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Influence of Contact Conditions on Thermal Responses of the Hand

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ABSTRACT

A series of experiments was conducted to evaluate how contact pressure and surface roughness influence the heat flux conducted out of the skin or object during contact. Changes in skin temperature assist in identifying objects held in the hand. In the first experiment an infrared thermal imaging system was used to measure skin temperature and contact area as participants generated forces ranging from 0.1 to 6 N with their index finger. The results showed that skin temperature decreased by an average of 5.5 °C across the range of forces studied and that the changes were greatest between 0.25-0.35 N and from 4-6 N. The second and third experiments examined the effect of the surface roughness of an object on skin temperature and on the perceived coldness of the object. A set of six copper blocks was machined to create a range of surface profiles. There was a slight decrease in skin temperature as the surface roughness of the object increased, contrary to theoretical predictions. Although small, these changes were perceptible as participants consistently chose the rougher of two stimuli when asked to select the cooler stimulus. These results indicate that contact pressure and surface roughness influence the change in skin temperature during contact and that they can have a perceptible influence on the perceived properties of objects held in the hand. Thermal models need to account for these effects if realistic feedback is to be presented in a thermal display.

CR Categories: G.3 [Mathematics of Computing]: Probability and Statistics – Experimental Design; H1.2 [Model and Principles]: User/Machine System; H.5.2 [Information Interfaces and Presentation]: User Interfaces – Theory and methods; User-centered design

Keywords: temperature, thermal display, perception

1. INTRODUCTION

When an object is held in the hand, the thermal properties of the object and skin as well as their initial temperatures determine the heat flux conducted out of the skin or object on contact. The changes in skin temperature that occur during contact can assist in identifying an object and its material composition. As the resting temperature of the skin is typically higher than the temperature of objects in the environment, heat flux is conducted out of the skin during contact. The resulting decrease in skin temperature

activates cold thermoreceptors which signal to the central nervous system the magnitude and rate of temperature change [1].

In virtual environments or in teleoperated robotic systems, thermal cues can provide important information about the virtual or remote object. Thermal feedback systems have therefore been developed that can be incorporated into haptic devices so that a more realistic image of the virtual object can be presented (for a review see [2]). Thermal displays that assist in object identification usually consist of thermal stimulators such as Peltier devices, thermal sensors and a temperature control system that monitors and controls the surface temperature of the thermal display. A critical aspect in developing a thermal display is the characterization of the thermal responses of the hand as it makes contact with an object. A number of thermal models have been developed that simulate the thermal interaction between the hand and an object, most of which are based on the bio-heat equation formulated by Pennes [3], each with different assumptions and boundary conditions [4-7]. When implemented in a thermal display these models predict the thermal responses of the skin and object during contact and if the control algorithms are accurate, the changes in skin temperature and associated thermal sensations should be similar to those produced by real objects. Thermal models are therefore evaluated both physiologically (i.e. in terms of the changes in skin temperature) and psychophysically (i.e. generating the appropriate perceptual response).

Most thermal models consider the initial temperatures and thermal properties of the object and skin; some also include the effects of blood perfusion on the skin temperature response [4, 8, 9]. Other factors such as contact pressure and surface roughness are known to influence the thermal responses of the hand but have not been as extensively studied from the perspective of incorporating their effects in thermal models. There have, however, been a considerable number of experiments that have analyzed how the rate of cooling of the fingers changes as a function of contact force, contact material and surface temperature [10, 11]. That research has focused on developing a predictive model that specifies the contact duration required for skin temperature to reach the criterion for the onset of pain.

In the context of formulating a thermal model that can account for the influence of various contact conditions on the thermal response of the hand, Ho and Jones [12] analyzed how contact pressure affected the changes in skin temperature over the range of contact forces typically used in manual exploration (0.1-2 N). They developed an infrared thermal measurement system [13] to image the temperature distribution across the finger pad as

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participants produced different contact forces. Using this system, they found that as contact pressure increased up to approximately 3 kPa there was a continuous decrease in skin temperature, but that at higher contact pressures the decrease in temperature fluctuated. The theoretical predictions and measured data were consistent in characterizing the time course and amplitude of the change in skin temperature as a function of contact pressure, although at low contact pressures the model underestimated the decrease in temperature [12]. Additional experiments at very low and higher forces are required to understand the precise relation between contact pressure and changes in skin temperature and how pressure influences the perceived coldness of objects.

Simulations of the effect of surface roughness on the heat flux conducted out of the skin on contact have been performed using copper as the simulated material with an RMS surface roughness of 8 and 30 μm . With the initial temperatures of the finger pad and copper set at 34 °C and 24 °C respectively, the simulation indicates that surface roughness can influence the heat flux conducted out of the skin (see Figure 1). This suggests that surface roughness could affect the perceived coldness of an object, particularly during the first 1 s of contact.

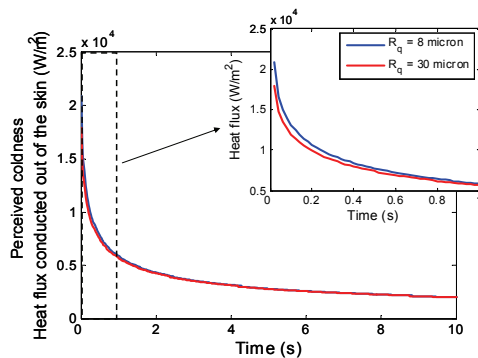


Figure 1. Heat flux conducted out of the skin when making contact with simulated copper surfaces of varying roughness.

Contact pressure and the surface roughness of the finger and object influence the heat flux conducted out of the skin through their effects on the thermal contact resistance that exists at the interface between the skin and an object. This results in a difference in temperature between the skin and object surfaces. Thermal contact resistance depends on a number of variables that are related to the thermal, mechanical, and surface properties of the two surfaces in contact [14]. When thermal contact resistance is included in thermal models, the influence of an object's surface and mechanical properties on skin temperature are characterized, and so more realistic time constants for the thermal responses of the skin and object are obtained [7, 12, 15].

The objective of the present series of experiments was to determine how two variables that influence thermal contact resistance, namely contact force and surface roughness, affect skin temperature and hence the perceived coldness (or warmth) of objects held in the hand. The effect of contact force on the change in skin temperature was analyzed using a more extensive range of forces than that studied previously. The thermal changes associated with varying the surface roughness of an object in contact with the hand have not been analyzed previously, although it has been shown that cooling the skin attenuates the perception of roughness [16]. The thermal model that has been implemented in a display predicts that surface roughness affects

the heat flux conducted out of the skin which should result in a change in the perceived temperature of objects in the hand.

2. EXPERIMENT ONE: CONTACT PRESSURE

The compression of the finger pad that occurs as a force is produced can result in changes in skin temperature due to the collapse of blood vessels in the region of compression driving the blood away from the contact area to capillaries under the nail bed [17]. At low contact forces of up to about 0.5 N, there is capillary perfusion of the finger pad, but as the force increases further there is a progressive decrease in blood flow which is reduced by 70% at 3 N as compared to that occurring at 0.5 N [18]. Contact pressure also affects skin temperature and thermal sensing by altering the area of contact between the finger and an object, which affects the spatial extent of the thermal stimulus being processed. As the area of thermal stimulation increases, the stimulus becomes more detectable [19].

The first set of experiments was designed to examine the relation between contact pressure and skin temperature using an extensive range of forces that are comparable to those employed during grasping and the manual exploration of objects.

2.1 Participants

Ten normal healthy adults (five women and five men), aged between 19 and 51 years (mean: 27 years), participated in the experiment. The participants had no known abnormalities of the tactile or thermal sensory systems and no history of peripheral vascular disease. The research was approved by the local ethics committee.

2.2 Apparatus

An infrared camera (A40M, FLIR Systems) was used to measure the change in skin temperature on the finger pad as different target forces were produced. The spatial resolution of the thermal image recorded by the IR camera was 400 μm which is sufficient for capturing thermal information on the finger pad [15]. The system has been calibrated using thermistors on the finger pad and the results indicated that the infrared thermal measurement system provides accurate temperature measurements [12]. In order to measure the change in skin temperature and contact area simultaneously, the contact material had to be transparent in both the infrared and visible spectrum and be safe to handle. Barium fluoride (BaF_2) (Crystran LTD) meets these requirements and so was used as the contact window in this experiment. The BaF_2 window was 10 mm thick and had a diameter of 43 mm. It was stored at room temperature. A beam splitter made from germanium (Ge) with an anti-reflective coating separated the infrared radiation and visible light from the contact area. It measured 32 mm in diameter and was 3 mm thick.

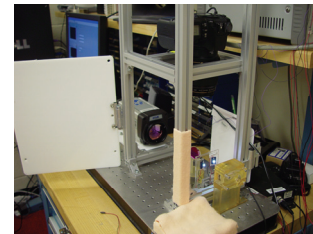


Figure 2. Experimental set-up for measuring contact force and skin temperature. The thermal camera (center) and digital camera (top) both captured images of the finger pad.

The skin temperature distribution and contact area was captured by the infrared camera. A 6-axis force transducer (Nano 43, ATI Industrial Automation) with a 20-mm diameter hole in the center was attached to the BaF₂ window and measured the contact force without obscuring the infrared and visible radiation from the finger pad. The force transducer was connected to a data acquisition unit (NI PCI-6023E, National Instruments) and was controlled using a program in Labview 8.5 (National Instruments). A computer monitor positioned in front of the participant displayed the target force (white line) and the force the participant was generating with the index finger (red line). A photograph of the experimental set-up is shown in Figure 2.

2.3 Procedure

Each participant's right index finger pad was cleaned with isopropyl rubbing alcohol (70%). A thermistor was glued to the side of the index finger pad using biocompatible cyanoacrylate (Liquid Bandage™, Johnson & Johnson). The thermistor was chosen on the basis of its small dimensions and thermal mass. Medical tape (Nexcare) was used to secure the thermistor leads along the hand and wrist. Participants' initial skin temperatures ranged from 29.3 to 35.6 °C, with an average of 33.0 °C. The average room temperature, contact material temperature and beam splitter temperature during the experiment were 23 °C, 25 °C and 23 °C respectively, as measured with the thermistors.

Nine target contact forces (0.1, 0.25, 0.35, 0.5, 1.0, 1.5, 2.0, 4.0 and 6.0 N) were chosen to investigate the influence of contact pressure on skin temperature. There were two trials at each force, each of which lasted 10 s. Prior to each trial, participants were instructed to place their right hands on the recirculating chiller to maintain skin temperature at 33 °C. After hearing an auditory cue, participants moved their hands from the chiller pad and placed their finger in a holding position in front of the contact material and transducer holder. A second sound cue was then presented that indicated that participants should make contact with the contact material and match the target force presented on a computer screen in front of them. The target force and the actual force produced were presented on the screen as two lines and participants were asked to overlap these lines in order to match the force. During contact, the thermal and digital cameras captured images of the finger pad, and the data acquisition system recorded the data from the four thermistors and the force transducer. A third auditory cue signaled the end of the trial, at which point participants withdrew their right hand from the fixture and placed it back on the recirculating chiller pad.

2.4 Results

Thermal images of the finger pad (see Figure 3) were used to estimate the contact area as a function of force.

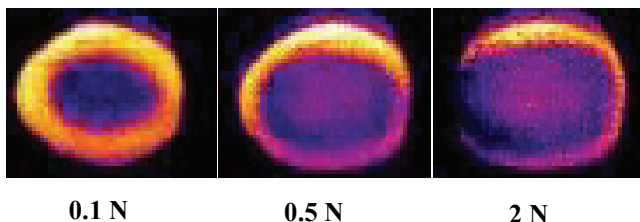


Figure 3. Thermal images of the finger pad as it produced the forces indicated.

The perimeter of the contact region on the finger pad was manually demarcated on the thermal image and then the area estimated using MATLAB (Mathworks, Inc.). The contact area

increased rapidly as a function of force at low forces, as demonstrated by the 64% change in area as the force increased from 0.1 to 1 N. The viscoelastic properties of the finger pad determine this relation between force and contact area. At low forces (less than 1 N) the finger pad is relatively compliant [20] but as the force increases the finger pad stiffens and so the change in contact area with force becomes more limited.

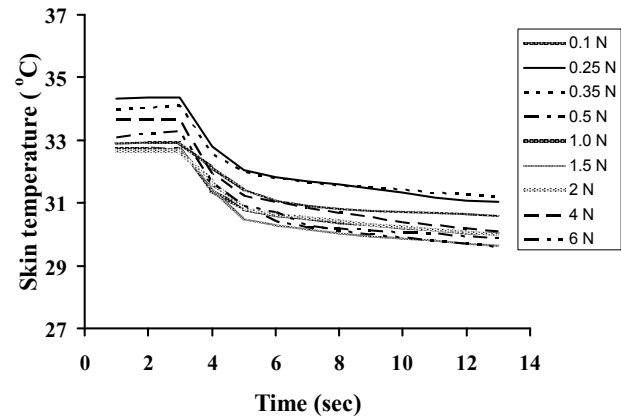


Figure 4. Mean decrease in skin temperature as a function of contact force during 10 s of contact, averaged across ten participants.

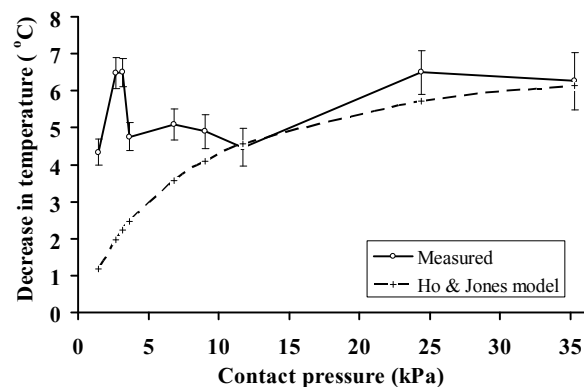


Figure 5. Mean (\pm SEM) decrease in temperature as a function of contact pressure after 10 s of contact, averaged across ten participants. Predictions of the thermal model [6] are also shown.

The decrease in skin temperature during the 10-s contact period as a function of force is shown in Figure 4. For all forces, there was a rapid decrease in temperature during the first 2 s of contact and then a more gradual decline. The overall decrease in temperature was calculated as the difference between the initial skin temperature and the skin temperature averaged across the contact area at the end of the contact period. These data are illustrated in Figure 5 where it can be seen that the decrease was greatest at low pressures of around 2.7 to 3.2 kPa (0.25-0.35 N) and between 24.5 and 35.3 kPa (4-6 N) and was smaller for pressures between 3.7 and 24 kPa (0.5-4 N). The changes in temperature were substantial averaging 5.5 °C across the range of forces studied. A repeated-measures ANOVA with force as the within factor and change in temperature as the dependent variable indicated that there was a significant difference in the change in temperature as a function of force ($F(8,72)=3.8$, $p=0.03$).

The decrease in skin temperature as a function of force was non-linear and highly dependent on the magnitude of the force.

As can be seen in Figure 5, the thermal model [6] underestimates the changes in temperature at low contact pressures but is accurate to within 0.25 °C at pressures above 12 kPa. At low forces there is capillary perfusion of the finger pad and so the magnitude of the decrease in temperature is surprising, but was a consistent feature of the individuals tested. The under-estimation of the change in temperature at low forces presumably reflects limitations in the thermal contact resistance model.

3. EXPERIMENT TWO: SURFACE ROUGHNESS

In this experiment the effect of varying the surface roughness of the contact material on the change in skin temperature was studied. Roughness was defined in terms of the spatial period of the surface, as is common in studies of tactile perception [21]. Simulations of the change in temperature as a function of the object's surface texture had indicated that the heat flux conducted out of the skin on contact would be slightly greater for smoother surfaces. There do not appear to be any data that indicate whether the surface roughness of an object influences the perception of temperature and so this experiment measured the temperature of the finger as it made contact with a range of copper surfaces. Copper was chosen because of its high contact coefficient, low deformation, resistance to moisture from the finger pad, and machinability. The effect of surface roughness on the thermal response of the hand was studied prior to any perceptual studies so that the predictions of the thermal model could first be verified.

3.1 Participants

Ten normal healthy adults (four women and six men), aged between 22 and 51 years (mean 30 years) participated in the experiment. Five of these people had also taken part in the first experiment. The participants had no known abnormalities of the tactile or thermal sensory systems. The research was approved by the local ethics committee.

3.2 Apparatus

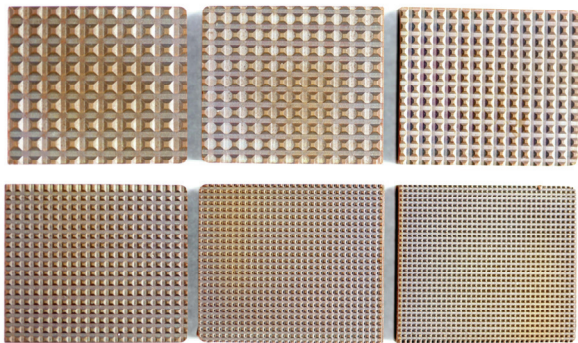


Figure 6. Copper stimuli with spatial periods ranging from 3 (upper left) to 0.8 mm (lower right).

The surfaces of six copper blocks (25.5 x 28.5 mm, 6 mm thick) were machined with a pattern of truncated pyramids using a wire EDM method (Charmilles Technologies Robofil 1020SI Wire EDM). The truncated pyramids were a constant height of 0.5 mm, and spaced at periods of 0.8, 1, 1.5, 2, 2.5, and 3 mm to convey smooth and coarse textures, as illustrated in Figure 6. Measurements were made of the height and spatial periods of these stimuli using a surface roughness tester (Mitutoyo SurfTest SV-3000S4) and indicated that the surface profiles had been

machined accurately. The RMS surface roughness ranged from 165 µm (0.8 mm spatial period) to 216 µm (3 mm spatial period).

A thermistor (Model 56A1002-C8, Alpha Technics) was glued to the edge of the contact area on the finger and another thermistor was mounted in free air to record the ambient temperature, which was maintained at 23 °C. Both thermistors were connected to a data acquisition unit (Model 34970A, Agilent Technologies), which was controlled with a Labview 8.5 program. A digital force gauge (Model DFS-20, SHIMPO) was mounted on a fixture at elbow height to allow participants to control the force of contact to 1 N. The force gauge was attached to a shielded connector block (Model NI BNC-2110, National Instruments), which was in turn connected to a data acquisition unit (NI DAQCard-6036E, National Instruments) for communication with the Labview 8.5 program. An aluminum fixture held the copper block in place, and was screwed onto the digital force gauge. The force gauge was zeroed with the aluminum fixture and the copper block on it.

3.3 Procedure

The right index finger pad was cleaned with a cotton swab of isopropyl rubbing alcohol (70%) and then a thermistor was glued on the margin of the contact area using a biocompatible cyanoacrylate. Medical tape secured the thermistor leads along the hand and wrist. The initial skin temperatures ranged from 29.5 to 36.1 °C, with a mean value of 32.1 °C.

The six copper stimuli were stored at room temperature. Each block was presented three times giving a total of 18 trials per participant. The order of presentation was randomized. There was at least a one-minute break between trials, during which participants placed their right hand on the recirculating chiller.

Each trial began with the participant's right hand resting on the chiller pad. At the first sound cue participants moved their hand from the chiller pad and positioned the index finger above the copper surface. A second sound cue indicated that participants should make contact with the copper at a constant force of 1 N. A third sound cue signaled the end of the 10 second contact interval, and participants removed their finger from the block and placed it on the chiller pad. Labview recorded the skin and ambient temperature at a frequency of 1 Hz. It was not possible to capture the change in temperature of the copper block in this experiment. Several methods were tried, including embedding a thermistor below the contact surface, and taking a thermal image directly after contact. The copper block did not hold a thermal signature that could be captured after 10 s of contact.

3.4 Results

The change in skin temperature as a function of the spatial period of the copper surface is shown in Figure 7. As the spatial period of the surface increased (i.e. the surface became rougher) there was a progressive decrease in temperature, although the overall change in temperature was relatively small, averaging 1.94 °C across the six surfaces. The ANOVA indicated that there was not a significant difference between the six surfaces in terms of the changes in skin temperature, but there was a significant linear trend ($p=0.02$) in the data which suggests that there is a small but consistent decrease in skin temperature as a function of the surface roughness of the object in contact with the hand.

The thermal model predicted that when the hand is in contact with a smoother surface the heat flux conducted out of the skin would be slightly larger than when the hand is in contact with a rough surface. However, the results suggest that the heat flux (and associated decrease in temperature) is greater for rougher

surfaces. Although the contact area on the top of each stimulus is the same for all stimuli (37.5 mm^2), it appears that with the rougher surfaces the finger was able to deform more around the textured surface and so in fact there was a larger contact interface, resulting in a slightly greater decrease in skin temperature. At a force of 1N, the finger did not penetrate into the textured array of the smoother surfaces, but would presumably do so at higher contact forces.

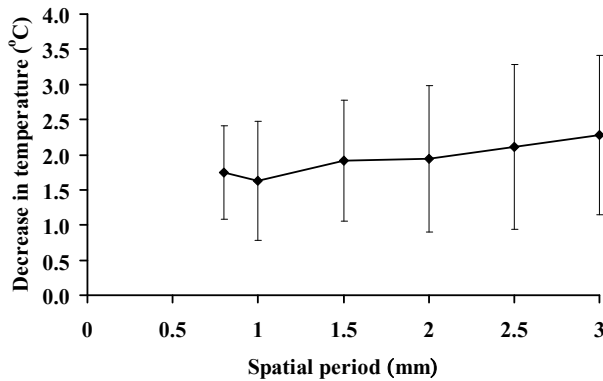


Figure 7. Change in skin temperature as a function of the spatial period of the surface. The means and standard deviations of the ten participants' data are shown.

4. EXPERIMENT THREE: PERCEIVED TEMPERATURE

The results from the second experiment showed that there was a small change in skin temperature as a function of the surface roughness of the contact material. The objective of the third experiment was to determine whether the thermal changes associated with the surface roughness of the object influenced the perceived coldness of an object in contact with the finger.

4.1 Subjects

Ten normal healthy adults volunteered to participate in this study. There were six males, and four females ranging in age from 21 to 40 years old (mean age 26 years). The subjects had no known abnormalities of the tactile, proprioceptive, or thermal sensory systems and no history of peripheral vascular disease.

4.2 Apparatus

Two identical digital force gauges (Model DFS-20, SHIMPO) were mounted adjacent to each other on an aluminum frame (see Figure 8). Fixtures were constructed to house the copper test stimuli on top of each force gauge. The fixture consisted of an aluminum base (35 mm x 38 mm, 16 mm thick) tapped with a M6 thread, with black opaque acrylic panels to obstruct the participant's view of the stimuli. There was a slot in the back of each fixture through which the copper stimuli could be inserted. The fixtures were numbered 1 (left finger) and 2 (right finger). The copper stimuli were stored at room temperature, which was maintained at 23 °C.

The force gauges were connected to a shielded connector block (NI BNC-2110, National Instruments), which was then connected to a data acquisition unit (NI DAQCard-6036E, National Instruments) controlled by a Labview 8.5 program. Two thermistors were used to monitor the skin temperature and room temperature. The thermistors were connected to a separate data acquisition unit (Model 34970A, Agilent Technologies), which was also controlled by a Labview program.

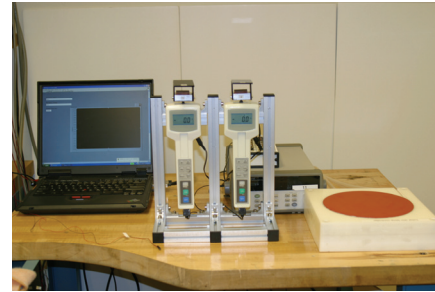


Figure 8. Apparatus used to measure perception of temperature as a function of surface roughness. The force gauges and recirculating chiller pad are shown.

4.3 Procedure

Each participant's finger pads were first cleaned and then a thermistor was glued on the side of the finger pad so as not to interfere with contact. Medical tape secured the thermistor leads along the hand and wrist. The participants' initial skin temperatures ranged from 30.1 °C to 36.8 °C, with an average value of 34.1 °C. The room temperature was maintained at 23 °C, and measured with a thermistor in free air.

Four test stimuli with spatial periods of 1, 1.5, 2.5, and 3 mm were chosen based on the measured temperature differences recorded in the second experiment. Each of the four stimuli was paired with the other stimuli including itself which gave a total of 10 pairs. Each pair was presented five times, resulting in a total of 50 trials per subject. Within each block of ten trials, the order of presentation of the test stimuli was randomized. The copper blocks were stored at room temperature, which was maintained at 23 °C. Participants were instructed to place both hands on the recirculating chiller between trials to control skin temperature.

Three auditory cues generated by a Labview 8.5 program signaled the sequence of events in each trial. Participants started with both hands resting on the chiller pad. At the first sound cue, they removed their hands from the chiller and placed their right and left index fingers in the holding position in front of the force gauges. At the second sound cue, participants inserted their right and left index fingers into the fixtures holding the copper blocks and placed their fingers on the copper. Participants were instructed to choose the cooler of the two materials by reporting which finger made contact with the cooler surface (1 (left) or 2 (right)). They were encouraged to lift and replace their fingers on the stimuli to sense the temperature, but were restricted from lateral scanning of the surface. A third sound cue indicated that participants should remove their fingers from the test stimuli, and place them on the chiller pad. The subjects were not told which spatial patterns were used, and no feedback was given as to the correctness of their judgments.

4.4 Results

In this experiment the responses were analyzed in terms of the number of correct responses, that is, successful identification of the "cooler" of the two surfaces, as defined in terms of the measured thermal responses recorded in the previous experiment. The chance level was 50% and a threshold level of 72% correct responses was chosen as indicating that participants could reliably discriminate between a stimulus pair. The percentage of correct responses for the various combinations of stimuli is shown in Table 1. As can be seen in the table, participants were able to

discriminate reliably between copper stimuli when the difference in their spatial periods was 1.5 mm or greater. As the stimulus surfaces became rougher they were perceived to be cooler than surfaces that had a smoother texture. The results from the trials in which the same stimulus pair was presented to both fingers indicate that there was no systematic bias in the participants' responses as the means were 50% for the left and right fingers, as would be expected based on responding by chance.

Table 1. Percentage of correct discriminations as defined in terms of selecting the rougher (cooler) surface

Spatial period	1 mm	1.5 mm	2.5 mm	3 mm
1 mm		64	76	82
1.5 mm			70	80
2.5 mm				58

5. CONCLUSIONS

This set of experiments demonstrated that both the contact pressure between the hand and an object and the surface roughness of the object influence the change in skin temperature during contact. Thermal models do not appear to be able to capture the changes in temperature at very low contact forces, presumably due to limitations in estimates of the thermal contact resistance between a rigid and deformable surface.

The decreases in skin temperature are considerable at low forces and are clearly perceptible. Moreover, the findings presented here suggest that the changes in contact area and skin temperature with very small variations in finger forces may be used optimally to sense the properties of objects in contact with the hand.

Skin temperature is also affected by the surface profile of an object in contact with the hand. These changes are perceived with the result that rougher surfaces seem to be cooler than smoother surfaces made from the same material. Tactile-thermal interactions such as these provide insights into the mechanisms involved in haptic object perception and should be incorporated in thermal models implemented in haptic displays.

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