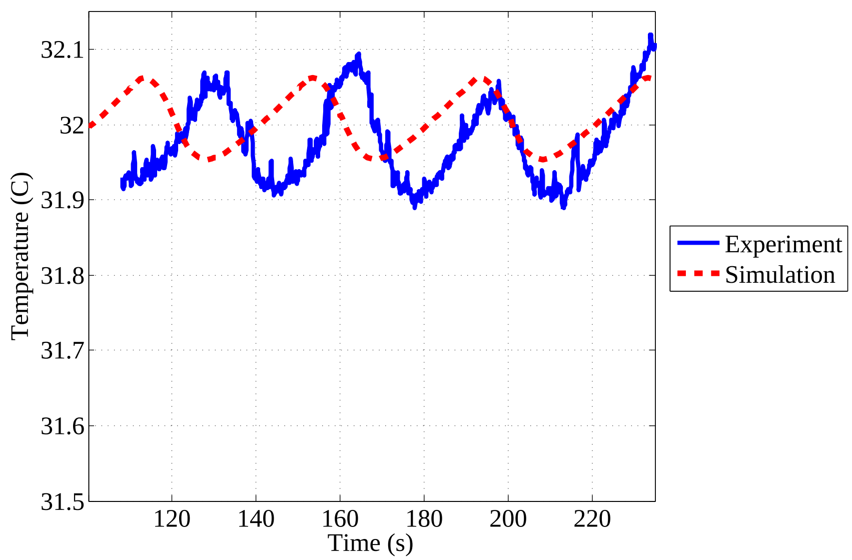

Figure 4.11: The temperature difference between the experiment and the simulation 1.6 mm under an actuator.

4.5 Discussion

The results of the simulation showed that the temperature on the surface of the skin remained at 31.5°C throughout the simulation which suggests that there was no actual heating occurring on the skin, and that the thermal display did not change the average temperature in the area of stimulation. Similar to the applied pattern, the readings under the actuators showed that the temperature was cooling quickly and warming slowly within 0.2°C which is an indication that the effect of continuous cooling was still present at 1.0 mm under the polyurethane layer. Even though the effect of continuous cooling lost 80% of its efficiency at this depth, these results can give an indication about the intensity of this method of stimulation at different depths of the skin. However, hot and cold receptors are usually located between 0.2 mm and 0.5 mm under the skin [90] [91] which suggests that the efficiency of this the continuous cooling should be much higher.

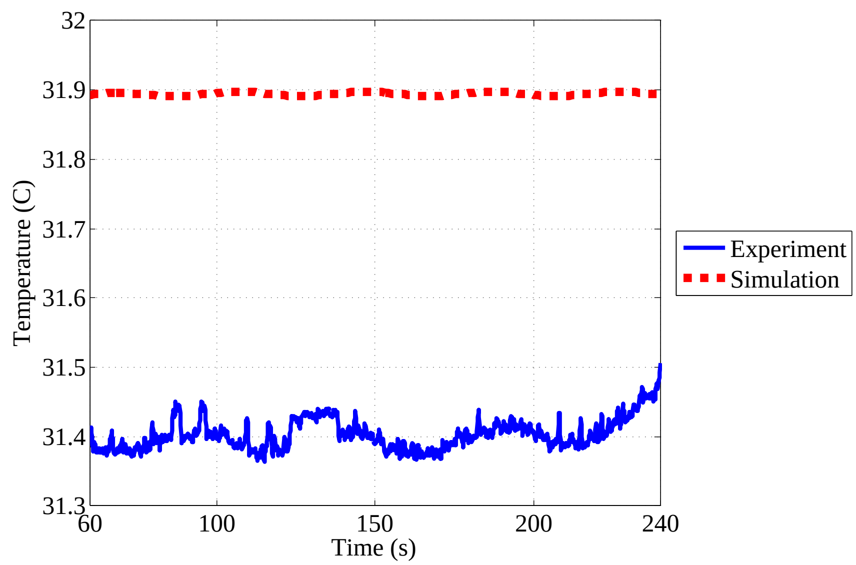

Figure 4.12: The temperature difference between the experiment and the simulation 1.6 mm under the area between the actuators.

The simulation results also showed that the temperature readings in the areas under and between the actuators increased as the depths of the temperature probes increased. In fact, the fluctuations of the readings tended to taper off as the probes became closer to the copper tube. Additionally, the temperature was more constant between the actuators which indicates that approximately 44.4% of the stimulation area did not perceive the continuous cooling effect that is associated with temperature change. However, the unstimulated area should not affect the overall sensation of continuous cooling. Studies have shown that the thermoreceptors are poor at discriminating between two spatially divided stimuli [71] [92].

Furthermore, the model can be modified to study the effect of spatial summation. Studies have shown that thermal threshold is inversely related to the area of stimulation [53]. However, this relation is less distinct for the perception of cold [67] [93]. Spatial summation can be further investigated with the model used in this study. The actuators' layout can produce a combination of different sizes and shapes of thermal stimulation to test warm and cold thresholds on areas between 2 cm^2 and 48.53 cm^2. Moreover, the size of the actuators can be increased or decreased in a way that keeps the total area of stimulation constant to investigate the effect of spaces between the actuators and whether the thermal intensity changes. In contrast, the total area of stimulation can be increased by adding more actuators to the system to study the effect of the stimulation area on the temperature distribution and the overall perception of cold. This type of actuator can alternatively be replaced by a hot and cold liquid channels system to generate the same effect of continuous cooling. The simulated model will provide the ability to test efficiency of such a system and whether it can be a practical replacement to the thermoelectric devices which are currently used.

On the other hand, the results of the physical model showed differences in the temperature readings between the areas that are located under the actuators and the areas between the actuators, as illustrated in Figure 4.9 and 4.10. All of the temperature readings in the experiments were recorded using 30/10 heating/cooling rate with a diagonal pattern. The temperature under the actuators showed that the effect of continuous cooling is still present even at 1.6 mm under the skin, whereas the temperature between the actuators remained constant with different stimuli temperatures.

The results of the physical experiments were very similar to the findings of the simulation model. This similarity is best illustrated in Figure 4.11 where both results had the same behavior even though they were out of phase. This lag was caused by the time delay associated with the proportional control system of the stimuli that depended on the temperature feedback of the thermistors. Figure 4.12 also shows a comparison between the temperatures of the model and the experiments which shows that both temperatures were constant in the area between the actuators.

However, there was an average difference of 0.5°C between both results. The comparison also showed subtle fluctuations in the temperature recorded from the experiments. These differences and fluctuations may have been caused by the possibility that the wirings of the thermistors might have been directly exposed to the actuators. Due to the conductive nature of these wires, some temperature variations could have been conveyed to the thermistors which led to the difference and fluctuation in the temperature. This problem can be avoided in the future by fully immersing the thermistors and the wirings in the polyurethane sheet horizontally during the preparation process. The polyurethane layer should provide some insulation to the thermistors' wirings and connectors. Another way for insulation is to apply heat shrink tubings on the wirings.

The physical setup can be further improved to achieve more accurate results. For instance, during the making process of the polyurethane sheet, it was noticed that micro air bubbles formed and were trapped in the material while it cured. To minimize the likelihood of air bubbles forming in polyurethane layer, the material can be heated before curing to release the excess air. A light vibration can also be applied on the mold prior to pouring the material to release air from it. Another suggestion to improve the results of the experiments is to add more temperature sensors in the skin-like layer. The data acquisition device that was used to collect the temperatures had 16 analog inputs, 12 of which were allocated to controlling the thermal display device hence, due to this limitation, it was not possible to add more than four sensors. This number was sufficient enough to record the temperature at different stimulation areas, however, more sensors will be needed to monitor more locations in the skin.

The 21/7 and 45/15 rates were also tested in the simulation using the diagonal pattern. The results showed that all of these heating/cooling rates had the same amplitude as represented in Figure 4.8. The figure also shows that the 45/15 rate had the least heating and cooling cycles during the same time interval. In the experiments, discussed in chapter 3, subjects reported that 30/10 and 21/7 heating/cooling rates were statistically significantly colder than the 45/15 rate as illustrated in Figure 3.8. The latter results may be related to the fact that the 45/15 rate had less cooling cycles and longer periods between them which made the effect of continuous cooling relatively irregular.

Irregular and inconsistent perception of cold was also observed in the experiments, discussed in chapter three, at which different heating/cooling ratios were applied, as illustrated in Figure 3.11. Subjects perceived cooling from two, three, or four actuators depending on the ratio that was being applied on the skin. To overcome this problem, a new pattern can be used such that one cooling cycle reaches the cold threshold by the time the previous cooling cycle switched to heating without changing the average temperature of skin. The simulation can provide more information about the temperature readings at the times where subjects provided a feedback to the thermal stimuli which may help us investigate whether or not the cold perception was indeed inconsistent. Additionally, the proposed overlapping pattern can also be tested on the model to verify the continuity of the cold perception.

The results of the simulation gave some explanation of the efficiency and the intensity as well as the spatial distribution of the method of continuous cooling. These results were also validated in the physical experiment which showed similar information about the temperature distribution inside the skin layer. These findings suggest that the simulation can be harnessed to further analyze more advanced and technically challenging versions of this particular type of thermal displays like adding more actuators and temperature probes to the system. Additionally, the simulation can be used to observe the thermal behavior of the skin layer when a continuous heating stimulus is applied. The continuous heating effect occurs when some actuators are slowly cooling while others are quickly warming without causing a change in the average temperature of the skin as explained in section 3.6. Modeling this type of thermal stimuli will provide an insight of the temperature distribution inside the skin. Furthermore, knowing the temperature readings at different depths of the skin, and the thermal conductivity of the skin will provide useful information about the heat flux that is transferred out or into the skin. The model can calculate the heat flux that is transferred between the actuators and the skin which is the driving factor of temperature perception. The calculated amount and direction of heat flux from the model can later be used to control the thermal actuators more accurately via a flux meters instead of depending on a temperature feedback.

4.6 Conclusion

This chapter presented a simulation of an approximate model of the skin that was developed to investigate the thermal perception of the skin when asymmetrical hot and cold stimuli are applied. The results showed that the average surface temperature of the skin did not change during the thermal stimulation. The simulation also showed that the effect of the continuous cooling method was still present at depths up to 1.8 mm under the surface of the skin. A physical model was built and used to validated the simulation. The results of the physical experiments were similar to the findings of the simulation. It was shown that the simulation model can be utilized to predict the temperature and thermal behavior of the skin in different scenarios of this particular type of thermal stimuli.

Chapter 5: Conclusions and Future Work

Thermal perception occurs as a result of the difference in the temperatures between the surface of the skin and an object. It is because of this difference we are able to detect and identify thermal cues about that object. In this dissertation, I presented a novel method that can generate a unique thermal display that may be able to help us better understand temperature perception in the field of thermal haptics.

5.1 Conclusions

I started this dissertation by investigating the general sense of temperature perception and the level of comfort in closed environments. Several field surveys were conducted studying the ability of occupants of these environments to perceive and predict temperature. The surveys were carried out in two locations in the United States and Jordan. The surveys also investigated the influence of culture and climate on temperature perception and thermal comfort. The results showed statistically significant differences in perception and temperature prediction between genders. Female subjects were generally more sensitive to temperature drop and more accurate in predicting the operating indoor temperature. However, the prediction of male and female participants became more accurate when the indoor temperature increased. The results also showed a statistically significant difference in temperature perception, measured by the thermal comfort scale, when the temperature increased by 3°C in the summer surveys and when the temperature decreased by the same amount during the fall surveys. However, neither of these differences exceeded the level of comfort during the surveys. This finding suggests that there is a range of "neutral" sensation which allows us to slightly increase the indoor temperature in summer or decrease it in winter without sacrificing the level of comfort.

The previous findings encouraged a focus on an individual level by applying temperature changes on large areas of the skin in a way that this change is perceived without changing the level of comfort of the body. The idea was to apply dynamic localized temperature changes on the forearm to create a sensation of a continuous cooling or heating. Two thermal display devices of four and 12 actuators were successfully designed and constructed to test this method through a series of experiments on over 20 participants. The design of the thermal display devices allowed the testing of several heating and cooling rates and ratios as well as different patterns of stimuli. The results showed that the continuous cooling and heating sensations were successfully perceived. This sensation was perceived without causing a change in the average temperature on the area of stimulation which is an important advantage for this method. It will allow us to test the possibility of dissipating heat from or into the body in order to expunge internal heat and start to decrease the core temperature. By applying the changing temperature patterns as discussed in this dissertation, it may be possible to affect the body's perception of temperature and, maybe eventually, affect a change in the thermoregulation channels.

This method demonstrates the use of the nonlinear phenomenon of temperature perception of the skin. It has a great potential of conveying the temperature of objects in virtual reality applications without applying excessive temperature differences on the skin. Since human skin is more adept at detecting changes in temperature or heat fluxes than actual absolute temperatures, it is proposed that a device that could convey a sensation of constant heating or cooling would be highly effective in conveying a clearly discernible, but not overwhelming, signal.

These results provided the motivation to further develop a finite element model to simulate the effect of the twelve-channel thermal display device on the skin. A model of the forearm was simulated using a layer of polyurethane rubber, approximating the skin model, and a copper tube, representing the core of the forearm. The thermal display device, however, was simulated using twelve blocks of aluminum that had the same dimensions of the real actuators and were fixed on top of the skin. In the simulation, the continuous cooling thermal display was applied using three heating and cooling rates. The results showed that the average surface temperature of the skin model did not change when the stimuli were applied. The results also showed that the effect of continuous cooling was present at depths up to 1.8 mm below the surface of the skin.

To validate these results, a physical model of the forearm was constructed using a copper tube and a thin layer of polyurethane rubber as a skin. Several experiments of a continuous cooling effect were successfully conducted using the physical model. The results of the experiments showed that the temperature readings of the skin followed the same trend of the temperatures that were observed in the simulation. Similar to the simulation results, the physical experiments also showed that the temperature readings in the area under the thermal stimuli increased as the average applied temperature increased. The trend of the readings, however, did not change with the increasing temperature. These results show that the thermal display has a temporary effect on the areas that are located directly under the actuators, but it does not appear to have the same effect on the areas between the actuators.

These findings can give us more information about the importance of the actuators' size and how they are interspaced during the stimuli, which may help in delivering a more efficient continuous cooling sensation in the future. The results also suggest that a simulation of continuous cooling or heating stimuli can be used to further investigate other cases or conditions of this method at which experimentations are challenging, or not possible, to conduct in the real world. It provides us with a safe and an ideal environment where this method can be tested over a large range of average applied temperatures. The results of the simulation could have a great impact on our understanding of temperature perception and the spatial resolution of the skin. For example, the thermal actuators can be reshaped or resized to test the effect of the sizes and shapes of the actuators on perception. More actuators can also be added to cover a larger area of stimuli.

5.2 Future Work

The future efforts can be aimed to designing and building an improved and more advanced thermal display devices. The current device has twelve actuators that are individually controlled by temperature sensors. Therefore, the generated thermal perception effect has been described in terms of temperature differences, however, it will be most effective if implemented in terms of heat flux since human skin measures the rate of heat flux. To do that, the temperature sensors should be replaced with flux meters that can be fabricated using two resistance temperature detectors applied on both sides of a thin film with known thermal conductivity. This method will give us a better control over the actuators by applying precise amounts of heat flux on the skin.

It has been shown that a continuous heating sensation can be perceived using slowly cooling actuators and quickly heating actuators. The results however, showed that there is a range at which the continuous heating effect is most active. For example, the experiments showed that a 33°C continuous heating display was not statistically significantly warmer than a constant stimulus at the same temperature. Further, a 29°C continuous heating display had a cooling effect on subjects. To investigate the different effects of operating temperatures, the continuous heating effect can be tested at stimuli temperatures ranging from 25°C to 35°C and compared with constant stimuli at the same temperatures. The results will provide a heat perception map that shows the range of temperatures at which this method is most efficient.

Finally, the finite element model can be used in the future to increase the number of actuators that are used in the thermal display. For instance, a model of 24 actuators can be tested to investigate the effect of the stimulation area on the perception of temperature. Furthermore, the model itself can be modified to test the perception in different environments and conditions such as higher or lower room temperatures.

List of References

[1] Daniel S Moran and Liran Mendal. Core temperature measurement. *Sports Medicine*, 32(14):879–885, 2002.

[2] Mike Zerkus, Bill Becker, Jon Ward, and Lars Halvorsen. Thermal feedback in virtual reality and telerobotic systems. 1994.

[3] Graham Wilson, Stephen Brewster, Martin Halvey, and Stephen Hughes. Thermal icons: evaluating structured thermal feedback for mobile interaction. In *Proceedings of the 14th international conference on Human-computer interaction with mobile devices and services*, pages 309–312. ACM, 2012.

[4] Hsin-Ni Ho and Lynette A Jones. Development and evaluation of a thermal display for material identification and discrimination. *ACM Transactions on Applied Perception (TAP)*, 4(2):13, 2007.

[5] ASHRAE Handbook. Fundamentals 2013. *Atlanta, USA: ASHRAE*, 2013.

[6] Lynette Jones, Michal Berris, et al. The psychophysics of temperature perception and thermal-interface design. In *Haptic Interfaces for Virtual Environment and Teleoperator Systems, 2002. HAPTICS 2002. Proceedings. 10th Symposium on*, pages 137–142. IEEE, 2002.

[7] Ernst Heinrich Weber. *Tastsinn und gemeingefühl*. Number 149. W. Engelmann, 1905.

[8] Herbert Hensel and Yngve Zotterman. The response of mechanoreceptors to thermal stimulation. *The Journal of physiology*, 115(1):16, 1951.

[9] D. R Kenshalo. Correlations of temperature sensitivity in man and monkey, a first approximation. *Sensory functions of the skin with special reference to man*, pages 305–330, 1976.

[10] Rom McGuffin, Rick Burke, Charlie Huizenga, Hui Zhang, Andreas Vlahinos, and George Fu. Human thermal comfort model and manikin. *Center for the Built Environment*, 2002.

[11] Taeyoung Han, Linjie Huang, Sean Kelly, Charlie Huizenga, and Hui Zhang. Virtual thermal comfort engineering. *Center for the Built Environment*, 2001.

[12] Larry Berglund. Mathematical models for predicting thermal comfort response of building occupants. In *Ashrae Journal-American Society of Heating Refrigerating and Air-Conditioning Engineers*, volume 19, pages 38–38. Amer Soc Heat Refrig Air-Connditioning Eng INC 1791 Tullie Circle NE, ATLANTA, GA 30329, 1977.

[13] AP Gagge, Y Nishi, and RR Gonzalez. Standard effective temperature-a single temperature index of temperature sensation and thermal discomfort. *Proceedings of the CIB Commission W*, 45:229–250, 1972.

[14] Noël Djongyang, René Tchinda, and Donatien Njomo. Thermal comfort: A review paper. *Renewable and Sustainable Energy Reviews*, 14(9):2626–2640, 2010.

[15] Poul O Fanger et al. Thermal comfort. analysis and applications in environmental engineering. *Thermal comfort. Analysis and applications in environmental engineering.*, 1970.

[16] MA Humphreys. A study of the thermal comfort of primary school children in summer. *Building and Environment*, 12(4):231–239, 1977.

[17] Richard J De Dear, Gail Schiller Brager, James Reardon, Fergus Nicol, et al. Developing an adaptive model of thermal comfort and preference/discussion. *ASHRAE transactions*, 104:145, 1998.

[18] N Yamtraipat, J Khedari, and J Hirunlabh. Thermal comfort standards for air conditioned buildings in hot and humid thailand considering additional factors of acclimatization and education level. *Solar Energy*, 78(4):504–517, 2005.

[19] J Fergus Nicol and Michael A Humphreys. Adaptive thermal comfort and sustainable thermal standards for buildings. *Energy and buildings*, 34(6):563–572, 2002.

[20] Richard De Dear. Thermal comfort in practice. *Indoor air*, 14(s7):32–39, 2004.

[21] Stefano Paolo Corgnati, Roberta Ansaldi, and Marco Filippi. Thermal comfort in italian classrooms under free running conditions during mid seasons: assessment through objective and subjective approaches. *Building and Environment*, 44(4):785–792, 2009.

[22] C Huizenga, S Abbaszadeh, Leah Zagreus, and Edward A Arens. Air quality and thermal comfort in office buildings: results of a large indoor environmental quality survey. *Proceeding of Healthy Buildings 2006*, 3, 2006.

[23] RJ De Dear, KG Leow, and SC Foo. Thermal comfort in the humid tropics: Field experiments in air conditioned and naturally ventilated buildings in singapore. *International Journal of Biometeorology*, 34(4):259–265, 1991.

[24] Nyuk Hien Wong and Shan Shan Khoo. Thermal comfort in classrooms in the tropics. *Energy and buildings*, 35(4):337–351, 2003.

[25] Alison G Kwok and Chungyoon Chun. Thermal comfort in japanese schools. *Solar Energy*, 74(3):245–252, 2003.

[26] MJ Duever, JF Meeder, LC Meeder, and JM McCollom. The climate of south florida and its role in shaping the everglades ecosystem. *Everglades: The ecosystem and its restoration*, pages 225–248, 1994.

[27] Irina A Strigo, Franco Carli, and M Catherine Bushnell. Effect of ambient temperature on human pain and temperature perception. *The Journal of the American Society of Anesthesiologists*, 92(3):699–707, 2000.

[28] Kate E Charles. Fanger's thermal comfort and draught models. 2003.

[29] Sami Karjalainen. Gender differences in thermal comfort and use of thermostats in everyday thermal environments. *Building and environment*, 42(4):1594–1603, 2007.

[30] BW Jones, K Hsieh, and M Hashinaga. The effect of air velocity on thermal comfort at moderate activity levels. *ASHRAE Trans.;(United States)*, 92(CONF-8606125-), 1986.

[31] C Cândido, RJ De Dear, Roberto Lamberts, and L Bittencourt. Air movement acceptability limits and thermal comfort in brazil's hot humid climate zone. *Building and Environment*, 45(1):222–229, 2010.

[32] Amory Lovins. Air-conditioning comfort: Behavioral and cultural issues. 1992.

[33] John F Busch. A tale of two populations: thermal comfort in air-conditioned and naturally ventilated offices in thailand. *Energy and buildings*, 18(3):235–249, 1992.

[34] Alison G Kwok, James Reardon, and Karl Brown. Thermal comfort in tropical classrooms/discussion. *ASHRAE Transactions*, 104:1031, 1998.

[35] Helen Chapin Metz. Jordan: A country study. Library of Congress, Federal Research Division, 1989.

[36] Tyler Hoyt, Stefano Schiavon, Alberto Piccioli, Dustin Moon, and Kyle Steinfeld. Cbe thermal comfort tool. *Center for the Built Environment, University of California Berkeley, http://cbe. berkeley. edu/comforttool*, 2013.

[37] JuYoun Kwon and Jeongwha Choi. The relationship between environmental temperature and clothing insulation across a year. *International journal of biometeorology*, 56(5):887–893, 2012.

[38] Igor Knez and Sofia Thorsson. Influences of culture and environmental attitude on thermal, emotional and perceptual evaluations of a public square. *International journal of biometeorology*, 50(5):258–268, 2006.

[39] A. Manasrah, N. Crane, R. Guldiken, and K. B. Reed. Perceived cooling using asymetrically-applied hot and cold stimuli. *IEEE Transactions on Haptics*, PP(99):1–1, 2016. DOI: 10.1109/TOH.2016.2578334.

[40] Hsin-Ni Ho and Lynette A Jones. Contribution of thermal cues to material discrimination and localization. *Perception & Psychophysics*, 68(1):118–128, 2006.

[41] Barry G Green. The effect of skin temperature on vibrotactile sensitivity. *Perception & Psychophysics*, 21(3):243–248, 1977.

[42] Richard A McFarland. Relationship of skin temperature changes to the emotions accompanying music. *Biofeedback and Self-regulation*, 10(3):255–267, 1985.

[43] Paul C Castle, Adam L Macdonald, Andrew Philp, Anthony Webborn, Peter W Watt, and Neil S Maxwell. Precooling leg muscle improves intermittent sprint exercise performance in hot, humid conditions. *Journal of applied physiology*, 100(4):1377–1384, 2006.

[44] David Yarnitsky and Jose L Ochoa. Warm and cold specific somatosensory systems. *Brain*, 114(4):1819–1826, 1991.

[45] Dan R Kenshalo, Charles E Holmes, and Paul B Wood. Warm and cool thresholds as a function of rate of stimulus temperature change. *Perception & Psychophysics*, 3(2):81–84, 1968.

[46] Tomohiro Amemiya, Hideyuki Ando, and Taro Maeda. Virtual force display: Direction guidance using asymmetric acceleration via periodic translational motion. In *Eurohaptics Conference, 2005 and Symposium on Haptic Interfaces for Virtual Environment and Teleoperator Systems, 2005. World Haptics 2005. First Joint*, pages 619–622. IEEE, 2005.

[47] H Goldsmid. *Thermoelectric refrigeration*. Springer, 2013.

[48] JC Stevens. Thermal sensibility. *The psychology of touch*, pages 61–90, 1991.

[49] Graham Wilson, Martin Halvey, Stephen A Brewster, and Stephen A Hughes. Some like it hot: thermal feedback for mobile devices. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*, pages 2555–2564. ACM, 2011.

[50] Ken Parsons. *Human thermal environments: the effects of hot, moderate, and cold environments on human health, comfort and performance*. Crc Press, 2002.

[51] Barry G Green. Temperature perception and nociception. *Journal of neurobiology*, 61(1):13–29, 2004.

[52] Lynette A Jones and H-N Ho. Warm or cool, large or small? the challenge of thermal displays. *Haptics, IEEE Transactions on*, 1(1):53–70, 2008.

[53] Dan R Kenshalo, Thomas Decker, and Anne Hamilton. Spatial summation on the forehead, forearm, and back produced by radiant and conducted heat. *Journal of comparative and physiological psychology*, 63(3):510, 1967.

[54] HH Molinari, JD Greenspan, and DR Krenshalo. The effects of rate of temperature change and adapting temperature on thermal sensitivity. *Sensory processes*, 1(4):354–362, 1977.

[55] Joseph C Stevens and Lawrence E Marks. Spatial summation and the dynamics of warmth sensation. *Perception & Psychophysics*, 9(5):391–398, 1971.

[56] Ian Darian-Smith and Kenneth O Johnson. Thermal sensibility and thermoreceptors. *Journal of Investigative Dermatology*, 69(1):146–153, 1977.

[57] Ruth Defrin, Anat Benstein-Sheraizin, Adva Bezalel, Ofira Mantzur, and Lars Arendt-Nielsen. The spatial characteristics of the painful thermal grill illusion. *Pain*, 138(3):577–586, 2008.

[58] Sydney Alrutz. On the temperature-senses. *Mind*, 6(3):445–448, 1897.

[59] Torsten Thunberg. Förnimmelserne vid till samma ställe lokaliserad, samtidigt pägäende köld-och värmeretning. *Uppsala Läkfören Förh*, 1:489–495, 1896.

[60] Albert Y Leung, Mark S Wallace, Gery Schulteis, and Tony L Yaksh. Qualitative and quantitative characterization of the thermal grill. *Pain*, 116(1):26–32, 2005.

[61] Barry G Green. Synthetic heat at mild temperatures. *Somatosensory & motor research*, 19(2):130–138, 2002.

[62] AD Craig and MC Bushnell. The thermal grill illusion: unmasking the burn of cold pain. *Science*, 265(5169):252–255, 1994.

[63] Goran Pavlaković, Ina Klinke, Helena Pavlaković, Klaus Züchner, Antonia Zapf, Cornelius G Bachmann, Bernard M Graf, and Thomas A Crozier. Effect of thermode application pressure on thermal threshold detection. *Muscle & nerve*, 38(5):1498–1505, 2008.

[64] ASHRAE Standard. Standard 55-2004. thermal environment conditions for human occupancy. ashrae. *Atlanta, USA*, 2010.

[65] H Hensel and T Huopaniemi. Static and dynamic properties of warm fibres in the infraorbital nerve. *Pflügers Archiv*, 309(1):1–10, 1969.

[66] H Hensel and RD Wurster. Static behaviour of cold receptors in the trigeminal area. *Pflügers Archiv*, 313(2):153–154, 1969.

[67] Joel D Greenspan and Dan R Kenshalo. The primate as a model for the human temperature-sensing system: 2. area of skin receiving thermal stimulation (spatial summation). *Somatosensory research*, 2(4):315–324, 1985.

[68] Ilpo Kojo and Antti Pertovaara. The effects of stimulus area and adaptation temperature on warm and heat pain thresholds in man. *International journal of neuroscience*, 32(3-4):875–880, 1987.

[69] Louise M Harding and Alison R Loescher. Adaptation to warming but not cooling at slow rates of stimulus change in thermal threshold measurements. *Somatosensory & motor research*, 22(1-2):45–48, 2005.

[70] David K Lee, Sandra LB McGillis, and Joel D Greenspan. Somatotopic localization of thermal stimuli: I. a comparison of within-versus across-dermatomal separation of innocuous thermal stimuli. *Somatosensory & motor research*, 13(1):67–71, 1996.

[71] Richard H Taus, Joseph C Stevens, and Lawrence E Marks. Spatial localization of warmth. *Perception & Psychophysics*, 17(2):194–196, 1975.

[72] Katsunari Sato and Takashi Maeno. Presentation of rapid temperature change using spatially divided hot and cold stimuli. *Journal ref: Journal of Robotics and Mechatronics*, 25(3):497–505, 2013.

[73] Joseph C Stevens and Lawrence E Marks. Spatial summation of cold. *Physiology & Behavior*, 22(3):541–547, 1979.

[74] Joseph C. Stevens and Kenneth K. Choo. Temperature sensitivity of the body surface over the life span. *Somatosensory & motor research*, 15(1):13–28, 1998.

[75] KO Johnson, I Darian-Smith, and C LaMotte. Peripheral neural determinants of temperature discrimination in man: a correlative study of responses to cooling skin. *Journal of Neurophysiology*, 36(2):347–370, 1973.

[76] R Melzack, G Rose, and D McGinty. Skin sensitivity to thermal stimuli. *Experimental neurology*, 6(4):300–314, 1962.

[77] Wouter M Bergmann Tiest and Astrid ML Kappers. Thermosensory reversal effect quantified. *Acta psychologica*, 127(1):46–50, 2008.

[78] Katri Salminen, Veikko Surakka, Jukka Raisamo, Jani Lylykangas, Roope Raisamo, Kalle Mäkelä, and Teemu Ahmaniemi. Cold or hot? how thermal stimuli are related to human emotional system? In *Haptic and Audio Interaction Design*, pages 20–29. Springer, 2013.

[79] Shuzo Murakami, Shinsuke Kato, and Jie Zeng. Combined simulation of airflow, radiation and moisture transport for heat release from a human body. *Building and environment*, 35(6):489–500, 2000.

[80] Hsin-Ni Ho and Lynette A Jones. Thermal model for hand-object interactions. In *Haptic Interfaces for Virtual Environment and Teleoperator Systems, 2006 14th Symposium on*, pages 461–467. IEEE, 2006.

[81] John Rugh and Desikan Bharathan. Predicting human thermal comfort in automobiles. In *Proceedings of the 7th Vehicle Thermal Management Systems Conference, Paper*, pages 01–2008, 2005.

[82] John P Rugh, Robert B Farrington, Desikan Bharathan, Andreas Vlahinos, Richard Burke, Charlie Huizenga, and Hui Zhang. Predicting human thermal comfort in a transient nonuniform thermal environment. *European journal of applied physiology*, 92(6):721–727, 2004.

[83] Dusan Fiala, Kevin J Lomas, and Martin Stohrer. Computer prediction of human thermoregulatory and temperature responses to a wide range of environmental conditions. *International Journal of Biometeorology*, 45(3):143–159, 2001.

[84] Z Wang, Y Li, YL Kowk, and CY Yeung. Mathematical simulation of the perception of fabric thermal and moisture sensations. *Textile Research Journal*, 72(4):327–334, 2002.

[85] SKS Boetcher, EM Sparrow, and MV Dugay. Characteristics of direct-contact, skin-surface temperature sensors. *International Journal of Heat and Mass Transfer*, 52(15):3799–3804, 2009.

[86] Lu Hu, Ashish Gupta, Jay P Gore, and Lisa X Xu. Effect of forced convection on the skin thermal expression of breast cancer. *Journal of biomechanical engineering*, 126(2):204–211, 2004.

[87] Patrick T McKnight. Finite element analysis of thermoelectric systems with applications in self assembly and haptics. 2010.

[88] Myron L Cohen. Measurement of the thermal properties of human skin. a review. *Journal of investigative dermatology*, 69(3):333–338, 1977.

[89] Theodore L Bergman and Frank P Incropera. *Introduction to heat transfer*. John Wiley & Sons, 2011.

[90] Robert K Adair. A model of the detection of warmth and cold by cutaneous sensors through effects on voltage-gated membrane channels. *Proceedings of the National Academy of Sciences*, 96(21):11825–11829, 1999.

[91] JW Ring and Richard Dear. Temperature transients: a model for heat diffusion through the skin, thermoreceptor response and thermal sensation. *Indoor Air*, 1(4):448–456, 1991.

[92] Gi-Hun Yang, Dong-Soo Kwon, and Lynette A Jones. Spatial acuity and summation on the hand: The role of thermal cues in material discrimination. *Perception & Psychophysics*, 71(1):156–163, 2009.

[93] Sherry L Berg. *Magnitude estimates of spatial summation for conducted cool stimuli along with thermal fractionation and a case of secondary hyperalgesia.* PhD thesis, ProQuest Information & Learning, 1979.

Appendices

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Doyle, Hannah <HDoyle@ashrae.org> Thu, May 5, 2016 at 1:18 PM
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Best regards,

Hannah Doyle

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Hannah Doyle
Conference Programs Assistant
ASHRAE
1791 Tullie Circle NE
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Date: Dec 31, 1969

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Appendix C: Temperature Readings vs Number of Nodes

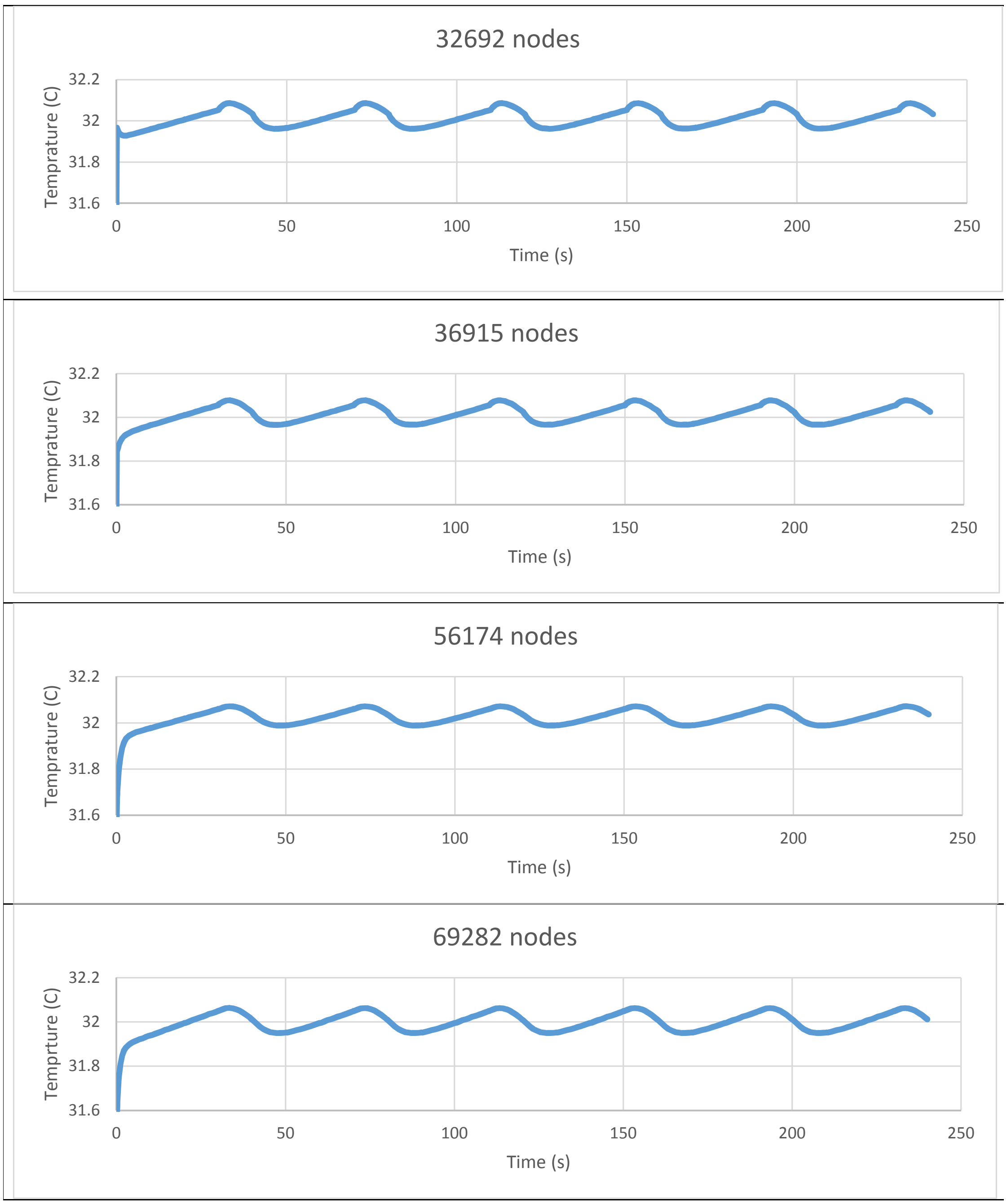

Figure C.1: Temperature readings versus the number of nodes in the stimulation area.

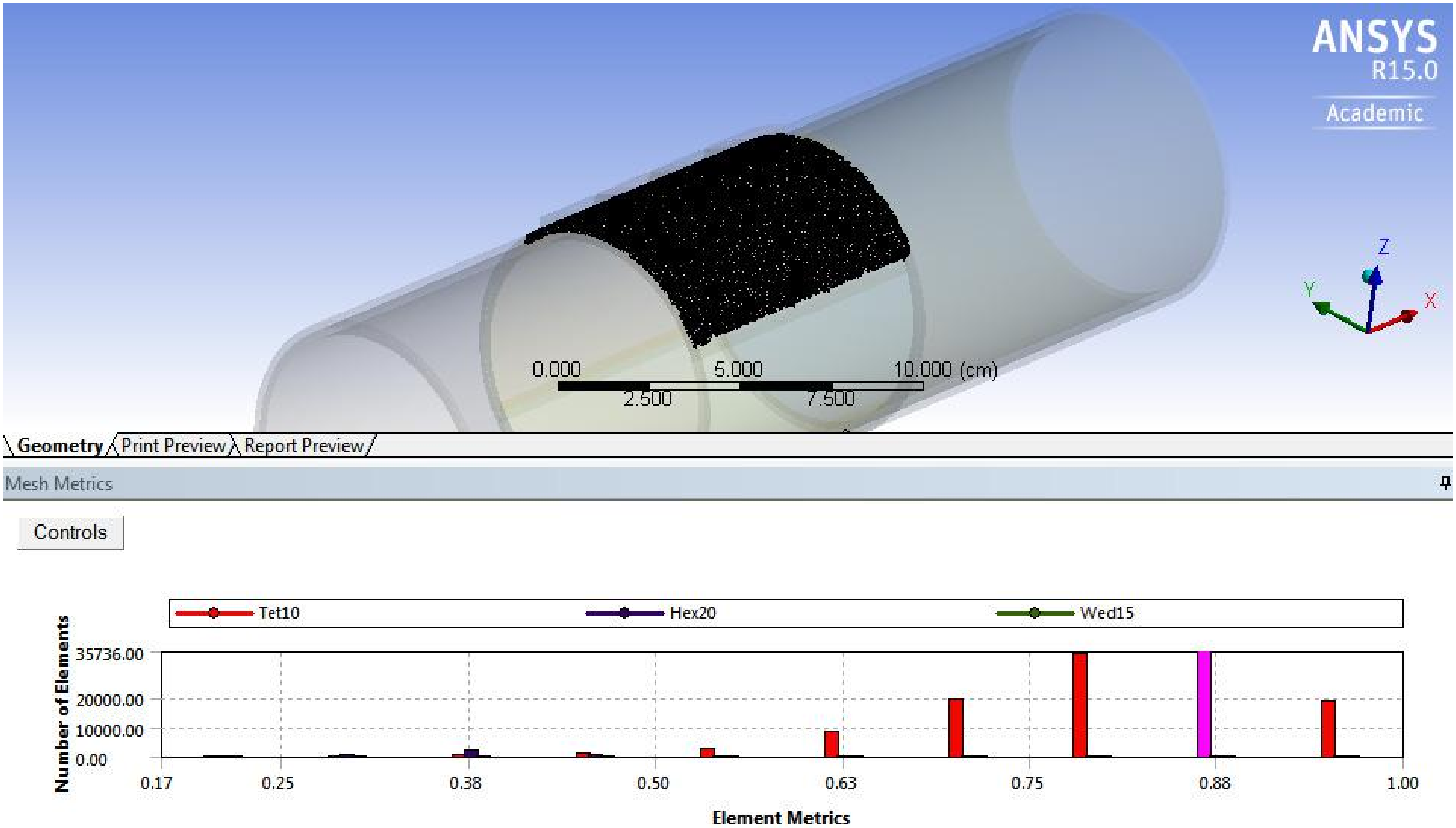

Figure C.2: The element quality of the stimulation area.

Appendix D: Temperature Readings vs Depth

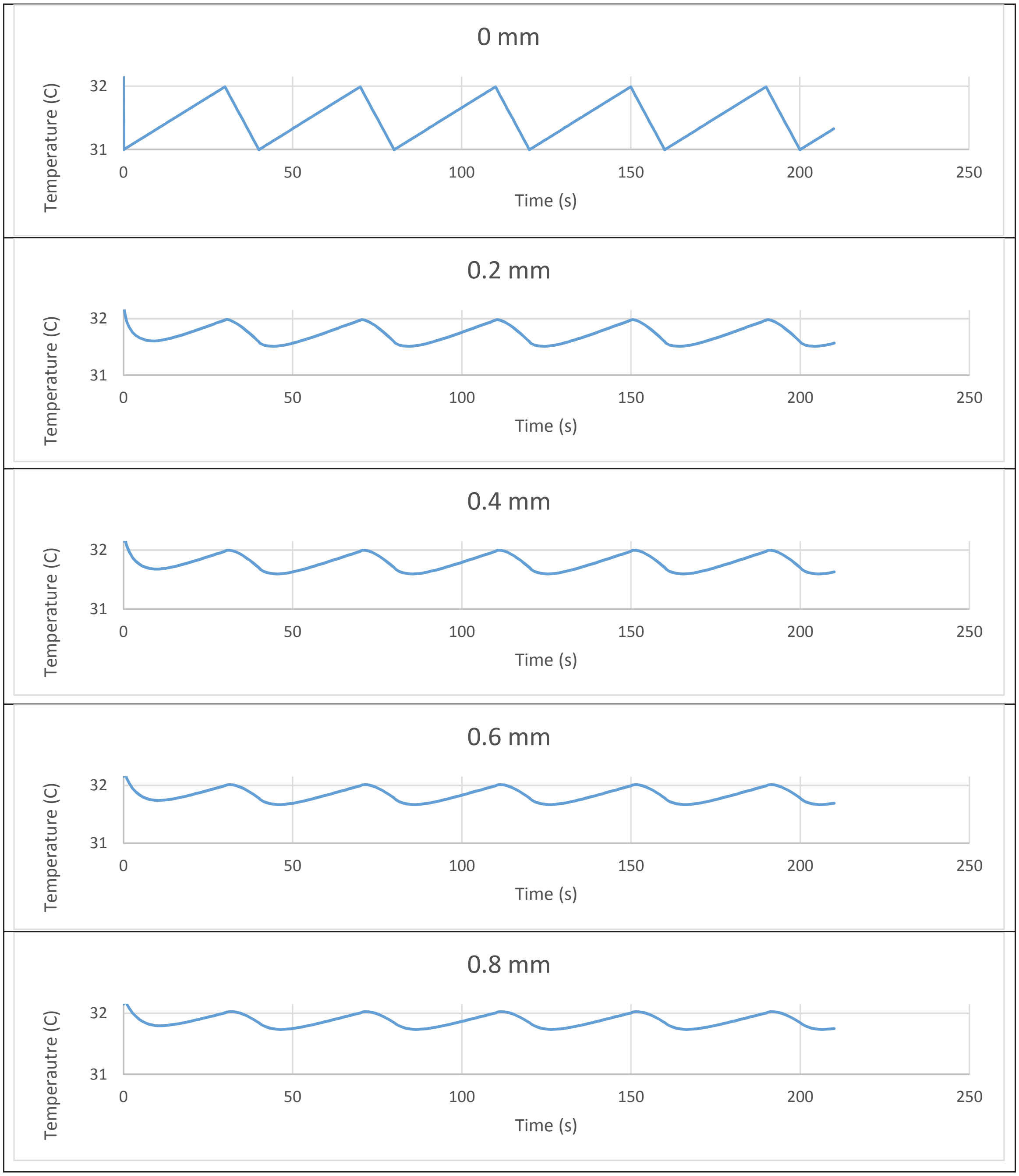

Figure D.1: Temperature readings versus the depth of the stimulation area.

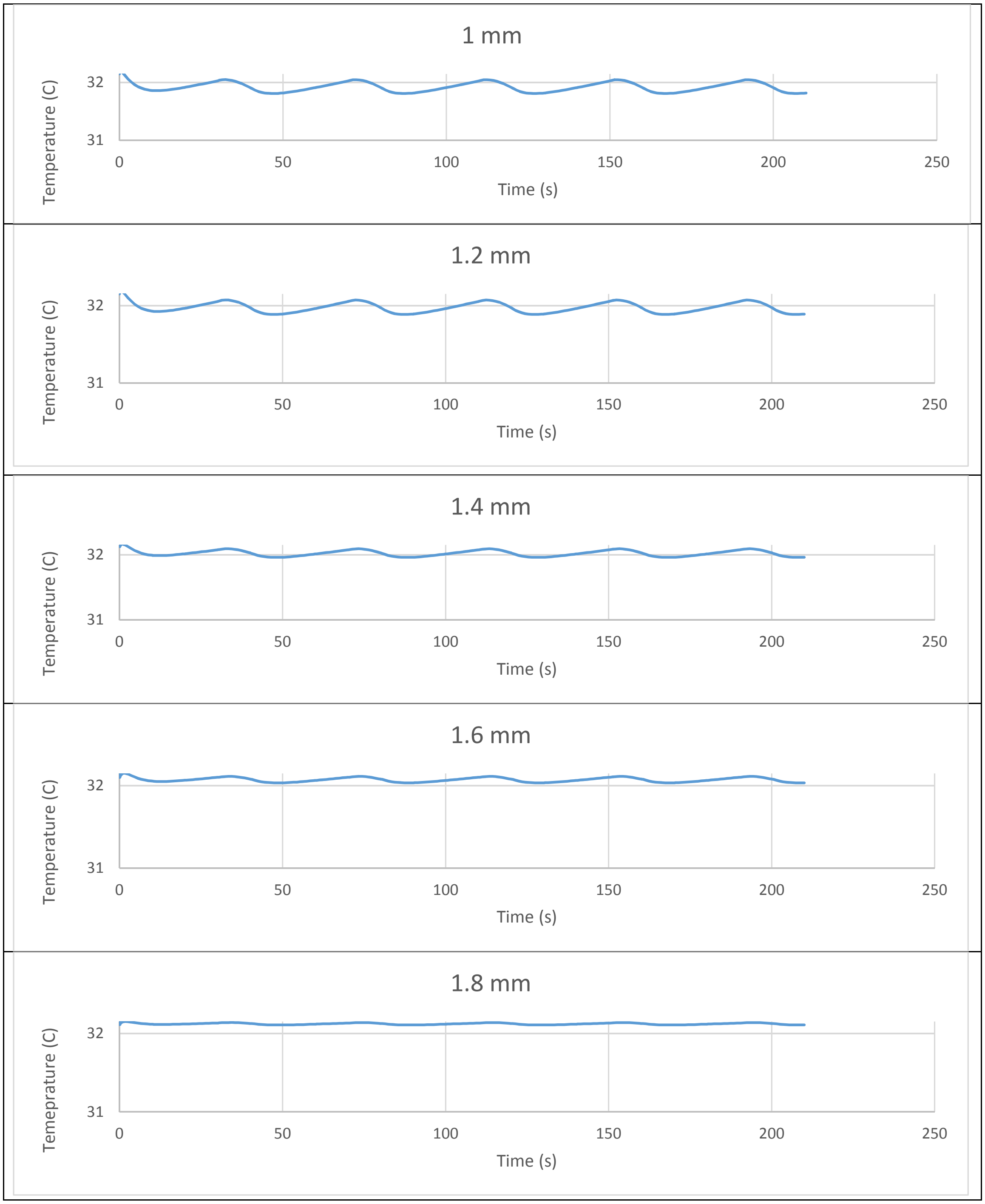

Figure D.1: Continued.