Material Discrimination and Thermal Perception

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Abstract

This research is focused on the development of a thermal display and understanding the nature of the thermal cues used to identify objects haptically. The objective of the present set of experiments was to measure material discrimination when thermal cues are the main source of information about the materials. A two-alternative forced-choice task was used to assess discrimination. Of the five materials presented to the hand, nylon was the only material reliably discriminated as being warmer than the other materials. A second experiment was conducted to determine the magnitude of the skin temperature changes when contact was made with the materials. The results indicated that thermal responses were small, averaging 0.5ºC. These findings suggest that temperature cues can be used to discriminate between materials, but only when the thermal differences are large. It appears that subjects respond more to variations in heat capacity than thermal conductivity when discriminating between materials.

1. Introduction

Thermal displays have been developed for evaluating human temperature perception [1,2] and as part of haptic devices used to interact with computer-generated virtual environments or to control robots [3-6]. Most thermal displays consist of a Peltier thermoelectric device, a temperature sensor and a heat sink [7].

Thermal feedback has been incorporated into haptic displays usually with the objective of conveying information about the thermal properties of objects encountered in the environment. This feedback can assist in identifying objects, and in creating a more realistic image of a remote object. The design of the haptic display has usually constrained the placement and configuration of the thermal device. The Salford University Force/Tactile/Thermal feedback glove provides thermal feedback via a Peltier heat pump mounted within a finger sleeve of the glove that rests on the dorsal surface of the index finger. The heat pump is light and small and can produce rapid heating and cooling in the order of 20°C/s over a temperature range of –5 to 50 °C [8]. In contrast, the Thermostylus, a thermal display that was designed to be appended to the force-reflecting Phantom interface (SensAble Technologies), makes contact with the finger pad of the index finger when the Phantom is held in a three-jaw chuck grasp [6]. In this haptic display, the thermal interface is a Peltier device covered by an aluminum plate, and heating and cooling rates of 11°C/s and 4.5°C/s, respectively, have been achieved.

A novel application of a thermal display was developed as part of a "haptic doorknob" by MacLean and Roderick [5]. The doorknob incorporates haptic, auditory and thermal displays and was designed to convey clues upon human contact about the space beyond the door, such as the mood or number of people. A Peltier device is embedded in the mechanical portion of the doorknob, and the stationary aluminum back functions as a heat sink. The display can output approximately 10°C above and below ambient temperature in 30 seconds, and uses a proportional integral and derivative (PID) controller.

In 1997, Dionisio [4] introduced a thermal kit for graphics-based virtual reality applications called the Thermopad. This kit focuses on the more global integration of all heat transfer modalities and was designed to be used with other haptic displays. It was envisaged that as the user walks through a computer-based virtual environment, the appropriate conductive (Peltier), convective (fan) and radiative (IR lamp) heat would be presented to convey the perception of moving by an open window or a fire blazing in a fireplace [9].

Thermal displays such as those described above have been used to simulate contact with various materials [10, 11]. The objective of these simulations was to determine how accurately subjects could identify materials using

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only thermal cues. In their experiment on object identification based on thermal cues, Caldwell and Gosney [10] placed an ice cube, heated soldering iron, aluminum block, and insulation foam in the hand of a teleoperated robot that was maintained at 40°C. A signal from a thermocouple on the robotic hand indicated the type and magnitude of thermal transient, which was then presented to the subject wearing a glove fitted with a Peltier device. Subjects were successful in identifying each material 80% of the time using these thermal cues.

In a further study of thermal cues and object identification, Ino et al. [11] measured the changes in finger temperature as subjects made contact with a range of materials while they were required to identify. On the basis of the changes in finger temperature upon contact, Ino et al. simulated the thermal transients associated with touching aluminum, glass, rubber, polyacrylate, and wood using a Peltier element, thermocouple and PID controller. Subjects were now required to identify which of the five materials was being presented using only the thermal cues presented to the fingertip. They found that the recognition rates for the simulated materials presented using the thermal display were equivalent to those measured with real materials, and that there was no significant difference in the information transmission rates associated with the real object and the Peltier-based display.

Several factors affect the capacity to perceive thermal changes including the baseline temperature of the skin, the amplitude and rate of temperature change and the region stimulated [for reviews see 12, 13]. The threshold for discriminating amplitude differences in temperature pulses delivered to the thenar eminence of the hand is 0.02-0.05°C for cooling pulses, and 0.03-0.09°C for warming pulses [14]. These thresholds are considerably lower than the threshold for discriminating changes in skin temperature, which is the more relevant measure for thermal displays. At a skin temperature of 34°C, the differential threshold for warming is 0.27°C and for cooling 0.26°C [15]. If skin temperature changes very slowly, for example at a rate of less than 0.5°C/minute, then changes of up to 4-5°C may not be perceived at all, provided that the temperature remains within the neutral thermal zone of 30-36°C [12].

An initial study on the use of thermal cues in object identification indicated that for subjects to perceive that two materials differ thermally, there had to be large differences in their thermal properties [16]. Measurements of the change in skin temperature as the finger made contact with the material revealed that the changes in skin temperature are slow and can take up to 200 s to stabilize. The time course of the change in skin temperature was much slower than the 1-2 s reported by Ino et al. [11], but was consistent with the long reaction and decision times reported for thermal stimuli [13,17].

The objective of the present set of experiments was to evaluate thermal discrimination using a set of materials that spanned a considerable range in thermal properties but which had similar surface features so that subjects would be constrained to focus on thermal cues to discriminate between the materials. In addition, we wanted to measure more systematically the change in skin temperature as the finger makes contact with different materials.

2. Material Discrimination Experiment

The first experiment was a material discrimination task that required subjects to discriminate between two materials presented to the fingers. Five women and five men aged between 22 and 45 years (mean age: 26 years) participated in the experiment. They had no known sensory or peripheral vascular abnormalities. Before testing, the subjects washed their hands thoroughly with soap.

2.1 Methods

Five different materials listed in Table 1 with their associated thermal conductivities and heat capacities were used in this experiment. The materials were stored at room temperature. Each sample was 12.4 mm in diameter. It was turned from 12.7 mm (½ inch) rod stock, milled and sanded to provide a flat, smooth contact surface with minimal textural cues. Two pieces of delrin were used to make a material presentation fixture as shown in Figure 1. The combined size of these pieces when screwed together was 103 x 63 x 46 mm. In the upper piece two 22 x 20 mm rectangular holes were machined into which the fingers could be inserted. In the lower piece two 12.5 mm diameter compartments were machined 43 mm apart directly under the holes. The material samples slid into these slots and were flush with the surrounding surface.

Table 1. Thermal properties of materials used [18]

Material	Thermal conductivity ($W\ m^{-1}\ k^{-1}$)	Heat Capacity ($J\ kg^{-1}\ °C^{-1}$)
Copper	388	385
Brass	116	380
Nickel	60	460
Stainless steel	25	500
Nylon	0.48	2000

Each of the five materials was paired with all other materials including itself which gives a total of 15 different combinations. These 15 trials were repeated five times. Each set of 15 pairs took approximately five minutes to present and there was a one minute break between each block of 15 trials. The ambient temperature of the room and the skin temperature of the index finger were measured at the beginning of the experiment. The room temperature averaged 25ºC and the mean finger temperature was 29.6ºC (standard deviation: 4.3ºC).

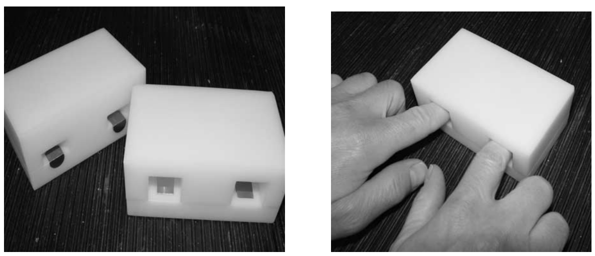

Figure 1. **Material discrimination fixture with samples and fingers inserted**

Prior to each trial two 50 x 12.4 mm materials were inserted into the two separate compartments as shown in Figure 1. Subjects then inserted their left and right index fingers into the compartments. The procedure was a two-alternative forced-choice method in which the subject had to choose the warmer of the two materials presented. There was no time limitation for their responses but subjects generally responded within 5-8 s. Subjects were not told what the samples were made from and did not see the materials during testing. They were allowed to lift and replace the finger on the material during each trial, but did not retract their fingers from the test fixture until they had made a response.

2.2 Results

There was no significant difference between the hands when the same material was presented to both hands as shown in Figure 2. An analysis of variance indicated that there was no effect of hand ($p=0.16$) and no interaction between hand and material ($p=0.37$).

Table 2. Percent of responses correctly identifying the warmer material in each pair presented

	Copper	Brass	Nickel	S Steel	Nylon
Copper					
Brass	54				
Nickel	52	56			
S Steel	42	52	68		
Nylon	96	92	94	92	

The responses for the trials involving different materials were analyzed in terms of the number of correct responses, that is, correctly identifying the "warmer" of the two materials. A threshold level of 71% correct was chosen as indicating that subjects could reliably discriminate between a pair of materials. The percent correct discriminations for the various combinations of materials are shown in Table 2. For all combinations that did not involve nylon, subjects were unable to discriminate reliably which of the two materials presented was warmer. The responses ranged from 42% to 68% correct for the four metals presented. In contrast to this performance, all material comparisons involving nylon were readily discriminated with response rates ranging from 92% to 96% correct.

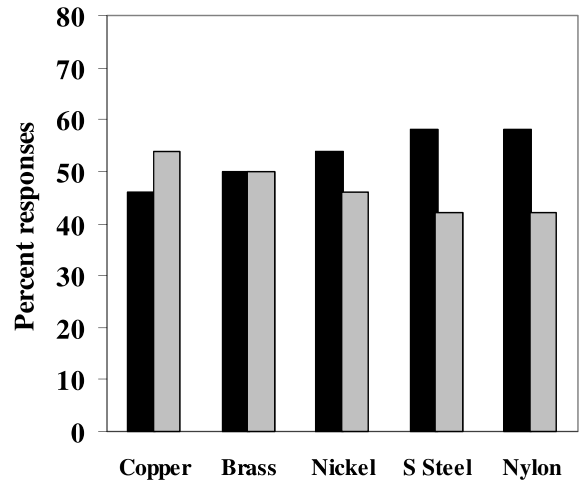

Figure 2. Percentage of responses indicating that the sample presented to the left (black) or right (gray) index finger was warmer

2.3 Discussion

The results indicate that when textural cues are minimized, thermal cues can be used to discriminate between objects when the differences in thermal capacity are large. For materials in which there were very few surface feature differences to aid in discrimination, the heat capacity of one material had to be at least four times that of the other for subjects to discriminate between them, and the thermal conductivity had to be at least 80 times greater. It appears from these results that heat capacity is the most relevant thermal property that subjects respond to in making judgments, as they were unable to distinguish between materials that spanned a large range in thermal conductivities (16-385 W $m^{-1}K^{-1}$) but had similar heat capacities (385-500 J kg^{-1} $ºC^{-1}$).

The present findings are consistent with those of Ino et al. [11] described earlier and of Dyck et al. [19] who designed a set of thermal stimulators known as the "Minnesota Thermal Disks" that are made from copper, stainless steel, glass and polyvinyl chloride (PVC). Dyck et al. [19] found that the only pairs of disks that normal healthy subjects could reliably distinguish on the palm of the hand as "cold" and "warm" were copper and PVC, and copper and glass. As in the present study, copper and stainless steel were not perceived as being different. The Minnesota thermal disks are considerably larger than our stimulus materials with a surface area of 1000 mm^2. This increased area of contact does not appear to result in better discrimination, which is surprising given the thermal sense's prodigious capacity for spatial summation. For the thermal system, changing the spatial extent of stimulation results in a change in the perceived intensity of the stimulus, and so thermal thresholds can be maintained constant by doubling the area of skin that is warmed and halving the intensity of the thermal stimulus [20,21]. This reciprocity does, however, break down at some critical area, depending on the body site being stimulated. This is usually near the threshold of pain [13].

3. Thermal Responses to Contact

The inability of subjects to discriminate between the various metals presented in the first experiment was surprising, and so a further study was conducted to measure the change in temperature on the finger pad as it made contact with the various materials. In the first study subjects were encouraged to use any strategy other than laterally stretching the skin to perceive thermal differences in the materials in contact with their fingers. In the present experiment, the thermal changes occurring on contact were of interest and so subjects did not perform a perceptual task but positioned their finger on the material. If thermal feedback is to be used effectively to facilitate the identification of unknown objects in a remote or virtual environment, then the time course of changes in skin temperature that occur when contact is made with an object need to be quantified. Earlier research [16] had suggested that these responses were slow and took tens of seconds to reach equilibrium.

3.1 Methods

The second experimental apparatus shown in Figure 3 was designed to control the position and measure the force exerted by the finger as it made contact with a variety of materials. The apparatus included a vacuum formed plastic mold of a finger that was screwed into a delrin base. The mold, pulled over an epoxy coated plaster cast, was originally made by immersing the hand in Earthium (MSW Creative, NV), a biofriendly silicone-like medium. The base of the mold contained a 12.5 mm diameter slot into which 12.4 mm diameter material samples could be inserted and exchanged during testing. The samples were turned from 12.7 mm (½ inch) rod stock, milled and sanded to provide a flat, smooth contact surface with minimal textural cues.

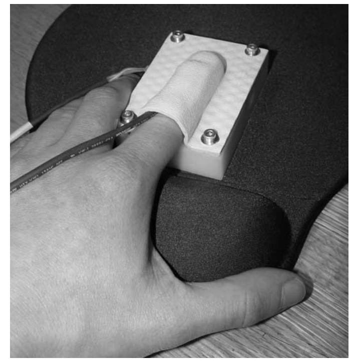

Figure 3. Apparatus used to measure changes in skin and material temperature during contact.

Three temperature sensors were tested to determine the most appropriate sensor for the present application. They included a custom manufactured thin film resistive temperature detector (RTD, JP Technologies), a J-type thermocouple (iron-constantan, accuracy ± 1.2-2.2°C), and a standard Omega thin film RTD (F3105), all of which operate over a range of 0-100°C. These three sensors were fixed to a Melcor Peltier device (DT 6-6) which was in turn mounted with thermal grease (Omegatherm 201) to a fluid cooled (30% ethylene glycol, 70% water) heat sink (VWR Recirculating Chiller). The temperature of the Peltier device was manually controlled with a DC Power Supply (Hewlett Packard, E3632A). A Visual Basic program controlled the data acquisition unit (Agilent 34970A), and sampled the sensors at 4 Hz.

The three sensors were initially at room temperature and responded similarly to the changes in temperature generated by a Peltier device. A series of 10 trials were repeated with different input voltage steps in the range of 0-7 V to heat and cool the Peltier device. The JP Technologies RTD was the most sensitive and reliable thermal sensor which made it the sensor of choice. It is a platinum serpentine resistor, measuring 4.2 mm x 5.6 mm x 5 μm thick, and emulates a typical strain gauge design.

The RTD sensor used for measuring finger pad temperature was offset laterally on the finger tip to enable direct contact between the finger and material and was affixed with a biocompatible cyanoacrylate (Dermabond, Closure Medical). A force sensor was included in the test fixture to identify the point of finger contact with the material and to help understand any fluctuations in finger temperature. An Omega load cell with an operating range of 0-9.8 N was positioned under the apparatus so that the forces transmitted by the finger through the material sample could be measured. The load cell was connected to the Agilent Data Acquisition Unit and controlled using a Visual Basic program similar to the one used to measure temperature.

Three subjects between the ages of 24 and 27 participated in this experiment. Initial skin (finger) temperatures ranged between 20-30°C and the ambient temperature was 24°C ±2°C as measured with an RTD in free air. The subjects were instructed to insert their fingers into the plastic finger mold in 2-3 s. The finger then stayed in contact with the material for the remainder of the 12 s trial, and subjects were told to attend to the thermal properties of the material presented. The data were sampled at 30 Hz. This was repeated once for all material samples, with 30 s breaks between trials.

3.2 Results

Figure 4 illustrates the initial finger temperature and thermal response to contact with three materials: brass, stainless steel and nylon. The initial skin temperature of each subject fluctuated considerably during the testing period, and only a small change in temperature was detected upon contact with the material sample. There was no consistent pattern of change in temperature associated with a specific material. The average skin temperature for Subject 1 was 21.5°C which increased 0.7°C upon contact. For subject 2 the initial skin temperature ranged from 25-31°C and increased on average by 0.4-0.6°C on contact. The initial skin temperature of Subject 3 averaged 28°C, varied 5.5°C during testing and changed 0.1°C upon contact.

The thermal response of the finger to contact with the three materials was fairly consistent for the same subject, but varied considerably between subjects as can be seen in Figure 4. This may be due to differences in the initial skin temperatures and in how the finger pad made contact with the material. The variation across subjects in baseline skin temperature of the finger was surprising given that the ambient temperature was 20-22°C. A steady decrease in skin temperature occurred in all three subjects throughout the one-hour testing period. This was attributed to a lack of finger motion after the sensor was attached to the finger.

An additional experiment was therefore conducted in which the hand was rewarmed to 30°C prior to each trial by placing it on the recirculating chiller for several minutes. This experiment followed the procedure described above. The results are shown in Figure 5 where it can be seen that there was a consistent thermal response to contact with a variety of materials. The temperature of the finger initially increased on contact with the material and then decreased. As the materials were all kept at room temperature, which was 21-22°C, the increase in temperature probably resulted from vascular changes in the finger pad as it was compressed on contact.

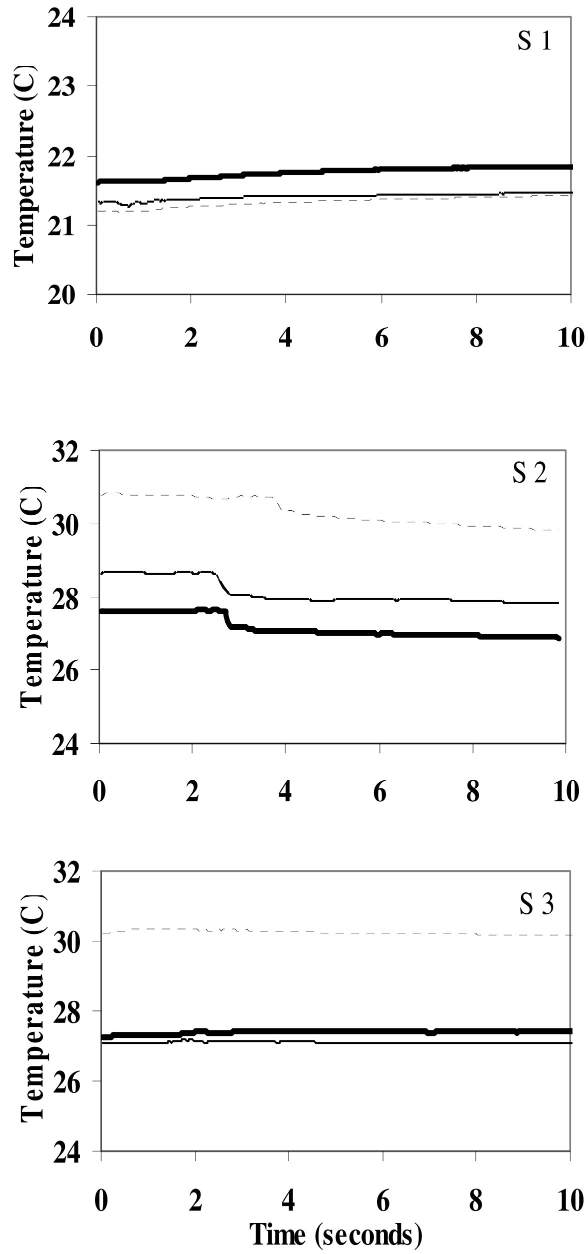

Figure 4. Change in finger temperature as contact is made (between 2-3 s) with brass (thick black line), stainless steel (dashed line) and nylon (fine black line).

When the finger makes contact with an object, the contact area begins as a single point and expands exponentially in size with compression. In the medial-lateral direction the contact distribution is symmetric, but it is not in the proximal-distal direction [22]. There are at least two ways that the force imposed by a finger on an object may affect thermal responses. First, compression of the finger pad may affect finger temperature by collapsing local blood vessels, which prevents continuous tissue-heat

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exchange. Second, compressing the cutaneous tissue of the index finger may enhance thermal sensing by increasing the area of contact with the object.

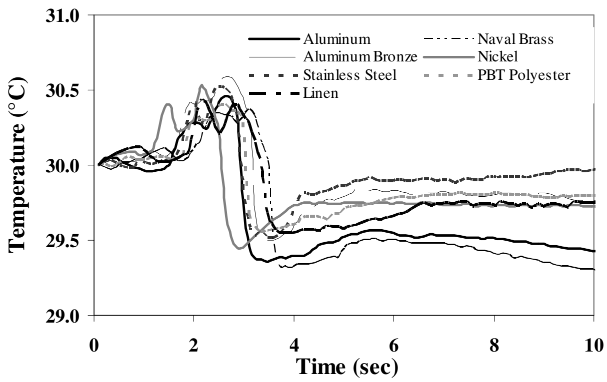

Figure 5. Change in skin temperature when the finger is actively maintained at 30ºC between trials as the finger makes contact with a range of materials. Contact with the material occurs at around 2 s.

Of the blood flow to the finger tip, 90% is considered to be involved in thermal regulation, and the remaining 10% is required for nutrition [23]. The digital arteries are protected by the underlying bone, and are unaffected by the pressure exerted by the finger pad. However, the larger, more compliant digital veins which run laterally to the bone have a lower internal blood pressure and collapse with compression which results in the accumulation of blood in capillaries under the nail bed [24], and an increase in skin temperature.

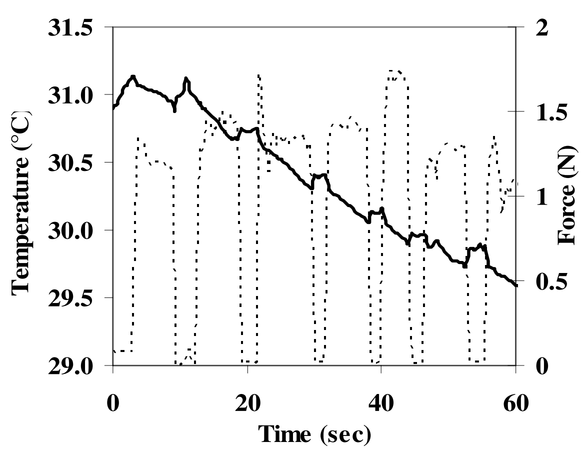

Figure 6. Change in skin temperature (solid line) and contact force (dashed line) as the subject made repeated contact with copper.

The forces generated by subjects as they made contact with the material were measured and found to be between 1 to 2 N which is similar to previously reported values of 0-2 N [3,11,22]. The forces averaged 1.5 N as shown in Figure 6, and were consistent from contact to contact. When the finger was lifted from the material the force immediately declined to 0 N and there was a small but highly repeatable increase in skin temperature of approximately 0.1°C, as can be seen in Figure 6.

A force of 1 N applied normal to the finger pad compresses two thirds of the corresponding contact area compressed by a force of 10 N [25], so the force levels generated by subjects in this study were presumably optimal in terms of maximizing contact area while minimizing force. As noted previously, for thermal stimuli in general, as the area of stimulation increases the ability to resolve changes in temperature improves [20,21].

3.3 Discussion

The peripheral thermal changes associated with contacting materials of varying conductivities and heat capacities were small, relatively slow and variable between subjects. The magnitude of these changes was consistent between the two experiments and remained small even when the hand was actively maintained at a constant temperature. Although the temperature sensor attached to the finger was offset from the contact position to enable the finger to make direct contact with the material, the changes in temperature at the contact surface should not be very different from those occurring within 5 mm of this area. There was no apparent difference between the thermal responses to materials that were reliably discriminated, such as stainless steel and nylon, and those that were not, such as brass and stainless steel. In the psychophysical study, subjects made repeated contacts with the materials to perceive their thermal properties by lifting and replacing their fingers, and the local thermal transients associated with contact may have been the basis for their discrimination. In the region of contact the finger temperature may have changed rapidly in the direction of the temperature of the material, and on withdrawing the finger the temperature would start to return more slowly to its baseline value. The rate at which these processes occurred depends on the thermal properties of the skin and material, and it is the difference in these rates for the materials touched that subjects had to discriminate.

Thermal thresholds on the hand are influenced by the baseline temperature of the skin. Within the neutral zone of 30-36°C the threshold for detecting cooling on the forearm increases from 0.15°C at 31°C to 0.3°C at 36°C, and for warming decreases from 0.4°C at 31°C to 0.2°C at 36°C [15]. If the rate of change of skin temperature is greater than 0.1°C/s, the thresholds for both warming and cooling do not depend in the rate of change [26]. Thermal sensitivity does vary over the surface of the hand with the

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highest sensitivity occurring on the dorsal surface of the hands and the lowest sensitivity on the skin of the finger pads and pads of the palms [27]. Cold and warm thresholds on the forearm and thenar eminence are similar in magnitude for people under 60 years of age [28]. These threshold values are smaller than the thermal changes measured as the finger pad made contact with the materials in the present experiment (0.4-0.7°C in Figure 5), and so the latter were presumably perceived by subjects.

The time course and amplitude of these responses are markedly different from those reported by Ino et al. [11] who for a single subject showed an immediate decline in skin temperature on contact with all materials. The decreases in skin temperature ranged from 0.1°C for wood to 7°C for aluminum, and occurred within 1 s and then stabilized within 500 ms, which is an extremely rapid and dramatic response for the peripheral thermal system. Caldwell and Gosney [10] reported that it took 3-5 s to obtain a successful thermal reading from the hand as it made contact with a range of materials, and in the present study the change in skin temperature did not stabilize for 2-3 s.

4. Conclusions

In conclusion, the results from the present set of experiments show that thermal cues can be used to discriminate between materials, but only when the differences in thermal capacity and conductivity are large. For materials in which surface feature differences could not be used to aid in discrimination, the heat capacity of one material had to be at least four times that of the other for subjects to discriminate accurately between them. The thermal conductivity differences between materials that could be discriminated were much larger, which suggests that subjects may respond more to variations in heat capacity than thermal conductivity when discriminating between materials. This later hypothesis can only be verified by using materials that span a greater range of heat capacities.

The thermal changes occurring in the finger tip as it made contact with the materials were small in the present study, and could not be used to distinguish which materials subjects were able to discriminate between. It is, however, possible that local thermal transients associated with repeated contact provided the basis for the perceptual performance seen.

The variation across subjects in the skin temperature of the finger was surprising at a constant ambient temperature. The fluctuation in skin temperature within subjects was also unexpected when the finger was constrained in its motion. These latter findings suggest that for a thermal display to be effective it would be advisable to record skin temperature and use this measurement to servo-control changes in temperature produced by the display. These results also suggest that thermal displays may only assist in the identification of objects if the differences in the thermal properties of the objects are large, such as discriminating between an object made from metal or glass. Under normal environmental conditions, the changes in skin temperature on contact do not appear to be large enough for more subtle discriminations to be made by subjects. However, thermal cues are responded to rapidly when they are large and rapid; this type of thermal input that may prove useful in a thermal display.

Acknowledgements

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