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Exploring Thermal Perception on Body Extremities

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A Master's Thesis
submitted to Keio University Graduate School of Media Design in partial fulfillment of the requirements for the degree of
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Abstract of Master's Thesis of Academic Year 2017

Exploring Thermal Perception on Body Extremities

Category: Science / Engineering

Summary

In recent years, with the boom of Virtual Reality (VR) technology, the utilization of thermal sensation has been much more common in the aspect of enhancing the immersion of VR experience. On the other hand, researchers have investigated much about human's thermal perception but they mainly focus on the thermal sensitivity of human's body. Such previous thermal researches have been done without the connection of VR environment. To develop a VR immersive thermal display, it's important to know how human perceive and interpret thermal stimuli and what kind of information can be conveyed to the user through the thermal stimuli. If we can utilize thermal stimuli in the same way as it affects human in real world, it's possible to simulate the real world in thermal aspect. So my subject here is to prove the hypothesis: thermal stimuli on body extremities lead to different recognition and interpretation. I conducted three experiment to exam the thermal perception on forehead, on wrist and on the bottom of foot. In the research, I successfully present spatial awareness and passing-through illusion to user and also introduce some principle for the thermal experience design on the foot. The result of the research proves the hypothesis. Hopefully, this research could make contribution to the research of human-computer interaction and other researchers could utilize the conclusions in their own research.

Keywords:

Thermal Stimulus, Body Extremities, Thermal Illusion, Thermal Perception

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Chapter 1
Introduction

In the research field of Virtual Reality(VR), researchers are trying to simulate the real world for decades. Though more than 80% of the information we get from the outside world is though eyes and it is possible to build a approximatively immersive VR world by visual stimuli or with auditory stimuli added in. But in such VR environment users would still sense some discordant ”noise” when they want to touch the object in the environment. Because current technology can not display the object's texture and temperature completely. Then users notice they are just exploring a fake world instead of real world. This would greatly hurt the experience of VR contents. Furthermore, a incomplete immersive experience may potentially lead to more problem referring to the VR sickness. For these 2 reasons, researchers try to introduce other kinds of sensations into the VR technology to build more ”real” world.

1.1 Thermal Stimulus

In Embodied Media project, we used thermal stimuli to enhance the VR experience. The reason why we choose thermal stimuli is that, first of all, thermal sensation is the one of most common sensations in our daily life. There is no need to teach user how to get the information through the thermal stimuli, because they did it in their daily life. Secondly, unlike auditory stimuli or visual stimuli, thermal stimuli is private. Current thermal elements attach to the user's skin directly. So it affects user and would not influence the people around. For the same reason, thermal stimuli system would not occupy too much space. Considering the fact that thermal actuator is relatively light, the thermal stimuli system can be implement as wearable device, so that it has the potential to be used in augmented reality(AR) or mixed reality(MR). Next, based on the parameter such as interval and rat of change (ROC) the sensation varies. And in some extreme situations, thermal stimuli could even lead to pain sensation. Further more, the thermal sensitivity varies among the location of skin. Thus, same thermal stimuli applied on different positions leads to different subjective intensity, which means thermal sensation has the potential waiting for further exploring. And division of labor extends the range of information we could convey in VR environment. For example, when user feel cold on hand, it's easy interpret this to seizing something cold. And in the same way of foot, he might interpret this to stepping something cold. Finally, thanks to the metaphor in our literature works, thermal sensation has a great connection to human emotion and recognition which appears to be a valuable tool to effect user's emotion.

1.2 Body Extremities

Judging from the life experience we know that body extremities are usually used to interact with ambient environment and get information from it. For instance, head is usually used to detect the air temperature, so in order to enter such environment, people need to decide whether he should put on more clothes or take off some. Hand is usually used to interact with objects in current environment, so from the temperature people could judge the objects that it's safe or not. As for feet, people use them to step on the ground to sense the temperature of the ground if it's beyond normal temperature the brain would alert and ask people to leave this environment. In general, thermal sensation from body extremities greatly influence the way we feel and interact with ambient environment. To simulate real world and make people feel environment more real, we have to investigate the thermal perception on body extremities so that we can apply thermal stimuli in the right way.

1.3 Research Contribution

This thesis contributes to the enhancement of VR. I investigated the thermal perceptions on human's body extremities. In the thermal perception research on head, user get aided thermal cues to detect the target in virtual environment. In experiment, three thermal modules were attached to user's forehead and each take response for a certain area. When user moves head and the target falls into any of the areas, the corresponding module get actuated and generate a thermal stimuli to user, thus user could search the target according to these thermal cues. In the research for hand, thermal illusion, a passing through feeling, has been generated on wrist for user. To achieve this, two thermal module were implemented on the two side of user's wrist. If the two modules are actuated in an interval, it's possible for user to have a illusion that something cold passes through his wrist which there is no such "something". And in research for foot, I conducted a experiment to exam the sensitivity of four locations on the bottom of foot. The first research indicate the potential of thermal stimuli which could be used as aided cueing method in navigation. Also it could be used in some video game's scenario as a kind of "super power or super sense". The second research also shows the potential of thermal stimuli The third research is a fundamental one. Before this research, previous works usually focus on one point or a narrow area of foot. But as we know bottom of foot is a relatively large area, if we want to go on the research further, for example using bottom of feet as a interface to simulate feelings such as walking on the shore or desert, we must know how to generate a overall thermal feeling on the bottom of foot. So as an initial step, the investigation of sensitivity difference on bottom of foot is important. So with these researches, readers could hopefully get some inspiration or use some recommended setup in their own research to make more progress on thermal perception research.

1.4 Application

It is worth emphasizing that the greatest power of VR technology, in my opinion, is capable of changing people's thoughts. People's behavior formed from the interaction with ambient environment. If we can build a "real" virtual environment and let user experience it or "train" in it over and over again. Would it be possible to "change" people's attitude and regularize their behavior subconsciously? In such system, it's very important to convince user that they interact with real people there, which means he can see them, hear them and feel the body temperature of them. What's more, referring to writers and painters, once the power of creating a world falls into human's hand, they are no longer satisfied with the simulation of a existed world. Creators are trying to use the technology to create some brand new world waiting people to experience. Unlike the world built by words or built by paint, VR world is capable of providing full diving experience for user. In such new world, user may experience a lot that is unique there. For example, a ghost passing through the body. But now, with the visual information and thermal stimuli, it's no longer impossible.

1.5 Structure of the Thesis

This thesis consists of 5 chapters. The first chapter is an overview of whole thesis. The research subject and contribution of are described in this chapter. In chapter 2, related works are introduce and some of the conclusion would be used in the experiment of this thesis. In chapter 3, "thermal stimuli on body extremities lead to difference recognition and interpretation" was hypothesized. To prove this, detailed proposal follows. In chapter 4, three experiments were carried out to investigate the thermal perception on different body extremities. The result of these experiments indicate the difference in thermal perception on body extremities. In chapter 5, conclusions were drew and limitation as well as future work is introduced.

Chapter 2
Related Works

2.1 Thermal Perception Researches

Since long ago, researchers have been showing the interests in thermal perception. Many methods have been found to generate thermal stimulus. Recent year, with the increase of usage of mobile device and the boom of VR/AR, they are trying to develop thermal display and combine it with VR/AR system. To make the thermal display effective and efficient, we must have a better understanding of thermal perception. Lynette A. Jones [14] has been concentrated in this field for many years. She made a summary of researches on thermal perception and also propose some recommends about how to develop a efficient thermal display.

Thermal Perception

There are two kinds of thermoreceptors spreading out in the epidermal and dermal skin layer. They are cold thermoreceptor and warm thermoreceptor. When a object attach to the skin, these kinds of thermoreceptors would encode the temperature change and transmit the signal to brain to help identifying the object. In this way, people would know the object's thermal properties such as heat capacity, the initial temperature and current temperature difference.

Thermal Thresholds

Among many factors that would influence the ability for people to perceive the temperature change, the amplitude and the rate of change (ROC) is the most common factors. The sensitivity of the skin varies from the locations of the body. one of the most common location where researchers exam thermal sensitivity is thenar eminence at the base of the thumb. Kenneth O Johnson [13] has reported human subjects are able to resolve a difference of 0.02^0-0.07^0 in the amplitudes of two cooling pulses. Also there is a range called neutral thermal zone(30^0C-36^0C), in which if thermal stimuli apply on the skin and skin temperature change in a very low speed, it's hard for stimuli to be aware of. However if the skin temperature is beyond the neutral thermal zone and changes in a relatively rapid rate, like 0.1^0C/s, even a small thermal change can be detected. Works by Dan R Kenshalo [17] [16] shows the thermal threshold in different ROC in figure2.1.As for the thermal threshold for different body parts, Joseph C. Stevens Kenneth K. Choo investigated the thermal threshold on index finger, thenar eminence and forearm. The result shows in figure2.2.

Resolution for Thermal display

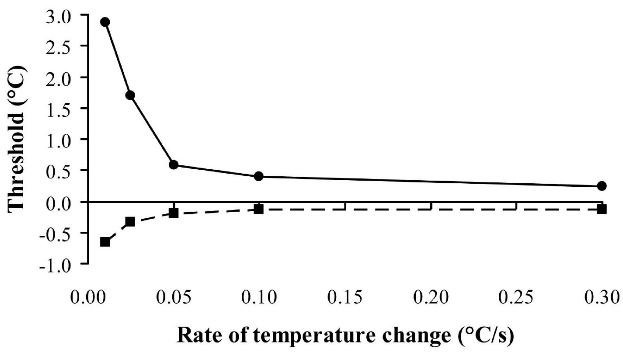


Figure 2.1: Warm(circles) and cold(squares) thresholds on arm in different ROC at an adapting skin temperature of 32^0.

Many methods have been tried to measure the tactile resolution of skin and they proved the high acuity of the skin. However, it's difficult for human to detect the exact position in which both warm and cold thermal stimuli applied on. This means thermal sense is poor at localization of thermal stimuli. So when develop a thermal display, the spatial summation of thermal sensation must be accommodated. All of above limited the number of thermal simulators in the thermal display. In addition, since the time of the response to the thermal stimuli is significantly longer than the response to other stimuli from the object, it's not suitable to present information that need a rapid response using thermal stimuli.

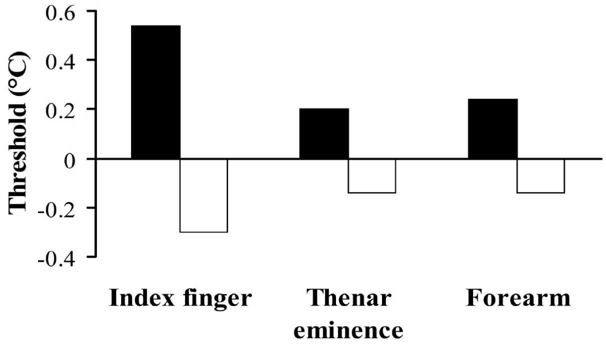


Figure 2.2: Warm(black bars) and cold(white bars) thresholds on different body parts. The warm thresholds were measured in ROC of 2.1^0C/s and the cold threshold were measured in 1.9^0C/s.

2.2 Tactile Illusion

A great amount of information from environment provided by tactile sensation. Through touching, human could detect the object's properties such as texture, softness and heat capacity. Also in the interaction of the object, the location or the orientation could be detected through the dynamic information. Thus tactile feedback could be used as one kind of method to present the information in the domain of Human-computer interface. Many researches have proven that it's a possible method to use vibration to develop a tactile display. Tactile Brush [12] is one of them. In this research, Ali Israr developed an algorithm that use tactile grid display to present tactile illusion and this algorithm could present a two-dimensional moving stroke. The research of Tactile Brush starts base on the understanding of vibro-tactile illusion. There are two kinds of vibro-tactile illusion use in this research, apparent tactile motion and phantom tactile sensation. Picture a in figure2.3 shows the measure to generate such thermal illusion by vibration stimuli. Two motors get actuated in different timing then user would feel both of the stimuli. Instead of feeling them separately, based on the value of inter-stimulus onset asynchrony(SOA). user feel the vibration "moves" from one motor to another one. Some other factors should be guaranteed in this phenomenon. First, two stimuli should be place in a close distance on the skin. Secondly, the actuation timing of these two stimuli should be overlapped.

There is another kind of tactile illusion called phantom tactile sensation. It means when two continuous actuated actuators are applied on a near location of the skin, they would create a illusory actuator in the position between them. Picture b in figure2.3 shows this phenomenon.

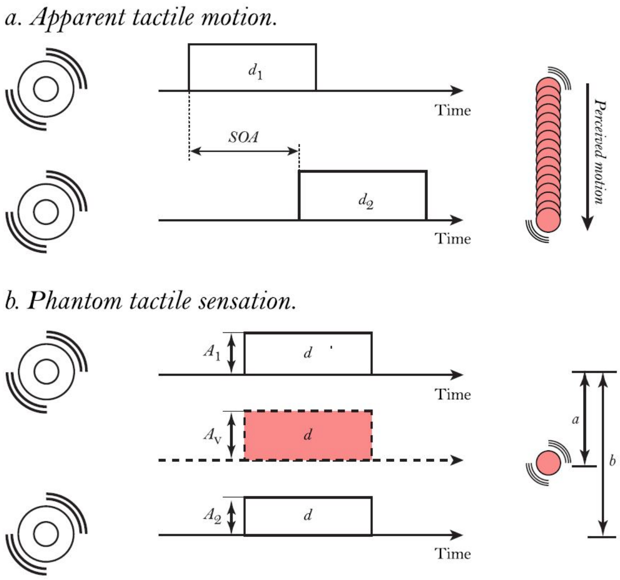


Figure 2.3: Vibro−tactile illusions

2.3 Haptic Displays

My research is based on the thermal perception on body extremities. So the investigation of similar works is a important task.

2.3.1 Haptx

Figure 2.4 shows a kind of industrial-grade haptic gloves called Haptx. With a set of elevated small sticks, the glove could generate force feedback on the tips. Based on motion tracking, it provides realistic touch and force feedback to virtual reality. Similar with my research, this project focuses on the haptic feedback and investigated haptic sensation on the hand.

2.3.2 FirstVR and UnlimitedHand

In CES2018, there is a VR system called FirstVR2.5. This system consist of two parts, a armband-like controller and a VR HMD. Wearing this system,user

Figure 2.4: Haptx

could interact with the VR environment in the most natural may. For example, in the FPS game, formerly user need to press the bottom on the game handle or click on mouse to convey the fire command. However, with this system, user don't need these controllers anymore. He only need to watch the gun on his hand in VR environment and imagine he has the gun in his hand. Then as what he supposed to do in real world, he pull his index finger to shoot. The controller would track the finger's movement and send the interactive command to the computer. Finally, user would see the trigger was pulled and enemy get hit. Without any interpretation, this kind of interaction is natural for user which is important to build a high immersive VR environment.

Figure 2.5: UnlimitedHand

The controller implemented in this system is UnlimitedHand lite. The full-function version is UnlimitedHand. It's also a armband-like product. With eight

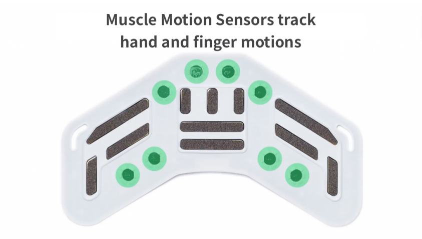


Figure 2.6: Muscle motion sensors

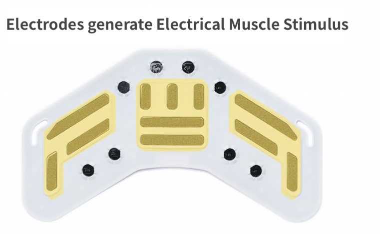


Figure 2.7: Electrical muscle stimulus actuators

muscle sensor2.6 attached on the arm, UnlimitedHand could read the data from the muscle on the arm which could be used to indicate the motion of fingers. UnlimitedHand also allow user to touch the virtual objects in the VR world. By applying the electric pulse signal to the user's forearm muscles, UnlimitedHand could control the finger movement to generate the haptic feedback. Figure 2.7 shows the electrical muscle stimulus actuators. So the UnlimitedHand is a input device as well as a output device. With these two patent-pending system combined, user could manipulate and feel the VR world.

2.3.3 Ambiotherm

There is research project called Ambiotherm. Ambiotherm is a VR system that combined wind simulation system, thermal feedback system and HMD. Researchers placed two rotating fans in front of the user's face to simulate the sensation of wind. They also put a thermal module on the user's neck. Depending on the virtual experience , the module could heat up or cool down to simulate weather. In this way Ambiotherm enhance the immersion of virtual reality with realistic weather simulations.

2.3.4 ThermoVR

ThermoVR [22] shown in figure 2.10 is a thermal display which could present hot/cold stimuli on user's face with peltier module. In this research, I investigated the thermal perception on face. Through the experiment, the study proves face is sensitive enough to perceive thermal stimuli as directional information. Based on the conclusion, Chen [6] developed a thermally enhanced weather checking system. In this system, user could not only see the number of the temperature or some pictures which are going to indicate the weather but also actually feel it. It's

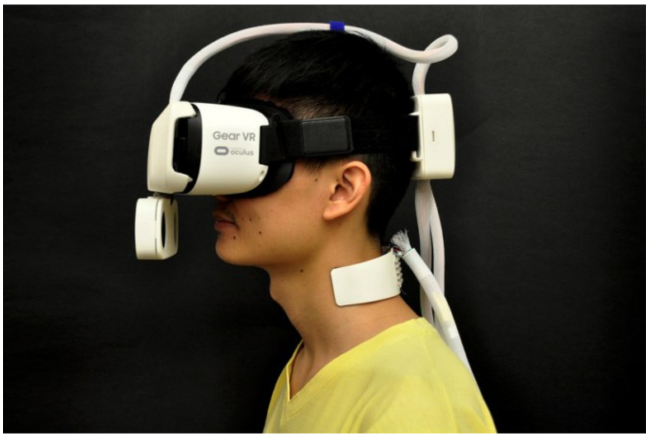


Figure 2.8: Ambiotherm

important to feel the temperature because the numbers or the pictures can not convey the weather information well especially the information we care most ”how much I should wear to get outside”. Based on the current weather, system would present thermal stimuli. In this way, user could perceive the thermal stimuli and directly feel the weather and make the decision.

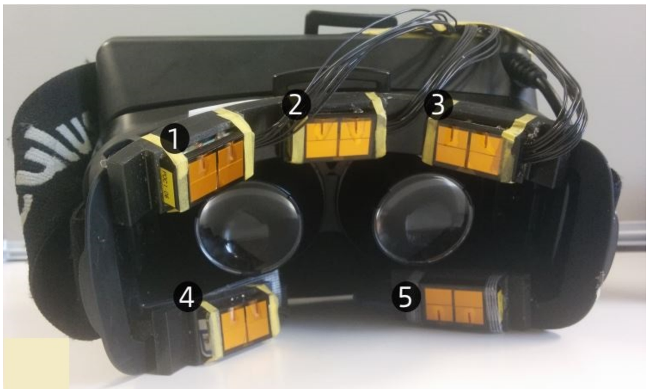


Figure 2.9: ThermoVR

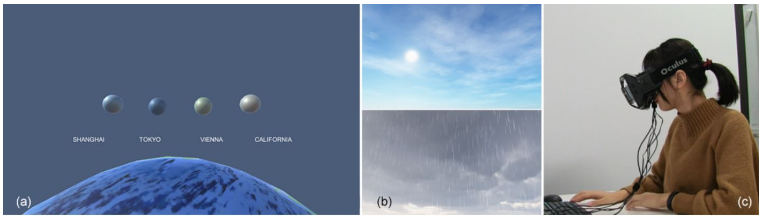


Figure 2.10: weather checking system

Chapter 3
Concept

3.1 Thermal Technology

Peltier modules (figure3.1) known as thermo-electric device have been widely used in the thermal display design. Peltier module generates thermal stimuli base on the peltier effect. It's the presence of heating or cooling at an electrified junction of two different conductors. Usually we attach two different conductor together. AS DC current to pass through them in a circuit, temperature difference occurs on the surface of them. In general, temperature on one side of the module would increase and the temperature on the other side of conductors would decrease. When used as thermal actuator in thermal display and attached to the skin, peltier modules change the temperature indeed, so user could perceive the stimuli consequently. However the problem here is, in some scenarios, it's necessary for module to present the information in a fast speed or even switch between cold and hot stimuli rapidly. Obviously single module is not capable of providing such stimuli. Even it's possible to change the direction of DC current as well as the stimuli, it takes time to remove the current heat effect and only when the temperature of module return to the skin temperature, it's possible for user to perceive the changed stimuli.

Based on this limitation, a well designed thermal module is introduced in my research. This kind of thermal modules consists of 4 peltier elements. They are divided in 2 groups. Diagonal modules belong to the same group. Modules of one group are especially used to generate one kind of thermal stimuli(hot or cold).

3.2 Hypothesis and Strategy

The main focus of this research is the interpretation of thermal stimuli by different body part. The research begins with a hypothesis: thermal stimuli applied on

Figure 3.1: Peltier module

different body extremities lead to different interpretations. If I can prove this, based on the different understanding of thermal stimuli, it's possible to present environmental information with a all-purpose thermal display.

This hypothesis is hard to be proven directly. So I specify this subject into three parts. In each part, I would choose a position of body extremities and present thermal feeling by generating thermal stimuli on it. In the research, the body extremities I chose are head, hand and foot. So three experiment are conducted on forehead, wrist and bottom of foot.

Based on life experience, head usually perceive the directional information from environment. So in experiment, three thermal modules are going to attached to subject's forehead. By actuating them in a certain pattern, I would exam weather it's possible to provide directional cues by thermal stimuli to give subject a spatial awareness. Hand, on the other hand, is also a efficient tool for human to interact with environment. Hand could get much information about he properties of object in hand. In the second experiment, two modules would be attached to the two side of the wrist. By actuating them in an interval, hopefully thermal illusion of passing through feeling could be presented to subject. The last experiment is going to be conducted on the bottom of feet. Unlike wrist or head, feet are usually well protected by shoes and socks. Thermal perception or thermal display on foot is not full investigated yet. In this condition, as a initial step for thermal perceptual research on foot, I am going to investigate the resolution of foot.

3.3 Possible Experience

If the hypothesis proves true, it means we should and we can utilize the property of thermal sensation on body extremities to develop thermal display. So it's possible for researchers to present a thermal VR environment or use thermal stimuli as an aid for current VR technology.

Education and Training

Fire drill is a important activity all over the world. As initial exercise, it's possible to build a VR environment to for students to know the process of fire drill and train them. To make the scene more real, it's important to convince them they are in a emergency. So thermal feedback here could be very helpful to performance such atomosphere.

Figure 3.2: firedrill

Entertainment

Thermal display can totally be applied in such field well. I would like to show an example of what kind of experience would be present by thermal display. The witcher 3 is a famous RPG(role play games) video game. It has earned great reputation all over the world. In this game, as a monster hunter Geralt, player need to accept commissions and execute them. In the scenario, Geralt has the talent to sense the environment around him. He can "see" the smell and the temperature of creatures and find cues of monsters by this talent. It's a odd experience for players because it's hard to be convinced that people could see the smell. Obviously current technology limits the performance of scenarios with such super sense in it. So if we apply thermal display to such scenarios, players can get aid of thermal sensation just like what they usually do in real world. Also, with the help from thermal sensation, much imaginary experience now comes true. In thermal sensation invovled VR environment, user can not only see him releasing a spell of fire ball and the heat remains in his hand, but also feel the cold sensation when hit by the magic of snowstorm form his enemy. What's more, with the research for thermal stimuli moves on, many kinds of thermal illusion or phantom effect has been found. So user could feel the sensation from outside environment. In the meanwhile, user could feel the inside thermal sensation of his body. In the experiment of this research, I successfully generated a thermal inside feeling–user would feel a cold stimuli passed through his wrist. This thermal illusion could be used as a aid sensation for the scene player being pierced by a weapon or a magic ice.

Figure 3.3: thermal information of environment

Figure 3.4: thermal cues

3.4 Experiments Design

Forehead, wrist and bottom of foot are typical body extremities of human. For the experiment on forehead, three thermal actuator are attach to subject's forehead horizontally. Based on the orientation of head, actuator are going to be actuated and subject could perceive the thermal stimuli as a kind of directional cues. In this way, hopefully, the thermal stimuli could present a spatial awareness for subject. For the experiment on wrist, two thermal pulses are going to be present to the two side of subject's wrist with an interval between them. Then subject would feel a sequential order of stimuli. Then because of the thermal illusion, subject would feel it is a continuous stimuli instead of two thermal pulses with an interruption between them. Thus a passing through feeling could be present in wrist. As for the experiment on bottom of foot, four thermal actuator would be attached to the bottom of foot. Modules would get actuated individually or in a combination simultaneously. Subjects would be required to localize the positions of stimuli on questionnaires. According to the result, the properties of thermal perception on foot would be revealed to some extent.

If I managed to prove the presence of unique properties for thermal perception on each body extremity, the hypothesis is going to be proven.

3.5 Summary

To exam the hypothesis, three experiment would be conducted on three body parts respectively. In all of three experiments, existing thermal display would be used to generate thermal stimuli and thermal stimuli in these experiment share the same ROC(3^0C/s). Based on the feature of body extremities, the thermal actuator would be placed on the proper position. The goal for the experiments is to investigate thermal perception on each body extremities.

Chapter 4
Exploring Thermal Perception on Body Extremities

There are mainly 3 researches I have carried out. The first one is using thermal feedback to generate spatial awareness for user. The second one is using thermal stimuli to generate a passing through feeling which is one kind of thermal illusion. And the third one is a thermal perception research on the bottom of foot. All of them share the same purpose which is to answer 2 questions: how human body perceive thermal stimuli and what kind of information can be conveyed by thermal stimuli.

4.1 Spatial Awareness on Forehead

Head based haptic feedback systems are widely used to provide haptic information about target and object locations for contexts such as navigational and obstacle detection tasks [20]. Majority of such systems have utilized vibrotactile [7], electrotactile [15] and pressure [3] based haptic feedback systems to deliver the haptic information. The forehead provides an ideal location for such feedback since it is one of the most sensitive sites to mechanical stimulation [1]. In addition, with the recent rise in head based wearable devices such as head mounted display (HMD), such haptic feedback systems could be co-located with the displayed visuals, conveying a richer experience to the user.

In addition, the forehead also has a relatively high density of thermoreceptors [8], making it one of the most *thermally* sensitive sites [4] on the human body. As such, recent research in head based haptics has started to explore providing thermal haptic feedback [21, 22] on the forehead. The work in Thermocons [21] investigated the thermal feedback as haptic feedback icons for information transfer. ThermoVR, explored combining thermal haptic feedback with head mounted displays for enhancing the virtual reality experience. In both these works, the thermal haptic feedback was provided while the participants maintained their heads in a stationary position. That is, the motion or the orientation of the head did not effect the haptic feedback information.

4.1.1 Goal

In the experiment,[1] I tried to convey the directional cues by thermal stimuli. Based on my previous work, I have investigated that sensitivity of face is high enough to detect the individual stimulus especially for cold stimuli. From the research by Victor Adriel de Jesus Oliveira [7], it has been proven that vibro-tactile stimuli could be used to convey directional cues and able to generate spatial awareness for user. indicate the method could be used in navigation. However, in my opinion, vibro-tactile stimulus is not a natural cuing method for people. Instead, thermal stimulus seems more reasonable to provide the navigational cues. Referring to the scene that beacon lead the ship throughout the fog area, Fire or the source of hot stimuli, in people's mind, usually means the hope, the destination and the goal. So I decide to use thermal stimuli to generate directional cues and provide spatial awareness to user.

Here I explore providing thermal haptic feedback during head motion for a localization of spatial cues task. I use three peltier modules placed on the forehead to provide thermal haptic spatial cues to guide the user to the target spatial orientation (Figure 4.1). Based on the orientation of the head, the haptic feedback is continuously updated through the three modules. As an initial step in this direction, I explored the performance of three different cueing methods for this system. my goal was to evaluate the performance of each of the cuing methods in terms of the detection error and the time taken for detection, for this three module set up to provide thermal haptic feedback on the forehead.

4.1.2 Design of the System

The thermal sensitivity of the skin varies significantly across different sites on the human body. As such, thermal haptics has been explored on various locations, such as the wrist [9], thenar eminence [9, 24], ear [2] for contexts such as thermal displays [18] and communication [10, 19]. However, the face has found to be the most thermally sensitive sites on the human body with the lips, cheeks and forehead having the lowest thermal thresholds [4].

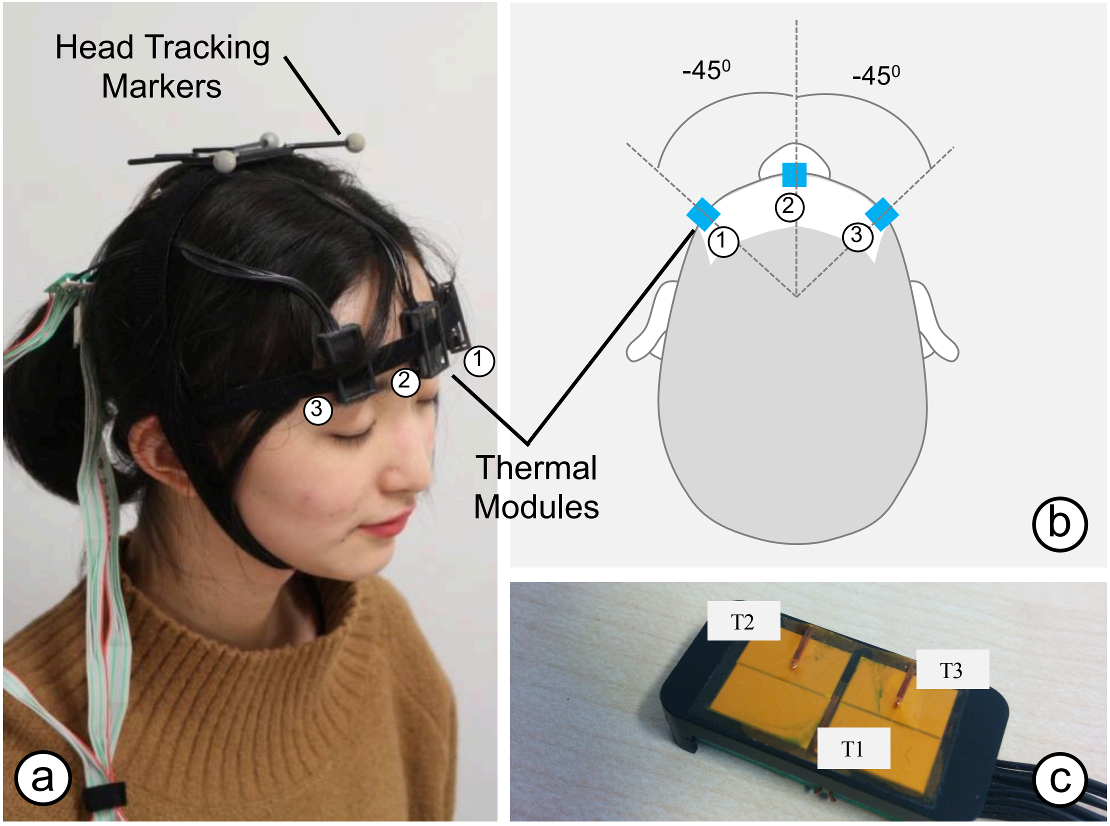


Figure 4.1: The apparatus of the forehead thermal feedback system (a) Participant wearing the system. Three peltier modules are placed on the forehead using a headband. Reflective markers on the top of the head are added to track the head rotation (b) The modules are placed at 0^0 and $\pm 45^0$ angles from the top of the head (c) A single peltier module. T1, T2, T3 are temperature sensors

Previous research has revealed that all body regions are more sensitive to cold stimuli than hot stimuli [4]. In addition, rates of change of temperature above 0.1^0C/s has minor effect on the perception threshold of thermal stimuli. Therefore, typical temperature change rates such as 3^0C/s reduces the thermal detection threshold resulting in higher sensitivity for thermal perception. This is seen in the works of Steven et.al. [4] where, the detection threshold for the forehead was approximately 0.1^0 at a rate of 2^0C/s for cold stimuli.

The research in Thermocons [21] and ThermoVR, both used and demonstrated these properties with thermal feedback on the forehead. Both works used 3^0C/s for one second as the thermal stimuli. In Thermocons, the participants wore three peltier modules mounted on a head band on their forehead. The objective with this work was to identify simultaneous multiple stimulation of thermal haptic cues. Similarly, in ThermoVR, the authors mounted five peltier modules on to a head mounted display with which they provided thermal haptic directional cues. Here, they evaluated the perception accuracy of the thermal cues and in addition, the immersion enhancement for virtual reality experience. Both works reported that cold stimulation were perceived significantly better.

Based on these recommendations, I mounted three peltier modules (12x10mm) on the forehead of the user using a head band as shown in Figure 4.1(a). Peltier modules are devices that are able to rapidly heat or cool skin. In addition, the modules are placed at 0^0, -45^0 and $+45^0$ on the forehead relative to the center of the head (Figure 4.1(b)). Each peltier module is driven by a full bridge motor controller (TA7291) and an Arduino Nano microcontroller[2] employing a closed loop PID (proportional, integral, derivative) temperature controller for accurate temperature control. The T1, T2, T3 temperature sensors (Figure 4.1 (c)) are used for the closed loop control. The controller is tuned to change the temperature at $\pm3^0$C per second rate. A user with the setup in use is shown in Figure 4.1(a). For the scope of this work, and based on the recommendations from previous works, I only provide cold stimuli to the user. The stimuli are provided at a 3^0C/s rate.

The modules are continuously actuated. That is, the temperature would continuously change during the length of the stimulation. In addition, when the stimulation is stopped, the thermal module is 'switched off' allowing the module to return to the original skin temperature naturally. If another stimulation occurs during this state, the stimulation is provided starting from the temperature at that point. In this manner, I aim to avoid actively actuating the module to return to the original skin temperature. This would prevent the user confusing this return state as another stimuli.

In order to obtain the head orientation data, an OptiTrack Trio tracking system was used. Three reflective spherical markers (10mm each) were attached to the top of the head. With the help of these markers the system continuously tracked the orientation of the head in the azimuthal plane (yaw angle).

4.1.3 Cuing Methods

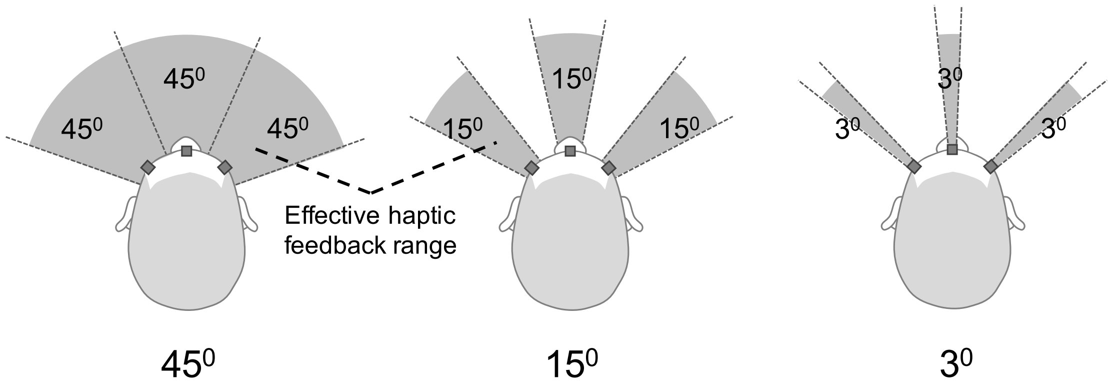


Figure 4.2: The three different cuing methods were identified for evaluation. When the head orientation is in the effective haptic feedback range, the corresponding thermal module is actuated. 45^0 covers the whole range around the head. 15^0 narrows the effective haptic feedback range for more accuracy. 3^0 has the narrowest effective haptic feedback range

Many previous works have explored different methods of presenting spatial haptic information on the head. In the Forehead Retina [15], authors provided rich tactile information using an electrotactile display mounted on the forehead. In this work, the environment image captured through a camera was directly translated into a stimulation pattern for a 512 electrode electrotactile array. In another research, Cassinelli et.al. [5] mounted distance sensors combined with vibrotactile modules around the head for providing information about the environment. Here, the authors used direct translation of distance information into vibrotactile feedback. In [20], Mann et.al., mounted six vibrotactile motors onto a helmet to provide obstacle information for blind navigation. In this work, the authors used a depth sensing camera in order to provide the obstacle information to the vibrotactile motors.

In a more recent study, Oliveira et.al. [7], studied different cuing alternatives for providing vibrotactile feedback on the head. The authors investigated the trade off between actuator density and precision by comparing three different cuing methods. The authors used five vibrotactile modules in three settings of directional cuing methods.

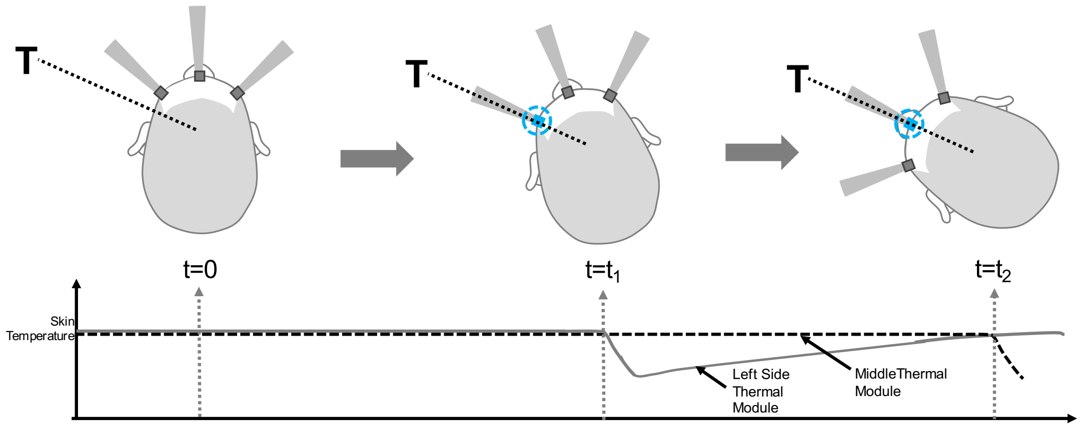


Figure 4.3: An example actuation scenario of the thermal haptic feedback system (T-virtual target). At the beginning, none of the actuators are actuated as the target is out side the effective haptic feedback range. As the user rotates the head, the target falls within the effective haptic feedback range of the actuator on the left side. Next, the head orientation results in the actuation of the module at the center. The users are required to confirm the target when they feel the thermal actuation in the center of their forehead. The graph at the bottom indicates the temperature changes of the corresponding left and middle thermal modules

I used a approach similar to that of Oliveira et.al. to define my cuing methods. Thus I identified three different cuing methods such as 45^0, 15^0 and 3^0 as the cuing methods (Figure 4.2). Therefore, the distribution of the peltier modules remain homogeneous for the different cuing methods. In the 45^0, the effective haptic feedback range covers a 45^0 angle around each actuator. The effective haptic feedback range specifies the spatial range within which the relevant peltier module is actuated. For the 15^0 and 3^0 conditions, the effective haptic feedback range is narrowed further.

An example actuation scenario is shown in Figure 4.3 for the 3^0 condition. As the user rotates the head, if the target falls into the effective haptic feedback range, the respective thermal module is actuated. The objective is to orient the middle actuator towards the target. That is, once the module in the middle was actuated (i.e. the users felt a cold stimulation in the middle module), the users could stop and select the target. The temperature changes of the corresponding thermal modules are also indicated in Figure 4.3. In this scenario, only the left and the middle modules are actuated once each. As such, the temperature changes are indicated in the graph at $t = t_1$ and $t = t_2$. Note that, once the left module passes the effective haptic feedback range, the actuation is stopped, allowing the temperature to gradually return to the skin temperature.

4.1.4 Experimental design

I performed an experiment to evaluate the performance of each cuing method using the thermal haptic feedback system on the forehead.

Task

I introduced a simple pointing task to measure the performance of each cuing method. In this task, the participants were presented a virtual target on the azimuthal plane. The participants were required to turn their head towards the target and select the final perceived target location using the thermal haptic feedback on the forehead. Using this method, I measured the error of the perceived target and the time spent in locating the target. The error was measured as the angular difference and the final head orientation (Figure 4.4(b)).

Stimuli

The experiment was carried out under three conditions (45^0, 15^0 and 3^0) where, for each condition, four targets were presented, -67.5^0, -22.5^0, 22.5^0, 67.5^0, as indicated in Figure 4.4(b). Each target was repeated five times giving a total of 60 trials. Each condition was conducted as a single session resulting in three total sessions. The session conditions were counter balanced with the 3x3 Latin Square method, and the target locations in each session were randomized.

The stimuli for each trial started from the skin temperature. The stimulation were maintained at 3^0C/s rate of change of temperature. Between each trial, there was a 20s resting period. Between each session the participants had a two-minute resting period. The total experiment for each participant lasted approximately 40 minutes.

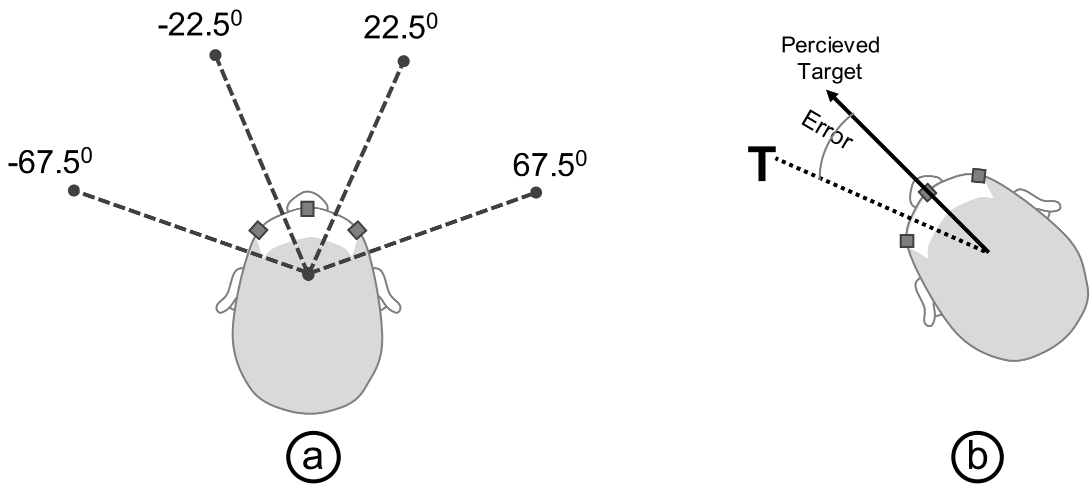


Figure 4.4: (a) Four virtual targets were presented to the users: -67.5^0, -22.5^0, 22.5^0, 67.5^0 (b) The precision was measured as the difference between the head orientation angle at the perceived target and the presented target

Procedure

The evaluation was carried out at 23^0 room temperature. At the beginning of the evaluation, each participant fulfilled a demographic questionnaire. Next, I briefly introduced the system after which the participant was equipped with the system (Figure 4.1(a)). During the set up, I ensured that the whole peltier modules made direct contact with the skin. The participant was not informed of the different cuing methods or the possible locations of the virtual target. Their objective was to turn their head towards the virtual target where they would feel the thermal stimulation in the middle of the forehead. Once they identified the target, they could press a button in front of them to confirm the target. Next, I allowed the participant a brief training session where they could perform the task five times with the objective of getting used to the system and stimulation.

Once the training session ended, the evaluation phase was commenced. Each trial began with a beep, after which, they could start rotating their head to locate the target. The participants were asked to locate the target in a fast and precise manner. Before each task, the participants were asked to re-orient their head to the 0^0 angle. After each session, the participants filled out a NASA Task Load Index (TLX) questionnaire [11] to self evaluate their task load.

Participants

10 participants (6 males, 4 females) of average age 27 (SD 3.2) voluntarily participated in my study. Each participant went through all the sessions. They were allowed to break or rest at any point during the evaluation.

4.1.5 Results

I measured the detection error and the detection time for the different cuing methods (45^0, 15^0 and 3^0).

Effect of Cuing Methods

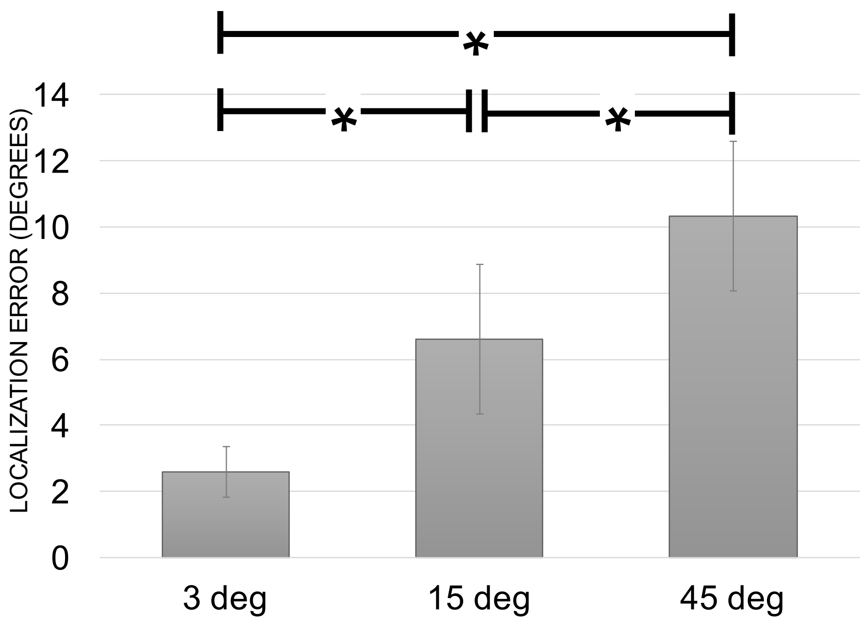


Figure 4.5: The overall error for the different cuing methods. A significant effect was observed with the 3^0 cuing method being the most accurate and the 45^0 cuing method being the least accurate

Figure 4.5 depicts the overall error for the three different cuing methods. The results were further analyzed One-Way Repeated Measures ANOVA and a posthoc Tukey Analysis. It was observed 3^0 cuing method (M:2.59^0, SD:0.75) was perceived with higher accuracy (lowest error). The 15^0 cuing method (M:6.59^0, SD:2.25^0) had the next highest accuracy with the 45^0 cuing (M:10.32^0, SD:2.27^0) method having the lowest accuracy. The One-way Anova test revealed a significant difference between the error values for the three different cuing methods ($F(2,27)=41.3770$, $p< 0.0001$). The 3^0 condition was significantly more accurate than the 15^0 ($p<0.01$) condition and the 45^0 condition ($p<0.01$). In addition, the 15^0 condition was significantly more accurate than the 45^0 condition ($p<0.01$).

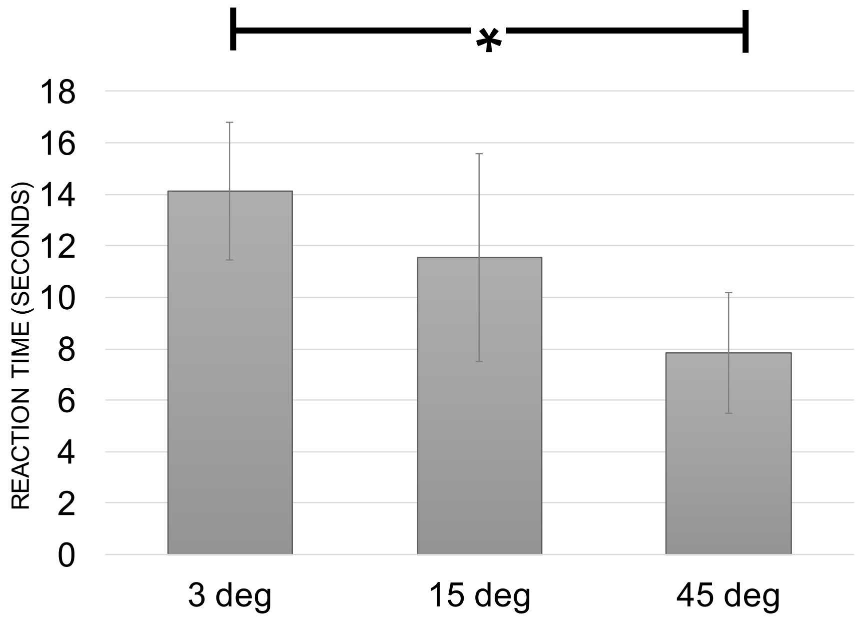


Figure 4.6: The overall detection time for the different cuing methods. The 45^0 condition was observed to be the fastest

As observed in Figure 4.6, the target detection time had a reverse trend as opposed to the overall error. The 45^0 cuing method reported the lowest time in locating a target (M:7.82s, SD:2.34s). Meanwhile, the 3^0 condition reported a slowest cuing method for locating the target (M:14.12s, SD:2.68s). The 15^0 cuing method reported an overall time of (M:8.05s, SD:4.025s). In addition, the further analysis revealed a significant effect ($F(2,27)=3.8745$, $p= 0.0332$) for the detection time. There was a significant difference between the 3^0 cuing method and the 45^0

cuing method (p<0.05).

Effect of Target Position

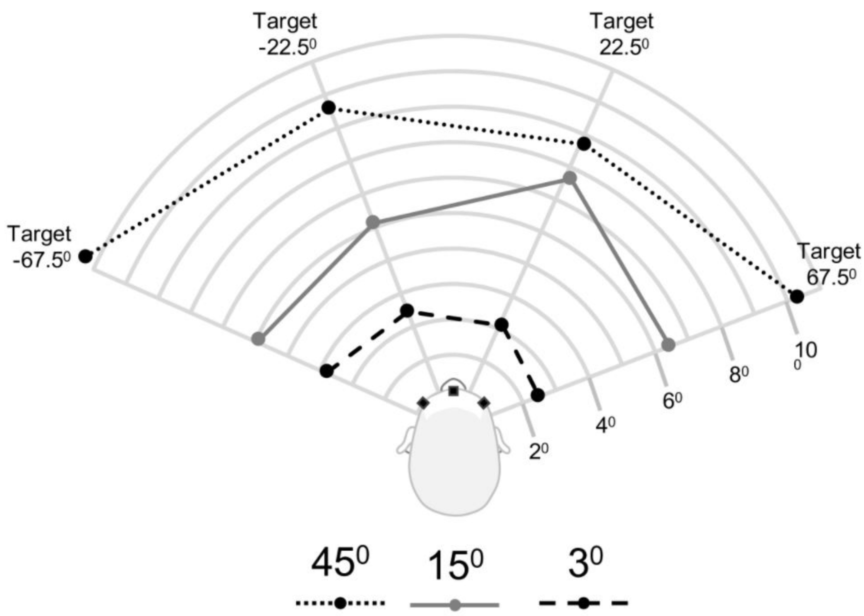


Figure 4.7: The errors observed at each target for the different cuing methods

Figure 4.7 indicates the individual errors levels at each target for the different cues. The overall curves reflect the observation of the results seen in Figure 4.7 with the 3^0 cuing method being the most accurate and the 45^0 being the least accurate cuing method. A further analysis with a Friedman test did not reveal a significant effect of the target location on the cuing method. This indicates that the targets did not present any major effect to the detection precision of the cuing method.

The detection time for each target for the different cues are indicated in Figure 4.8. Further analysis with a Friedman test revealed significant differences on the detection time and the based on the target location ($\chi^2(3)$= 11.88, p<0.05). The Nemenyi post-hoc pairwise multiple comparison tests indicated that detection of the $\pm67.5^0$ were significantly slower that $\pm22.5^0$ for 3^0 and 15^0 cuing methods (p<0.05). When starting from the 0^0 orientation, the targets presented for the 3^0

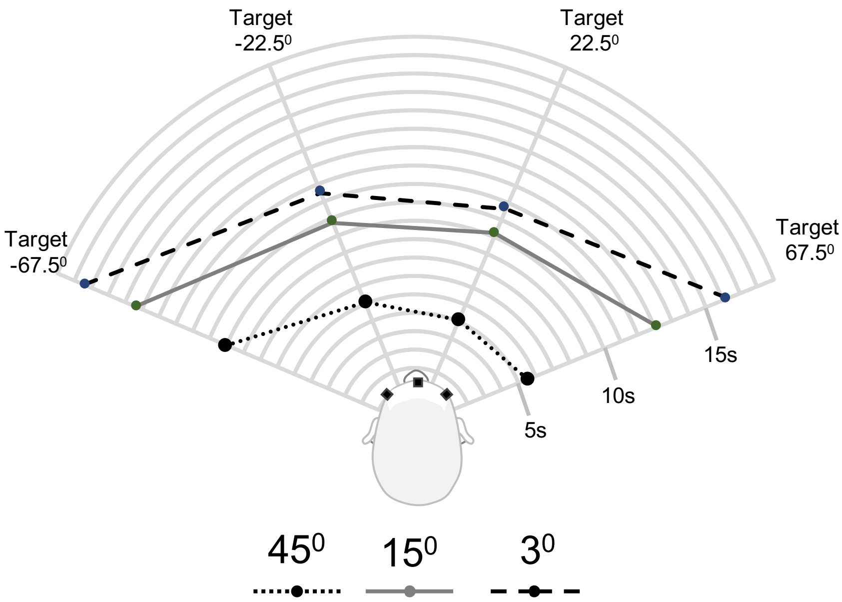


Figure 4.8: The detection times observed at each target for the different cuing methods.

and 15^0 cuing methods always fall outside the effective haptic feedback range. As such, the participants have no initial indication of which direction (left or right) to turn their head in order to find the target. Therefore, for the $\pm 67.5^0$ targets, initially if the participant turns in the opposite direction of the target, there would be no feedback. This notion was observed during the experiment as the participants spent a significant amount of time to locate the targets at the two extremes for the 3^0 and 15^0 cuing methods..

4.1.6 Workload

The Figure 4.9 indicates the NASA TLX scores for each of the factors under each cuing method. As observed, the 3^0 condition reported higher ratings for the Mental, Physical and Effort factors and overall work load. Overall, 15^0 condition was observed to be the least with the work load (weighted average). As observed during the experiment, participants reported that often, the initial identification of the target required the most work load during the 3^0 cuing condition. As such, although the 3^0 cuing method reported the highest accuracy, the continuous used

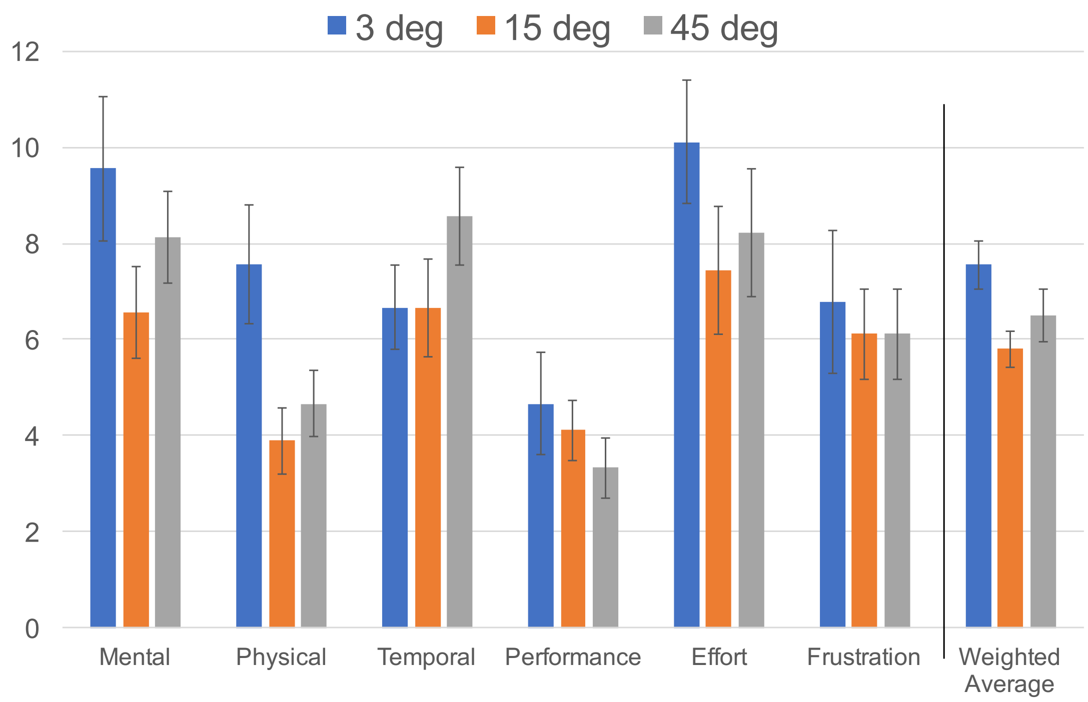


Figure 4.9: NASA TLX scores for each task load factor

of this cuing method could result in frustration or fatigue as commented by some participants.

4.1.7 Discussion

In this work, I explore providing different thermal haptic feedback on the forehead during head motion for a localizing spatial targets. I explored three different cuing methods that had different effective haptic feedback ranges. Based on the results, I demonstrated that 3^0 cuing method was the most accurate, with significantly lower levels of errors. However, 45^0 cuing method had the fastest detection time. In addition, the location of the target had an effect on the detection time where as it had no impact on the detection error. Overall, the results present promising characteristics for further analysis of providing thermal haptic feedback during head motion. Next I discuss some further observations, limitation and future steps in this research.

During the experiment, it was noticed that, under the 3^0 cuing condition, the participants initially spent a higher amount of time trying to locate the target. I observed that the participants moved their head in a faster manner until one of the modules were actuated and dramatically slowed down afterwards. This fast motion at the initial phase indicates that the targets pass the effective haptic feedback range too fast and cause a temperature change that is lower than the human thermal detection threshold. As such, towards the end of the 3^0 cuing method, I observed that the participants slowed down their head motion voluntarily. However, in the 45^0 cuing condition, the participants would feel the thermal feedback immediately, since all the target locations was directly inside the effective haptic feedback range. In addition, this observation is confirmed with the 3^0 cuing condition reported the highest work load.

Based on these observations, one way to improve the cuing methods is to combine the characteristics of the 3^0 and the 45^0 cuing methods. For example, a possibility is to have the left and the right modules to have a higher effective haptic feedback range and the middle module to have a narrower range such that it could improve the speed and accuracy. Such a cuing method "Tactile Fovea" was proposed and evaluated proposed and evaluated in the work of Oliveira et. al. [7]. However, with thermal actuation, this could result in the continuous actuation of the module resulting the temperature reach the pain thresholds. As such, in my next step, I intend to look deeper into a cuing method that can effectively combine the accuracy and speed.

Further feedback from the participants indicated that in certain instances, spending extra amount of time under the 45^0 cuing condition resulted in the temperature dropping too far. As such, one of the participants indicated that the 45^0 cuing method introduced a certain level of urgency to detect the target before the temperature dropped too far. In my current system, although there is a safety cutoff at 24^0C (to avoid the pain threshold:18^0C), this was an important comment to further discuss the cuing method. Therefore, a possible solution in addressing this comment (and also the above), is to stop the thermal actuation and maintain the temperature at a different skin temperature than the initial temperature. However, in such a scenario thermal *adaptation* could occur resulting in loss of perception of the stimulation.

Another possibility to improve the accuracy and the speed of the cuing method is to increase the number of thermal feedback modules. However, one limitation of thermal haptic feedback systems is that, the thermal module (the peltier module in this case) has to be directly in contact with the skin to efficiently produce the stimuli. Therefore, for head based thermal haptic systems, for most users the region with hair on the head cannot be utilized for stimulation. Therefore, I wish to experiment with the efficacy of increasing the number of actuator on the forehead in my future work.

4.1.8 Summary

This experiment introduces a thermal haptic feedback system that is capable of providing directional haptic feedback localizing spatial targets. The system uses three thermal modules (peltier elements) mounted on the forehead. As such, I identified three different cuing methods and evaluated the precision and the detection time for each of the methods. Out of the three different cuing methods the highest precision (lowest error) was reported for the 3^0 cuing method while the fastest detection time was reported for the 45^0 cuing method.

4.2 Thermal Illusion on Wrist

4.2.1 Goal

Thermal feedback has been used in combination with VR device to convey ambient information in VR environment. However, scenarios call for more embodied sensations which might not exist in real world. For example, the sensation of getting pierced by something. However, haptic illusions are capable of present such sensations to users. In recent work, researchers have explored providing illusory haptic sensations such as apparent motions and phantom sensations using a minimal number of haptic actuators [12]. Majority of such research has explored the haptic sensations on the surface of the skin with vibrotactile actuators. In addition, further research by Watanabe et.al. [25], has explored similar principles for implementing through body haptic illusory sensations. By sequentially actuating two actuators setup at the front and the back of the body, this work creates haptic sensation of movement passing through the body.

In this section, I propose a thermo-tactile interface on the wrist to provide such "passing through" feeling.

4.2.2 Implementation

As an initial step, the main scope of this work explores the sensations on the wrist of the user. The wrist provides an ideal location for such haptic systems to be integrated with smart devices such as smart watches in the future. I use, two peltier modules (20x12mm) as the thermal actuators to provide the thermal haptic stimuli. The two modules are attached to the front and the rear of the wrist using of a band ensuring a firm contact between the peltier modules and user's skin. Each peltier module is driven by a full bridge motor controller and an Arduino Mega micro-controller employing a closed loop PID (proportional, integral, derivative) temperature controller for accurate temperature control(Figure 4.10).

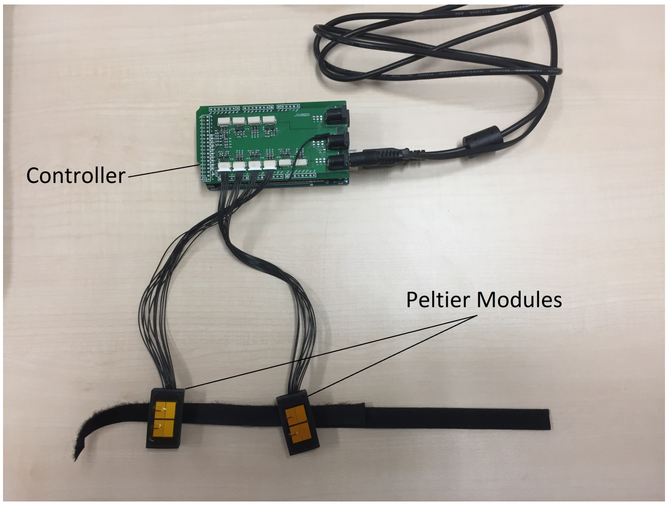


Figure 4.10: Setup for the experiment

4.2.3 Experimental design

Stimuli

The main object of this evaluation was to identify the effect of the stimulus onset asynchrony and the stimuli duration of the stimuli on the thermal haptic passing through illusion (Figure 4.11). As such, there are two independent variables in the experiment: duration (D) and Stimulus Onset Asynchrony (SOA). Duration refers to the stimuli duration (actuation time of the peltier module) .

For the scope of this work, I evaluate only the cold stimuli at a rate of 3/s. For each duration value, both peltier modules are actuated for the same duration

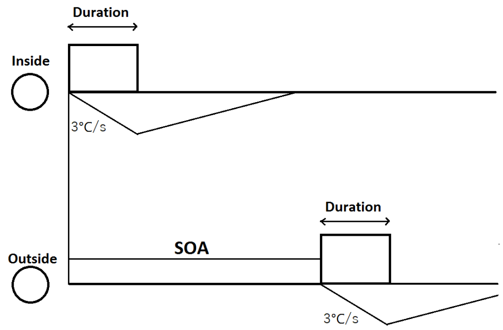


Figure 4.11: Pulse of stimuli and temperature change

(Figure 4.11). For the duration, four values were selected: D400, D600, D800, D1000. For each duration the seven SOA values were evaluated: 50ms, 150ms, 250ms, 350ms, 450ms, 550ms, 650ms. Each stimulus was repeated 3 times. Thus each user was presented 84 (4x7x3) stimuli. During the experiment, the order of four duration were randomized. Next, for each duration, the order of the SOA values too were randomized.

Task

In each task, the participants first reported if they felt any *feeling of passing* of the thermal stimuli through the wrist. Next, they were requested to rate the *the feeling of passing through* (FoP) on a scale of 0-3. If the two stimuli were perceived at the same time or if they were perceived as two completely different stimuli, then FoP was rated as 0.

Experiment Procedure

Before the test, as shown in Figure 4.12 I attached the interface onto the user's wrist. For each task, the stimuli would start from the inside module. Before the beginning of the experiment, participants were introduced to the stimuli during the instruction phase. For each test, firstly participant would perceive stimuli.Then according to the feeling he interprets it. Finally, participant record their answer. Stimuli are presented in every 15s.

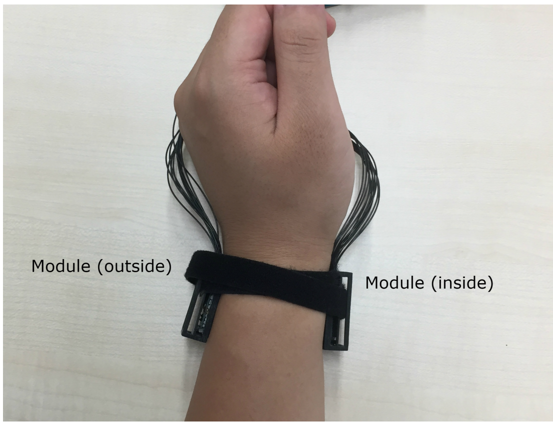


Figure 4.12: Interface on the user's wrist

Subjects

6 subjects (5 male,1 female) of average age 25.8 participated in the study. All of them went through the study. During the study, a rest is available when they feel it is necessary.

4.2.4 Result

The overall results are indicated in Figure 4.13. As observed, for the stimuli of D400, the peak FoP of 1.33 is reached between SOA 150ms and SOA 250ms. For the stimuli of D600, the peak FoP of 1.66 is reached approximately at SOA 350ms. For the stimuli of D800, the peak FoP of 1.63 is reached at SOA 450ms. Next, for the stimuli of D1000, the peak FoP of 1.56 is achieved approximately at SOA 250ms. In addition, as observed in the trend lines, I can observe that as the duration increases, the peak SOA is increased as well.

4.2.5 Discussion

In this experiment, I attempted to create a feeling of passing through with by sequentially actuating two thermal modules on the wrist. From the result, I observed that in all of the condition, participant perceives the feeling of passing through. In addition the maximum FoP was achieved during the duration of 800ms. The results successfully demonstrate the capability of providing passing through haptic illusion using thermal stimuli.

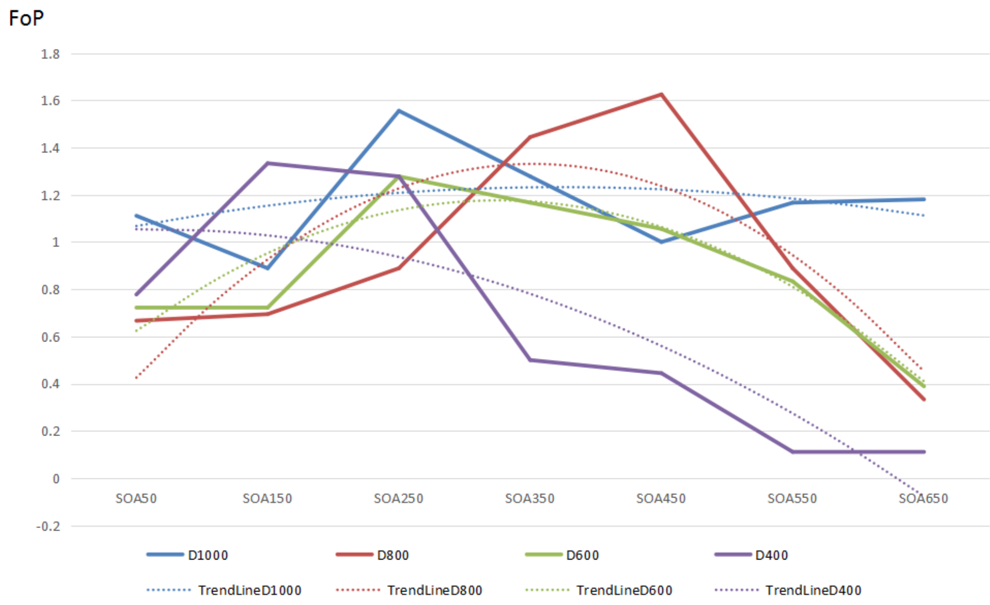


Figure 4.13: Result of the User Study

4.3 Sensitivity Difference on Bottom of Foot

4.3.1 Goal

The third experiment is going to exam the properties of thermal perception on foot. Different from the other body parts like forearm or forehead, thermal perception on the bottom of foot is not fully investigated yet. Since human use feet to step on the ground and get the information of the ground from the sensation on the bottom of feet, as a initial step, I start the research on the thermal sensitivity on the bottom of foot.

4.3.2 Implementation

Figure4.14 show the experiment system. PC sends the signal to the thermal display(thermal shoe). Then according the signal, thermal stimuli presented to the subject. After user perceived the stimuli, he would asked to .... In this experiment, I used the previous thermal display4.10 to produce thermal stimuli. I used 4 modules in this experiment and attached them in 4 locations. Modules kept a distance between each other. The locations of modules shows in figure4.16.

I chose this layout because for the further investigation, more kinds of thermal sensation such as motion illusion are going to be exam. This arrangement is capable of providing both vertical and horizontal stimuli. To make it comfortable for user to step on the modules and to avoid malposition, I modified one of the slippers into my "thermal shoe"4.15. I tapped four modules to the thermal shoe right in the position showed in figure4.16. After user put on the shoe, he could fasten the magic tap to make the attachment stay stable.

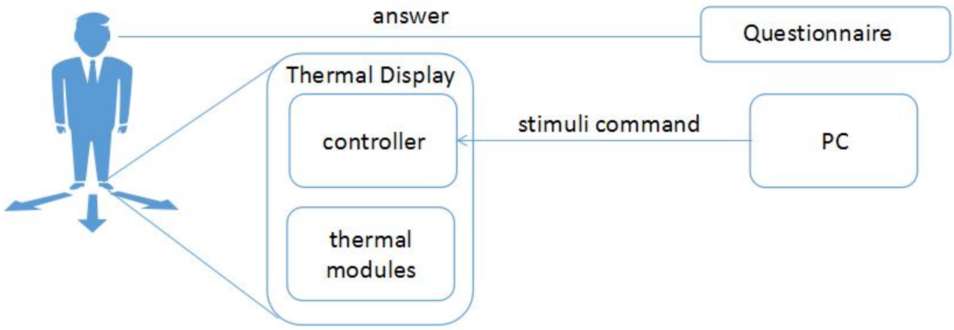


Figure 4.14: System of the experiment

Figure 4.15: Thermal Shoe

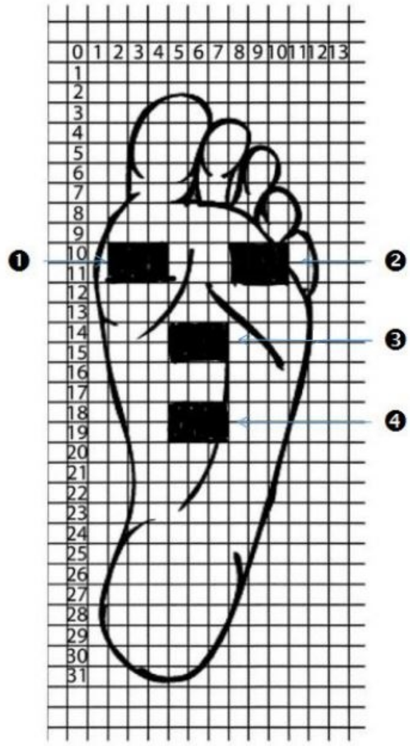


Figure 4.16: Layout of modules on questionnaire

4.3.3 Experimental Design

Questionnaire

To record the answer from subjects, I made a questionnaire showed in figure 4.17. In the questionnaire, the image of foot indicates the subject's foot. The image of foot is divided by a 13x31 grid. Such grid is used to define the affected area and show the properties of thermal perception on the bottom of foot.

Task

I introduced a simple task to measure the perception on foot. Before the experiment, subjects would get blank questionnaires. In each task, firstly, subjects could perceive a single stimulus or one kind of combination of stimuli on the foot for 3 times. Subjects need to draw the questionnaire with color pen in the position where he feels thermal stimuli. And the area he drew should be as large as the influenced area he felt. According to the number of module actuated in the same

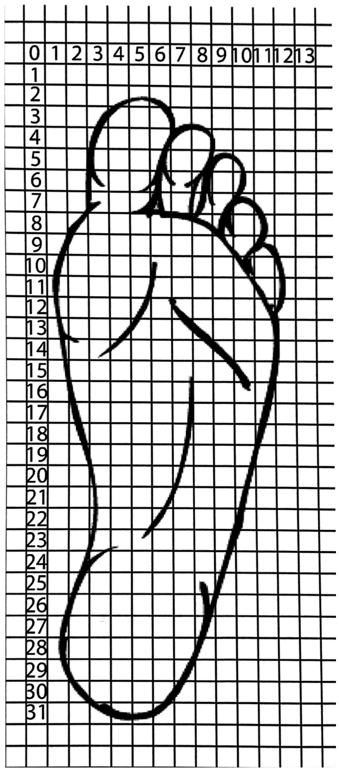


Figure 4.17: Questionnaire

time, the presented stimuli could be divided into 4 types. Both hot stimuli and cold stimuli are involved in this experiment. So there are 8 session in the experiment. And based on the permutation, there are different number of tasks in each session. For instance, in cold stimuli and 2 modules actuated condition, computer would randomly select 2 position among the 4 positions automatically and make sure there is no repeat in this session. So there are 6 (C_4^2) tasks in this session. The number of tasks shows in the table4.1. For each subject, 30 tasks would be carried out. Figure 4.19 is a example of a finished questionnaire for one task. In this task, stimuli in position 1 and in position 2 presented on the subject's foot. This questionnaire indicated that the subject perceived the thermal stimuli and could point out the location of the stimuli correctly. There are 5 subjects involved in this experiment.

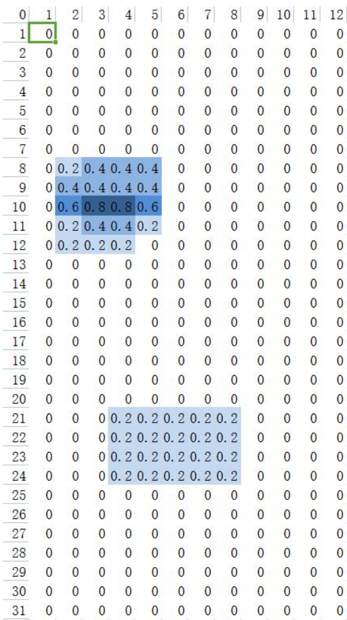
Table 4.1: number of tasks in each condition

number of tasks	1 module	2 modules	3 modules	4 modules
cold stimuli	4	6	4	1
hot stimuli	4	6	4	1

4.3.4 Result

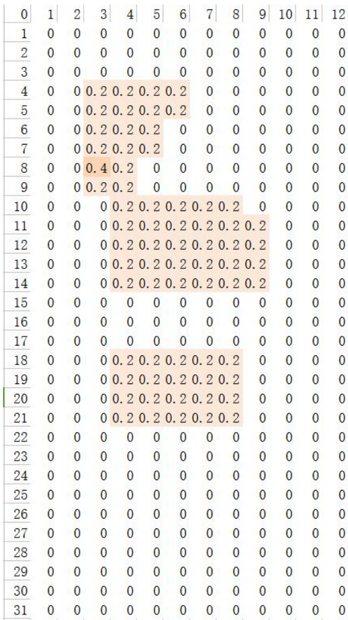
accuracy for location detection

After the experiment, I drew thermal graphs to clarify the properties of thermal perception on bottom of foot. Figure4.18 shows the comparison of thermal perception in position 1. Thermal graphs for stimulus on other position share same traits. The number in the foot area is the average times that user drew. These figures indicate that ,firstly, users could perceive the stimuli. Secondly, it's not easy for them to detect the exact position of stimuli. Thirdly, cold stimuli performs better than the hot stimuli.



0	1	2	3	4	5	6	7	8	9	10	11	12
1	0	0	0	0	0	0	0	0	0	0	0	0
2	0	0	0	0	0	0	0	0	0	0	0	0
3	0	0	0	0	0	0	0	0	0	0	0	0
4	0	0	0	0	0	0	0	0	0	0	0	0
5	0	0	0	0	0	0	0	0	0	0	0	0
6	0	0	0	0	0	0	0	0	0	0	0	0
7	0	0	0	0	0	0	0	0	0	0	0	0
8	0	0.2	0.4	0.4	0.4	0	0	0	0	0	0	0
9	0	0.4	0.4	0.4	0.4	0	0	0	0	0	0	0
10	0	0.6	0.8	0.8	0.6	0	0	0	0	0	0	0
11	0	0.2	0.4	0.4	0.2	0	0	0	0	0	0	0
12	0	0.2	0.2	0.2	0	0	0	0	0	0	0	0
13	0	0	0	0	0	0	0	0	0	0	0	0
14	0	0	0	0	0	0	0	0	0	0	0	0
15	0	0	0	0	0	0	0	0	0	0	0	0
16	0	0	0	0	0	0	0	0	0	0	0	0
17	0	0	0	0	0	0	0	0	0	0	0	0
18	0	0	0	0	0	0	0	0	0	0	0	0
19	0	0	0	0	0	0	0	0	0	0	0	0
20	0	0	0	0	0	0	0	0	0	0	0	0
21	0	0	0	0.2	0.2	0.2	0.2	0.2	0	0	0	0
22	0	0	0	0.2	0.2	0.2	0.2	0.2	0	0	0	0
23	0	0	0	0.2	0.2	0.2	0.2	0.2	0	0	0	0
24	0	0	0	0.2	0.2	0.2	0.2	0.2	0	0	0	0
25	0	0	0	0	0	0	0	0	0	0	0	0
26	0	0	0	0	0	0	0	0	0	0	0	0
27	0	0	0	0	0	0	0	0	0	0	0	0
28	0	0	0	0	0	0	0	0	0	0	0	0
29	0	0	0	0	0	0	0	0	0	0	0	0
30	0	0	0	0	0	0	0	0	0	0	0	0
31	0	0	0	0	0	0	0	0	0	0	0	0

(a) cold stimuli



0	1	2	3	4	5	6	7	8	9	10	11	12
1	0	0	0	0	0	0	0	0	0	0	0	0
2	0	0	0	0	0	0	0	0	0	0	0	0
3	0	0	0	0	0	0	0	0	0	0	0	0
4	0	0	0.2	0.2	0.2	0.2	0	0	0	0	0	0
5	0	0	0.2	0.2	0.2	0.2	0	0	0	0	0	0
6	0	0	0.2	0.2	0.2	0	0	0	0	0	0	0
7	0	0	0.2	0.2	0.2	0	0	0	0	0	0	0
8	0	0	0.4	0.2	0	0	0	0	0	0	0	0
9	0	0	0.2	0.2	0	0	0	0	0	0	0	0
10	0	0	0	0.2	0.2	0.2	0.2	0.2	0	0	0	0
11	0	0	0	0.2	0.2	0.2	0.2	0.2	0.2	0	0	0
12	0	0	0	0.2	0.2	0.2	0.2	0.2	0.2	0	0	0
13	0	0	0	0.2	0.2	0.2	0.2	0.2	0.2	0	0	0
14	0	0	0	0.2	0.2	0.2	0.2	0.2	0.2	0	0	0
15	0	0	0	0	0	0	0	0	0	0	0	0
16	0	0	0	0	0	0	0	0	0	0	0	0
17	0	0	0	0	0	0	0	0	0	0	0	0
18	0	0	0	0.2	0.2	0.2	0.2	0.2	0	0	0	0
19	0	0	0	0.2	0.2	0.2	0.2	0.2	0	0	0	0
20	0	0	0	0.2	0.2	0.2	0.2	0.2	0	0	0	0
21	0	0	0	0.2	0.2	0.2	0.2	0.2	0	0	0	0
22	0	0	0	0	0	0	0	0	0	0	0	0
23	0	0	0	0	0	0	0	0	0	0	0	0
24	0	0	0	0	0	0	0	0	0	0	0	0
25	0	0	0	0	0	0	0	0	0	0	0	0
26	0	0	0	0	0	0	0	0	0	0	0	0
27	0	0	0	0	0	0	0	0	0	0	0	0
28	0	0	0	0	0	0	0	0	0	0	0	0
29	0	0	0	0	0	0	0	0	0	0	0	0
30	0	0	0	0	0	0	0	0	0	0	0	0
31	0	0	0	0	0	0	0	0	0	0	0	0

(b) hot stimuli

Figure 4.18: comparison of thermal perception on position 1

varied thermal perception

I also observed the thermal perception varied from the location. The result reports the sensitivity of thermal sensation on position 1 and 2 is relatively weaker that it is on position 3 and 4. For the stimuli on position 4, some subjects reported that, instead of feeling the stimuli on the central of foot, they feel it is more like a stimuli on the heel. And usually they would have the feeling in all area of the heel.

thermal spread effect

Also from the subjects' questionnaires, heat spread effect is also a remarkable phenomenon in the experiment. No matter stimuli on more sensitive position (2 and 3) or less sensitive position(1 and 2), subject tend to draw larger than the affected area indeed. It means When nearby module actuated together, rather than two separated stimuli, subject would feel one single pulse of stimulus on a large area. This situation happens in hot stimuli condition more than the cold stimuli condition. So this finding may give the suggestion or principle for thermal contents design: hot stimuli is suit for presenting the overall environmental information(for example walking on the sand in desert) and cold stimuli have the potential to be used in scenario which needs more precise thermal performance (for example presenting the flow of water).

4.3.5 Discussion

Based on the result of the experiment, some principles could be followed in the future work for thermal experience design on foot. Firstly, from the answer, most subjects could perceive the thermal stimuli on the bottom of foot. It means bottom of foot has the potential to be a interface to perceive the thermal stimuli. Secondly, in the experiment many subjects mentioned that: "when all the modules get actuated, though I cannot identify the exact position since almost the whole bottom of foot feel the sensation, I could imagine that I am walking on the ice or on the ground the desert". This feedback indicate that thermal stimuli on the bottom of foot could be used as a tool to present the environmental information especially the information of ground. Thirdly, user might have problem in detecting the position of stimuli, so it's not recommended to user thermal stimuli to present precise information. However if you have to, the cold stimuli is recommended.

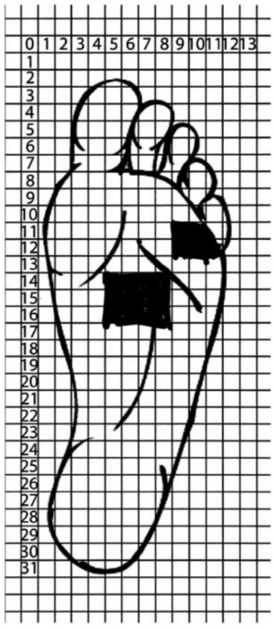


Figure 4.19: questionnaire for stimuli in position 2 and 3

Notes

1 This research on the forehead's thermal perception has been published in World Haptics Conference 2017 [23]

2 `https://www.arduino.cc/en/Main/ArduinoBoardNano`

Chapter 5
Conclusions

5.1 Conclusion

To exam the hypothesis that thermal stimuli applied on body extremities lead to different recognition and interpretation, I conducted three experiment investigating the thermal perception on forehead, on wrist and on foot. Though thermal stimuli in all three experiments share the same rate-of-change (3^0C/s), brain would interpret the stimuli into information according to the duty of body extremities. In the first experiment on forehead, I made a proposal of using thermal stimuli on user's forehead to present the direction of virtual object. Furthermore, I also evaluated three kinds of cueing method on spent time, accuracy and workload. In this experiment,I generated spatial awareness for user(user could detect the target in VR environment). In the second experiment, most of subjects perceived a passing through feeling by two stimuli in an interval. The last experiment investigate the thermal resolution and the heat-spread effect. Three experiment above show the different thermal sensation effects in different body extremities and this prove the hypothesis.

5.2 Limitation

In the experiment for thermal perception on foot, though the result report that subjects are able to detect the stimuli and point out the position roughly, it has also been observed that there is a heat-spread effect, which makes subjects feel a large influenced area and reduced the resolution of thermal perception on foot. Thus I Fail to create a application for thermal stimuli on foot. Meanwhile, the purpose of this research is to investigate the thermal perception of body extremities and to contribute to the design of thermal display. When talking about thermal display, referring to the current visual display, users are expecting a high resolution and vividly performance of thermal information which unfortunately is beyond the ability of current technology. Despite of this, thermal stimuli could be used as a low-context information carrier or just a single pulse in the field of navigation. Another limitation for current technology is the power supply. Since the utilization of thermal display is to be integrated it with Augment Reality or Virtual Reality environment, which means a wearable wireless system is expected in the future. Also after the experiments, some feedback from subjects is reported. User reported the impact when they perceived the thermal stimuli at the first time, because for many of them it's their first time perceive the artificial thermal stimuli. However after experiencing the thermal stimuli in the experiment, such impact weakens. One question was often mentioned after the thermal experience which is how to provide new impact feeling to the experienced users. On the one hand, the purpose of the thermal display is to present information and make user perceive it subconsciously. Less attention to the thermal stimuli itself is exactly what we want. On the other hand, in the industry field, it's important to keep providing product with impact for the consumer. The factor mentioned above might not fulfill the need. Since the fact that skin or furthermore the human body would eventually get used to the stimuli, in this case, instead of working on the thermal stimuli and trying to generate some new stimuli that could make user feel the impact, it's more reasonable to step by step improve the performance of thermal stimuli and apply the thermal stimuli to body parts. During this process, user could keep enjoy the impact until all the important position used to be the interface for thermal stimuli.

5.3 Future Work

Apparently, body extremities are the most common tools that we used to perceive the information from environment and interact with environment. Thus thermal stimuli on the body extremities has the potential to be used to present the environmental information. In the research, though I just investigated several pattern of thermal stimuli and generate some specific thermal sensation successfully, it indicate that more thermal sensation could be presented to the use. So for the future work, more specific thermal sensation that could be presented by artificial thermal stimuli should be explored. Meanwhile, the combination of these thermal sensation should be considered. In my case, I am going to combine the spatial awareness and the passing through feeling together as a integrated experience.

The scenario of riding a bicycle in the winter is right fit for the need. In this scenario, two sensation should be designed.They are design the could wind and the piercing feeling. As for the former one, referring to the first experiment, thermal modules on forehead could present the direction of the wind. What's more, based on the head's orientation, system could adjust the stimuli to reflect the direction of wind. As for the piercing feeling, referring to the second experiment, a cold passing through feeling could be generated in the wrist to simulate such feeling. In this way, the integrated thermal experience, riding in the winter, could be simulated.

References

[1] Ackerley, R., Carlsson, I., Wester, H., Olausson, H., and Backlund Wasling, H. Touch perceptions across skin sites: differences between sensitivity, direction discrimination and pleasantness. *Frontiers in Behavioral Neuroscience 8* (feb 2014), 54.

[2] Akiyama, S., Sato, K., Makino, Y., and Maeno, T. Thermon: Thermo-musical interface for an enhanced emotional experience. In *Proc. International Symposium on Wearable Computers* (2013), 45–52.

[3] Berning, M., Braun, F., Riedel, T., and Beigl, M. Proximityhat: A head-worn system for subtle sensory augmentation with tactile stimulation. In *Proceedings of the 2015 ACM International Symposium on Wearable Computers*, ISWC '15, ACM (New York, NY, USA, 2015), 31–38.

[4] C. STEVENS KENNETH K. CHOO, J. Temperature sensitivity of the body surface over the life span. *Somatosensory & motor research 15*, 1 (1998), 13–28.

[5] Cassinelli, A., Reynolds, C., and Ishikawa, M. Augmenting spatial awareness with haptic radar. In *2006 10th IEEE International Symposium on Wearable Computers* (Oct 2006), 61–64.

[6] Chen, Z., Peiris, R. L., and Minamizawa, K. A thermally enhanced weather checking system in vr. In *Adjunct Publication of the 30th Annual ACM Symposium on User Interface Software and Technology*, UIST '17, ACM (New York, NY, USA, 2017), 123–125.

[7] de Jesus Oliveira, V. A., Nedel, L., Maciel, A., and Brayda, L. Localized magnification in vibrotactile hmds for accurate spatial awareness. In *EuroHaptics 2016* (2016), 55–64.

[8] Green, B. G., and Cruz, A. "Warmth-insensitive fields": evidence of sparse and irregular innervation of human skin by the warmth sense. *Somatosens Mot Res 15*, 4 (1998), 269–275.

[9] Halvey, M., Wilson, G., Brewster, S., and Hughes, S. "baby it's cold outside": The influence of ambient temperature and humidity on thermal feedback. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*, CHI '12, ACM (New York, NY, USA, 2012), 715–724.

[10] Halvey, M., Wilson, G., Brewster, S. A., and Hughes, S. A. Perception of thermal stimuli for continuous interaction. In *CHI '13 Extended Abstracts on Human Factors in Computing Systems*, CHI EA '13, ACM (New York, NY, USA, 2013), 1587–1592.

[11] Hart, S. G. Nasa-task load index (nasa-tlx); 20 years later. *Proceedings of the Human Factors and Ergonomics Society Annual Meeting 50*, 9 (2006), 904–908.

[12] Israr, A., and Poupyrev, I. Tactile brush: drawing on skin with a tactile grid display. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*, ACM (2011), 2019–2028.

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

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

[15] Kajimoto, H., Kanno, Y., and Tachi, S. Forehead electro-tactile display for vision substitution. In *Proc. EuroHaptics* (2006).

[16] Kenshalo, D. Correlations of temperature sensitivity in man and monkey, a first approximation. In *Sensory functions of the skin in primates*. Elsevier, 1976, 305–330.

[17] Kenshalo, D. R., Holmes, C. E., and Wood, P. B. Warm and cool thresholds as a function of rate of stimulus temperature change. *Attention, Perception, & Psychophysics 3*, 2 (1968), 81–84.

[18] Kratz, S., and Dunnigan, A. Thermotouch: Design of a high dynamic temperature range thermal haptic display. In *Proceedings of the 2016 CHI Conference Extended Abstracts on Human Factors in Computing Systems*, CHI EA '16, ACM (New York, NY, USA, 2016), 1577–1582.

[19] Lee, W., and Lim, Y.-k. Thermo-message: Exploring the potential of heat as a modality of peripheral expression. In *CHI '10 Extended Abstracts on Human Factors in Computing Systems*, CHI EA '10, ACM (New York, NY, USA, 2010), 4231–4236.

[20] Mann, S., Huang, J., Janzen, R., Lo, R., Rampersad, V., Chen, A., and Doha, T. Blind navigation with a wearable range camera and vibrotactile helmet. In *Proceedings of the 19th ACM International Conference on Multimedia*, MM '11, ACM (New York, NY, USA, 2011), 1325–1328.

[21] Peiris, R. L., Chan, L., and Minamizawa, K. Thermocons: Evaluating the thermal haptic perception of the forehead. In *Proceedings of the 29th Annual Symposium on User Interface Software and Technology*, UIST '16 Adjunct, ACM (New York, NY, USA, 2016), 187–188.

[22] Peiris, R. L., Peng, W., Chen, Z., Chan, L., and Minamizawa, K. Thermovr: Exploring integrated thermal haptic feedback with head mounted displays. In *Proceedings of the 2017 CHI Conference on Human Factors in Computing Systems*, CHI '17, ACM (New York, NY, USA, 2017), 5452–5456.

[23] Peiris, R. L., Peng, W., Chen, Z., and Minamizawa, K. Exploration of cuing methods for localization of spatial cues using thermal haptic feedback on the forehead. In *World Haptics Conference (WHC), 2017 IEEE*, IEEE (2017), 400–405.

[24] Singhal, A., and Jones, L. A. Dimensionality of thermal icons. In *2015 IEEE World Haptics Conference (WHC)* (June 2015), 469–474.

[25] Watanabe, J., Fukuzawa, Y., Kajimoto, H., and Ando, H. Presentation of feeling when pierced using apparent movement passing through the body. *Journal of Information Processing 49*, 10 (oct 2008), 3542–3545.