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THERMAL PERCEPTION OF SKIN USING OPTICAL PROJECTIONS

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ABSTRACT

The largest human organ is skin, which covers and protects the body from external objects and serves as a medium of interaction with the outside world. Having adequate knowledge about human thermal perception aids in the design of devices that interact with skin and broaden our perspective of the affecting parameters in the perception process. A thermal projector was designed based on an Optima X316 Projector which is capable of creating different thermal patterns on a surface with different intensities by use of visible light waves. Skin temperature was measured via a FLIR A325-SC thermal camera. Using these devices we were able to create thermal patterns and control the rates at which the temperature of human skin is changed. A psychophysical experiment using the setup was used to determine skin thermal sensitivity and threshold. Subjects' skin was exposed to different thermal projections and their skin was heated at constant rates to certain degrees higher than their skin temperature. As their skin temperature was altered incrementally on each location, they stated whether they could feel the heat on their skin. The experiment showed that there was statistical significance between the rate at which the subjects' skin was heated and whether the subjects felt a temperature change. Statistical significance was also found between the amount of exposure time prior to the instance subjects felt a change in temperature and the rate at which the skin was exposed.

INTRODUCTION

One way humans identify objects is through bidirectional heat exchange between the skin and the object. For example we can sense the difference of plastic versus metal because the heat exchange between the skin and the metal is quicker than between the skin and the plastic, therefore the metal feels colder than the plastic [1]. This is one of the important haptic interactions that allow us to distinguish between different materials.

Thermal sensations are experienced in many aspects of human interaction and can be used to improve haptic devices. Current haptic displays render different 3D shapes, textures, and stiffness values by the use of haptic devices. These devices make use of haptic feedback types such as force or vibration. Most haptic displays have not explored the use of thermal haptics to assist in making these rendered objects seem more real. There have been a few studies on thermal feedback on human skin in haptic applications. Most of them employed peltier devices in their designs [2–5] which are not easily portable and can be unsafe since their range of temperature change is very high. Gallo et al. [6] developed an experimental setup that has eliminated this setback.

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The human perception of temperature is one of the slowest reacting compared to other haptic senses like force, pressure, skin stretch, and vibration [7]. Humans perceive changes in temperatures by means of thermoreceptors. Thermoreceptors are located throughout the skin. Skin sensitivity depends on the location and distribution of thermoreceptors. There are two types of thermoreceptors in skin: cold receptors and hot receptors. Cold receptors are located in the dermis of the skin while warm receptors are located more along the surface of the skin. Both hot and cold thermoreceptors show dynamic and static responses that represent the rate of change and absolute value of temperature [8].

Thermoreceptors behave nonlinearly in response to thermal stimulus. It has been shown that human skin is less sensitive to changes in the temperature at slower rates. Kenneth et al. [9] derived a map for thermal sensitivity of human skin. Figure 1 indicates that if the temperature of the skin is increased at a slow rate, less than 0.05°C/sec, then an observer can be unaware of a change of up to 2-3°C, provided that the temperature remains within the neutral zone of human temperature which is around 30-36°C. If the change occurs at a more rapid rate, such as at 0.1°C/sec, then observers can detect small increases and decreases in skin temperature [8].

In order to implement thermal perception to current haptic displays, the thermal perception of humans in different parts of the body needs to be studied more thoroughly. A better understanding of the thermal perception of humans can be manipulated to help virtual objects feel more realistic.

Studies have been performed that show how different emotions can cause temperature variations in the skin [11]. For example anger manifests itself by an increase in body temperature in the face, chest and the extremities of the arm. Shame, on the other hand, manifests itself by the reduction in temperature in the lower body, the extremities of the arm, and an increase in temperature in the cheeks and chest [12].

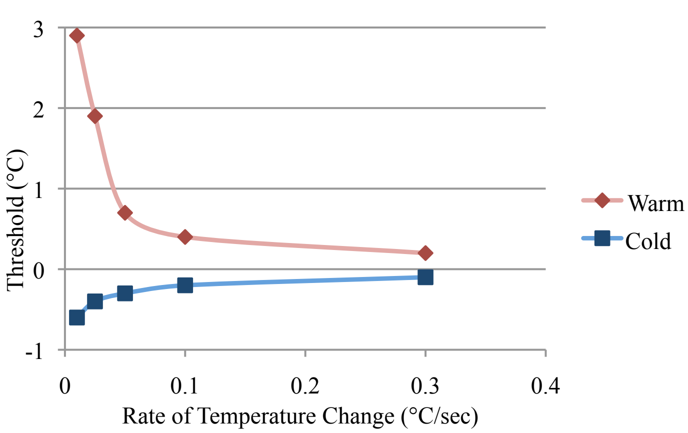

FIGURE 1. Thermal sensitivity of human skin to hot and cold stimulation at different rates [10].

Experiments have also been conducted in which subjects were presented with a "thermal grill" and some subjects experienced a sensation of pain. The thermal grill consists of equally spaced hot and cold sections that change the temperature of the skin only slightly above or below normal [13]. Even though the temperature of the skin is actually only changed slightly, the subjects still experienced a sensation of pain and discomfort when they were exposed to the thermal grill [13]. One of the proposed reasons why this occurs is because the skin is cooled and heated in such a small section that it tricks the body into thinking that the skin is at a higher temperature than it actually is, and the rate of increase of temperature also seems higher.

The goal of this project is to understand how individuals perceive dynamically changing temperature on their skin. The alternative approach presented here uses a modified projection system to create thermal patterns. The advantage of this approach is that no physical contact is needed with the skin, and it has the potential to be transformed into a portable thermal feedback system. We hypothesize that this device can deliver similar amounts of increased temperature and result in a similar perception as the peltier-based method. However, this projector-based method is only capable of heating, so other methods need to be employed to generate the cooling stimulus. This paper focuses on the generation of dynamic thermal patterns on the skin and understanding how humans perceive those patterns.

METHODOLOGY

In this experiment a thermal camera and an Optima X316 projector are used for closed-loop feedback control that creates temperature changes on an individual's skin and simultaneously measure the changes in temperature of the skin. The projector uses visible light at high intensities to increase the temperature of the skin. Due to intrinsic characteristic of this projector, the device can heat the skin at different rates by changing the shade of the image displayed. A white image provides the highest intensity of light and also creates the largest rate of temperature change. Black image generates the lowest intensity of light and therefore does not affect the skin temperature.

Naturally there is thermal disturbance in the environment due to factors like air conditioning and blood circulation in body and skin therefore a PID control is used to adjust the shade of the image to provide a constant temperature throughout the projected area. Using aforementioned precautions and strategies, a just noticeable difference (JND) evaluation can be performed. A thermal camera (FLIR A325-SC) is used to measure the response of the skin to the high intensity light. The camera provides temperature data for every pixel of the projector image.

In order to better understand the thermal perception of skin and what affects the dynamic and static temperature responses, a psychophysical test was conducted to determine the JND threshold of the skin. Subjects responded when they felt a temperature change on the projected area of their arm. Multiple temperature rates were used on each subject. To mitigate the risk of disturbing the initial temperature of the skin for each experiment, subjects' arms were cooled to room temperature before starting each experiment.

EXPERIMENTAL SETUP

Hardware

A thermal projector was modified that can create different thermal patterns on a surface with different intensities. This device is based on an Optima X316 Projector that was used to provide a temperature change on human skin by the use of visible light waves. The projector has a power density of 0.15 W/m^3 which can result in approximately a 1.2°C change in the temperature of the skin for an area of 11 x 8 cm. In this way we will control skin temperature over a certain area and try to measure thermal dissipation characteristics of skin in neighboring areas of the controlled region. Skin temperature will be measured via a FLIR A325-SC thermal camera with a resolution of 320x240 and a 60HZ frame rate. The accuracy of the camera measurement is +/-2% of reading and it can operate on a range of -20 °C to 120 °C. Since the maximum temperature in our scenario is 32°C, a maximum error of 0.64°C can be expected.

The thermal camera was mounted on top of the projector so that the camera view was the closest and at a small angle relative to the projection from the projector. Positioning is important to minimize image transformation so as to be able to properly read the incoming thermal image and project the outgoing projection image. Since the camera focal point was approximately two inches above the projector focal point (Figure 2) and the camera had to be tilted at approximately 27°with respect to the projector, a transformation was performed on every incoming thermal image so that there would be a one to one mapping between thermal camera and projector pixels. The transformation was done by choosing four corners of the rectangular cross-section sent to the projector and then choosing four corners of the cross-section seen by the thermal camera on the subject's arm. This enabled us to program MATLAB to develop a transformation matrix to change every incoming image back into the original shape and size as the one sent to the projector.

Software

Once the thermal camera image was transformed, the area of interest was isolated and the thermal data from the surroundings was cropped. PID control was deployed on every pixel in order to keep the temperature of the subject's skin at a constant value. Once the required light intensity was calculated for each pixel based on thermal camera recording, the resulting image was sent back to the projector and projected on the subject's skin. 250 frames were acquired in approximately 32 seconds of exposure time. This number of frames was chosen because of limited buffer size of camera memory. Additionally, we did not want the exposure time to be more that 40 seconds to prevent heating the subject's skin excessively.

FIGURE 2. System set up. The figure shows the Optima projector with the FLIR thermal camera mounted on the top of the projector, along with the fixtures developed to block the exhaust coming from the projector and the fixture where the subjects will place their arm.

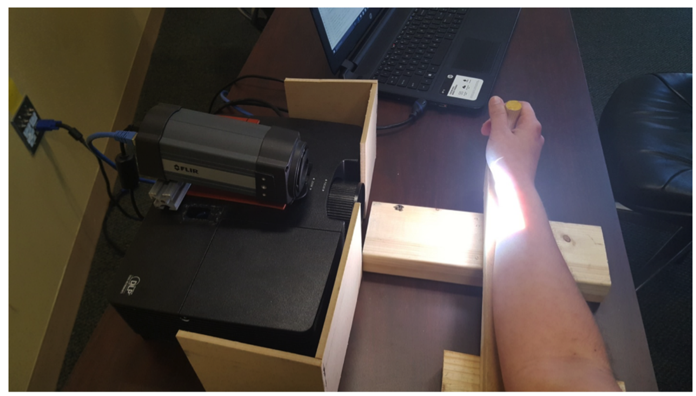

FIGURE 3. Experimental setup while an experiment is conducted.

PROCEDURE

Seven subjects (2 females) aged between 20 and 29 were part of the experiment. Subjects were asked to place their right arm across a wooden fixture and to grab a wooden dowel in order to minimize the movement of their arm (Figure 3). They were also given the choice to wear welding glasses or to close their eyes to obstruct any visual cues and rely solely on their thermal sensing of their skin. Information about the subject's age, gender, skin color and temperature ramp rate were recorded prior to every experiment. Prior to participating, each individual read and signed a consent form approved by the University of South Florida's IRB.

Temperature ramp rates of 1/30, 1/10 and 1/5 °C/s were tested for each individual subject. Subjects were told to inform the experimenter when they felt a temperature change in their arm. When the subject indicated feeling a temperature change, a button was pressed that stopped the experiment. Five frames of data were acquired after pressing the button in order to accurately look at the ramp rate of the temperature. After each experiment there was a 45 seconds delay to allow the subject's arm to return back to room temperature so that it did not affect the experiment results.

RESULTS

After conducting the experiment, a statistical analysis was performed to determine the significance between the rates at which the skin temperature was changed, the length of time the skin temperature was heated, and whether the subject felt a temperature change. Figure 4 illustrates results and the relationship between the rate at which skin was heated and the percentage of subjects that sensed a change in temperature. Figure 5 also shows a positive correlation between the total time the skin was exposed before the subject felt a temperature change and the rate at which the skin was heated.

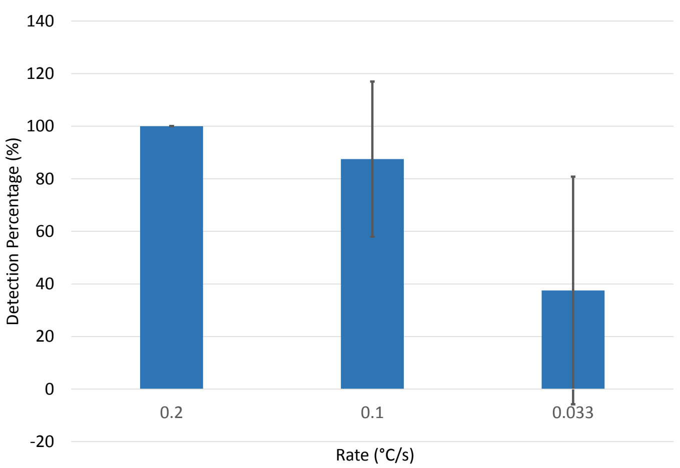

FIGURE 4. Results that show the correlation between the rate at which the skin was heated versus the percentage of subjects that felt a change in temperature.

A repeated-measures ANOVA was performed with a dependent variable of subject response and an independent variable of rate with three factors (0.0333, 0.1, and 0.2 °C/s). The subject's responses to whether they felt the change in temperature was statistically significantly different ($F(2,14) = 7.74$, $p < .001$). Post hoc analysis with Bonferroni corrections showed that the 0.0333°C/s and 0.2°C/s rates were perceived with a statistically

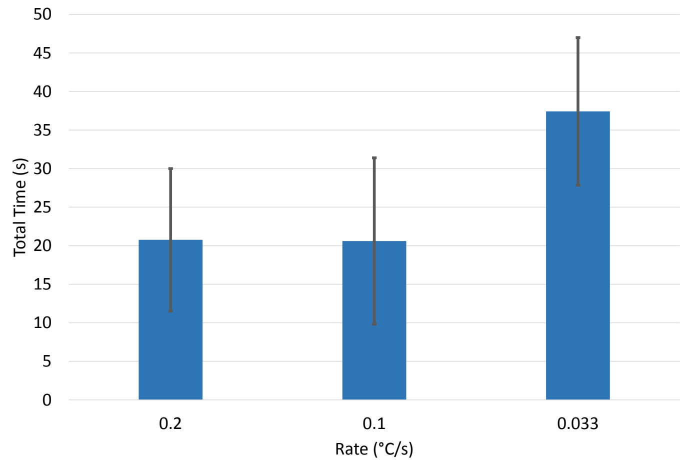

FIGURE 5. Results that show the correlation between rate at which the skin was heated versus the total amount of time the skin was exposed prior to the subjects sensing a change in temperature.

significant difference. The 0.1°C/s rate was not statistically significantly different than the other rates.

A repeated-measures ANOVA was performed with a dependent variable of the total amount of time the skin was exposed before the subject sensed a change in temperature, and an independent variable of rate with three factors (0.0333, 0.1, and 0.2 °C/s). The total time of exposure before they felt the change in temperature was statistically significantly different ($F(2,14) = 10.09$, $p < .001$). Post hoc analysis with Bonferroni corrections showed that the 0.0333°C/s rate was statistically significant different than both the 0.1°C/s and 0.2°C/s rates. There was no statistically significantly difference between the 0.1°C/s and 0.2°C/s rates. In this case, since the number of frames per second was known, the total frame numbers were divided by the camera recording frame rate which yielded lapsed time for each experiment.

These results show that the faster the rate at which the temperature is changed, the quicker the person perceived their skin being heated, and the slower the rate, the longer it took the person to perceive the temperature change. This result is in agreement with available evidence in the literature [10]. It is worth to mention that in some cases, subjects did not feel any temperature change at all in lower rates of temperature change, but this is true in other studies of thermal perception as well.

It is worth mentioning that although a desired rate of temperature increase was commanded to the system, the projector was not powerful enough to keep up with the rates desired. So even though the desired rates were 1/5, 1/10, 1/30 the achieved rates were slightly lower.

CONCLUSIONS

A system is developed that is capable of providing real time dynamic temperature changes, using a visible light projector and a thermal camera. The projector is able to generate heat by projecting different intensities of white light onto the human skin, and the heating can be provided at different rates using different levels of grayscale pixels. The thermal camera provides real time temperature readings of temperature of the skin. That information was used to design a closed loop control by means of a PID algorithm and change the outputting image according to the thermal camera inputs.

The system created provided basic temperature control to be used for thermal haptics. After the experiments were conducted, a positive correlation was shown between the rates at which the temperature was heated, the total amount of time the skin was exposed and whether the subject felt a change in temperature or not. Statistical significance was detected between theses parameters.

FUTURE WORK

In spite of being able to provide controlled heating to the skin, some improvements are needed for future experiments. Since the purpose of the research is to determine how humans perceive temperature and if skin temperature can be altered in certain ways to create a consistent perceptible thermal response, a method has to be developed to cool the neighboring areas of heating regions on the skin. Right now the system is only capable of heating the skin at constant rates. Also modifications need to be done to the projector in order to increase the intensities of the output image so that the skin temperature can be changed at the rates desired.

During the experiments it was observed that the average resting skin temperature of the subjects varied by up to two degrees Celsius. This affected the results between subjects because the increasing rate of temperature was set to start at the same temperature for all subjects (32°C). Because of this issue some subjects were exposed earlier than others and their total exposure time was also longer than others. Consequently, in order to be consistent with different ranges of skin temperature the system should be modified to start the temperature rate and the resting skin temperature specific for each subject. This way, each subject gets exposed at the same time and for the same amount of time.

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