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Discrimination of thermal diffusivity

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ABSTRACT

Materials such as wood or metal which are at equal temperatures are perceived to be of different ‘coldness’ due to differences in thermal properties, such as the thermal diffusivity. The thermal diffusivity of a material is a parameter that controls the rate with which heat is extracted from the hand when it touches an object of that material. This rate of heat extraction is an important cue for distinguishing materials and recognising objects by means of touch. We have measured the ability of human observers to discriminate between different rates of heat extraction. This was done using a device that displayed different transient temperature profiles to the finger. In different conditions, subjects were repeatedly asked to select the faster-cooling of two stimuli. The discrimination threshold was around 43 % of the extraction rate. A rate that was twice as slow also yielded twice the absolute discrimination threshold. When we halved the temperature difference between beginning and end of the stimulus, the threshold did not change as much. This shows that subjects can use the rate of heat extraction as a cue and that they can discriminate between materials if their thermal diffusivities are at least 43 % apart.

1 INTRODUCTION

Upon touch, different materials of identical temperatures generate different sensations of ‘coldness’ [15]. For instance, metal usually feels cool, while wood feels quite warm, even though both materials have the same temperature. This is due to the different thermal properties of these materials. The parameter that describes the rate at which heat spreads throughout a material is called the *thermal diffusivity* of that material, α, expressed in m^2/s. The thermal diffusivity depends on the thermal conductivity, k, the heat capacity per unit of mass, c, and the density of the material, ρ, through the relationship $\alpha = k/(\rho c)$. When heated locally at the surface, the heat spreads fast through a material with a high thermal diffusivity, causing it to extract heat quickly at the point of contact. Therefore, when touched with the hand, a material with a high thermal diffusivity extracts heat from the hand at a high rate, causing it to feel cold. Conversely, heat extracted by a material with a low thermal diffusivity does not spread around very fast, causing it to feel warmer upon touch. Besides the thermal diffusivity, other parameters such as object geometry and thermal contact resistance may play a role in the sensation of ‘coldness’ of materials.

Lately, this phenomenon has been the subject of an increasing body of research — for an overview, see [14]. The sensation of ‘coldness’ is important for the identification of materials by means of touch and can thus play a large role in object recognition, both in the real world and in virtual worlds. Although ‘coldness’ may not be available as early in haptic processing as other material properties [17], in daily life, the difference in ‘coldness’ between metal and wooden objects, or tiled and carpeted floors, is readily observed. Therefore, both from the viewpoint of haptic interface design and from that of fundamental knowledge about haptic perception, it is interesting to know more about the way in which the sensation of ‘coldness’ is related to physical material parameters. The difficulty in investigating this relationship has been the lack of a systematic spacing of these parameters in real materials. Attempts to overcome this difficulty have included the use of artificially generated ‘coldness’ sensations (e.g. [4,8,10,23]) and the use of stimuli that differ in geometry but not in material [2,3].

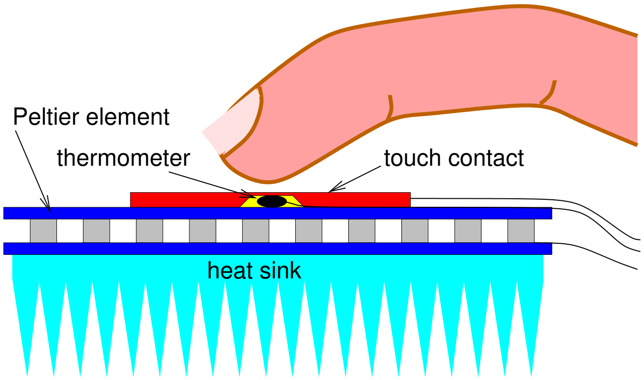

Figure 1: Schematic drawing of the setup (not to scale).

While most objects that are interacted with, are colder than the skin and thus extract heat from it, the reverse situation may occur as well: an object with a temperature higher than skin temperature will add heat to the finger touching it. Since there are different receptors for warm and cold perception, this reversed situation will generate a different sensation. The human ability to discriminate between ‘coldness’ of objects at ∼ 10 °C below skin temperature is somewhat better than the ability to discriminate ‘warmness’ of objects at ∼ 10 °C above skin temperature [3]. Apparently, with this temperature difference, the ‘cold’ receptors are more sensitive than the ‘warm’ receptors.

Studies with real materials have shown the human ability to distinguish between materials based on perceived ‘coldness’ [8, 9, 12, 13]. In order to make optimal use of this ability, for instance in a haptic display, it is essential to know the smallest difference in ‘coldness’, and therefore in thermal diffusivity, that can still be perceived. For this purpose, precise measurements of discrimination thresholds are necessary. Ideally, we would like to present subjects with stimuli that differ systematically in thermal diffusivity but not in other aspects, such as surface structure or geometry. Since such a stimulus set is difficult to realise using real materials, we have used a Peltier device to artificially extract heat from the finger, thus simulating the process that occurs when a material is touched that is at a lower temperature than the skin. In this way, we were able to display temperature transients that corresponded to different values of the thermal diffusivity. Using these transients as stimuli in a psychophysical experiment, we have measured precise discrimination thresholds for thermal diffusivity. This was done in different conditions to assess the influence of the rate of heat extraction and the temperature difference between hand and stimulus on the discrimination threshold.

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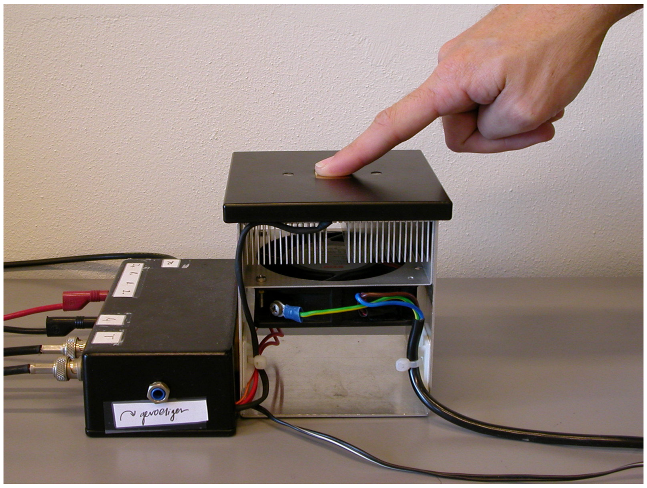

Figure 2: Photograph of the setup.

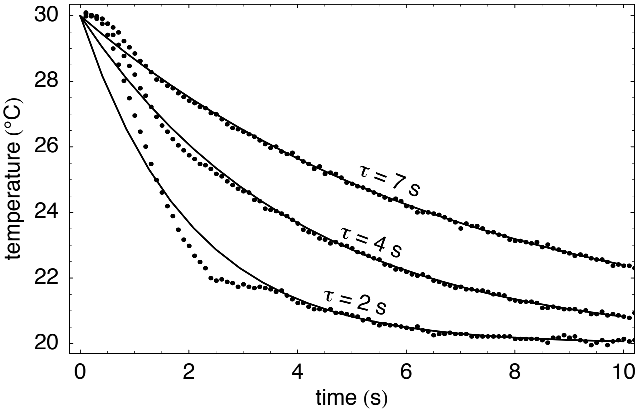

Figure 3: Examples of transient temperature profiles used as stimuli in experiment 1, with time constants of 2, 4 and 7 s. The solid lines are the nominal curves while the dots are the actual curves.

2 METHOD

2.1 Apparatus

In order to extract heat from the fingers upon touch, a device was designed and built consisting of a Peltier element, a semiconductor temperature transducer and a touch contact. A schematic representation is shown in figure 1. The Peltier element (Melcor PolarTEC PT8-12-40) is connected to a computer-controlled power supply (Delta Elektronica E015-20). It is covered by a housing that leaves the touch contact exposed. The touch contact is a 4 cm^2 gold-coated copper square. When the contact is touched, an impedance change is registered by the electronics and a signal is sent to the computer. Between the touch contact and the Peltier element sits a thermometer (Dallas Semiconductor DS600, accuracy better than ±0.5 °C) which is read out by a 12-bit ADC (National Instruments PCI-1200). A heat sink is mounted to the underside of the Peltier element and air is forced through it by a fan. The temperature is regulated by a software PID controller. The maximum rate of temperature change is about 5 °C/s. Custom-built software ensures that when the touch contact is activated, the device provides a pre-programmed temperature transient. In figure 2, a photograph of the device is shown.

2.2 Stimuli

The shape of the stimulus is based on the temperature change that occurs at the skin surface when it touches an object with a certain thermal diffusivity α. When touched by the skin, the object starts extracting heat from it which spreads out throughout the material. This spreading of heat is governed by the heat conduction equation:

$$\nabla^2 T(\vec{x},t) = \frac{1}{\alpha}\frac{\partial T(\vec{x},t)}{\partial t} \tag{1}$$

Here, $T(\vec{x},t)$ is the temperature of the material at location $\vec{x}$ and time t. A solution would be to write this as the product of a location-dependent part $X(\vec{x})$ and a time-dependent part $\Theta(t)$:

$$T(\vec{x},t) = X(\vec{x}) \cdot \Theta(t) + T_0, \tag{2}$$

where T_0 is an arbitrary additive constant. Through separation of variables, the partial differential equation (1) can be split up into two regular differential equations. Because we are only interested in the temperature at the point of contact, we can solve just the time-dependent part:

$$K\Theta(t) = \frac{1}{\alpha}\frac{d\Theta(t)}{dt}, \tag{3}$$

where K is a constant that depends on the geometry of the object. This equation has an exponential function as a solution. For the temperature at a certain location (the point of contact) we can now write

$$T(t) = \Delta T \exp(K\alpha t) + T_0, \tag{4}$$

where ΔT is given by the initial conditions. For a physical solution, $K < 0$. This corresponds to an exponential decay with a time constant $\tau = -1/(K\alpha)$. So, in order to describe the behaviour of objects with different thermal diffusivities but with the same geometry, we can just use exponentially decaying functions with different time constants. It should be noted that this model does not take into account effects like extra heat supply from the bloodstream in the finger, but it is expected that these effects only cause an offset in the cooling curve and do not significantly change the basic exponential shape.

In addition to the theoretical derivation above, there is also experimental evidence for this exponential shape. The temperature of the finger follows this profile until it freezes when cooled by cold air [18]. Temperature profiles resulting from cooling by different kinds of fabric show similar shapes [20]. Cooling curves of the hand holding objects of 6 different materials could also be very well described by exponential functions [7]. Similar measurements of subjects touching 4 different materials yielded similar patterns [6]. Finally, a numerical model has been made of a finger touching a surface [19]. In the same study, the temperature behaviour was measured using an artificial finger equipped with thermal sensors. The calculated and measured temperature profiles can be well approximated by means of exponential functions.

For these reasons, exponentially decaying functions of the form of equation (4) were used as stimuli in the present study. Because of the natural difference between skin temperature (∼ 30 °C) and object temperature (room temperature, ∼ 20 °C), a ΔT of 10 °C was chosen. Because of the limitations of the device (5 °C/s), the smallest time constant that could be presented with this ΔT was 2 s. Examples of the stimuli that could be presented are shown in figure 3. Because of the finite heat capacity of the touch contact, the rate of temperature change cannot change instantaneously at $t = 0$, as is visible from the initial deviations from the nominal curves. Particularly the fastest curve ($\tau = 2$ s) shows the overshoot followed by the return to the nominal curve that is characteristical for a PID controlled process. Subjects did not seem to be influenced by these deviations from the nominal curves.

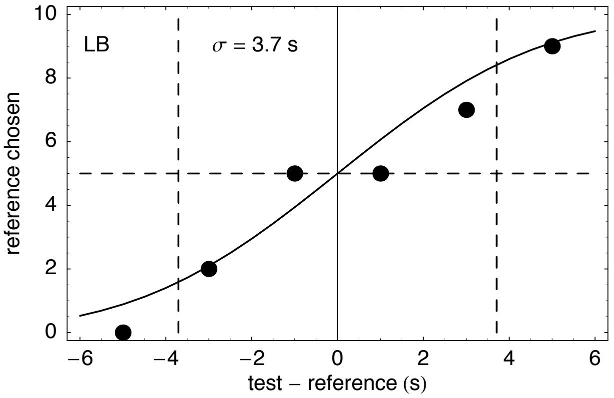

Figure 4: Representative example of the data for subject LB in the 5 °C temperature difference condition (dots), with a fitted function (solid line). The vertical dashed lines indicate the positions of $\pm\sigma$ of the cumulative Gaussian function. The horizontal dashed line indicates chance level.

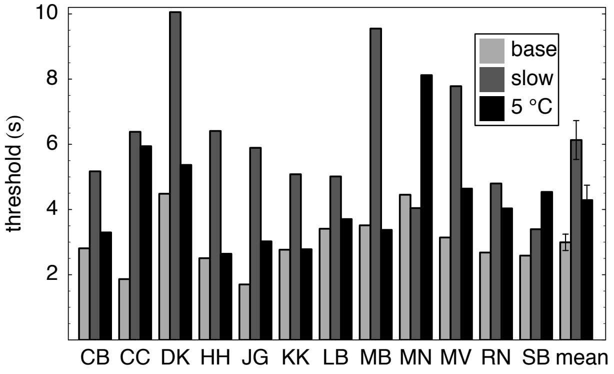

Figure 5: Thresholds of all subjects in the three conditions, plus the averages over subjects. The error bars with the averages indicate the standard error of the sample mean.

2.3 Subjects

Twelve university students took part in the experiment. Two were male and ten female. They were paid for their participation. They ranged in age from 17–26 years (average 21.9) and were all right-handed according to Coren's test [5].

2.4 Procedure

The experiment consisted of a two-alternative forced-choice task. Each trial, subjects were presented with a test and a reference stimulus, in random order, and had to choose the faster-cooling of the two. There were three conditions: a base, a 'slow' and a small-temperature-difference condition. In the base condition, the difference between the starting temperature and the asymptotical end temperature was 10 °C. There were six test stimuli with time constants of 2, 4, ..., 12 s. The reference stimulus was located in the middle of this range with $\tau = 7$ s. In the 'slow' condition, all time constants were doubled, thus ranging from 4–24 s with the reference at 14 s. The temperature difference was still 10 °C. In the third condition, the time constants were the same as the base condition, but the temperature difference was halved to 5 °C. In all conditions, the asymptotical end temperature was room temperature, because the hands and face of the subject were exposed to this temperature and it is therefore a natural reference point. During the course of the experiments, the room temperature varied between 20.0 and 22.8 °C.

Before each trial, the subject started with his/her hand resting on a block in an insulated box which was maintained at the starting temperature. In this way, the index finger was at the same initial temperature for each trial. At a signal from the experimenter, the subject removed his/her hand from the box and placed the index finger on the touch contact of the device. This started the temperature transient display. The subject held the touching force constant at 1 N with the help of a visual force indicator. Tests showed that subjects were able to do so with an accuracy of about ±10 %. After 10 s, the experimenter gave another signal and the subject replaced his/her hand in the insulated box. The device was then prepared for the second stimulus which was presented in the same way as the first. After feeling the second stimulus, the subject had to say which one cooled faster. The time between subsequent stimulus presentations was about 6 s, which was enough time to let the finger warm up to the starting temperature again. For six subjects, the finger temperature was measured at the start and the end of each session to check whether the finger did not cool down during the experiment. On average, there was an *increase* of the finger temperature over the course of the session of 1.7 ± 3.9 °C, which is not significantly different from zero (paired t-test, $t = 1.9$, two-sided $p = 0.081$). This indicates that there was no problem with the initial temperature changing over the course of the experiment.

Each of the six pairs of test and reference stimuli were presented ten times, resulting in 60 trials per condition. These were presented in random order, half with first the reference and then the test stimulus and the other half the other way around. Each condition was tested in a separate session of about 40 minutes. These took place either on different days or with at least one hour of rest in between, but never more than two sessions per day. For the order in which the conditions were tested, all possible permutations were used twice.

2.5 Analysis

The number of times that the reference stimulus was perceived to be the faster-cooling was plotted as a function of the difference between the standard and the comparison stimulus. In figure 4, a representative example of such a plot is shown. To this data, cumulative Gaussian functions were fitted using a maximum likelihood method. The σ of these functions, corresponding to the 84 % level, was taken as the threshold.

3 RESULTS

Two subjects (JG and MN) had in one condition a very high threshold that was out of range for the stimulus set used. Therefore, these conditions were remeasured for those subjects. The measured thresholds for the 12 subjects are shown in figure 5. Thresholds ranged from 1.7–4.5 s in the base condition, and are generally higher in the other conditions. Compared to the base condition with a standard time constant of 7 s, the average threshold doubled in the 'slow' condition with a reference time constant of 14 s. For these conditions, which have a temperature difference between start and end of the stimulus of 10 °C, the threshold is a constant fraction of 43 ± 13 % of the reference time constant. Since the thermal diffusivity α is inversely proportional to the time constant, the threshold is also 43 % of the thermal diffusivity.

In the 5 °C temperature difference condition, thresholds were on average a factor 1.4 higher than in the base condition. However, some subjects (HH, KK, LB and MB) showed thresholds that are identical to the base condition. An analysis of variance with repeated measures showed a significant effect of condition ($F_{1.3,14.4} = 13.6$, $p = 0.0013$). Bonferroni-corrected post-hoc analysis showed that the base and 'slow' condition were significantly different ($p = 0.0006$), but the 5 °C condition was not significantly different from the ‘slow’ condition ($p = 0.11$). The difference between the base and 5 °C conditions was significant ($p = 0.02$).

4 DISCUSSION AND CONCLUSIONS

The main finding from this experiment is that in the conditions tested, the discrimination threshold for thermal diffusivity is a constant fraction of 43 % when the temperature difference is 10 °C. The constancy of this figure can be explained if we assume that the perception of heat extraction rate adheres to the Weber-Fechner law, stating that the discrimination threshold is a constant fraction of the stimulus intensity. If this is indeed the case, we can use literature values of the thermal diffusivity (e.g. [1]) to predict which materials are hard to distinguish when only thermal cues were available. For instance, the difference between copper and aluminium is below threshold, as is the difference between granite and marble. On the other hand, wood and plexiglas, or glass and steel, should be easily discriminated.

In earlier discrimination experiments, some materials with diffusivity differences above the threshold of 43 % were not or poorly discriminated [9, 13]. Apparently, other factors that are not taken into account by the artificial extraction of heat, affect the ability to discriminate between stimuli. In the present experiment, the same finger was used for both stimuli, while in the earlier experiments, two hands were used. This fact may also have played a role in this discrepancy. Having to compare two simultaneous sensations from different hands may be more difficult than subsequent sensations from the same hand. This was already observed in relation to temperature perception [22]. Comparing simultaneous sensations imposes a higher cognitive load because attention has to be divided, likely resulting in higher discrimination thresholds. A similar distinction between sequential and simultaneous sensations was found in the context of curvature discrimination [21]. We must conclude that the diffusivity thresholds from this experiment are lower limits measured under ideal conditions.

The threshold of 43 % of the thermal time constant seems high if we compare it to other thresholds related to temperature perception. For instance, the threshold for detecting a drop in temperature lies between 0.1 and 0.3 °C when the rate of change is higher than 0.1 °C/s [16]. People are even better at discriminating between the intensity of two subsequent drops in temperature: for ‘cooling pulses’ presented to the thenar eminence, the average discrimination threshold ranges from 0.03–0.06 °C, depending on the intensity [11]. This corresponds to a Weber fraction of ~ 0.5 %. This illustrates the stark contrast between the two very different tasks of temperature discrimination and thermal time constant discrimination, the latter of which is apparently much more difficult, as shown in the present paper.

Because of the asymptotic character of equation (4), the temperature of the stimulus never quite reaches the ‘end’ temperature T_0. The difference between T_0 and the temperature at the end of the display period of 10 s depends on the time constant and the initial temperature of the stimulus. For instance, in the base condition, the temperature difference at the end of the display period between the reference and the slowest test stimulus is 1.9 °C. It could be suggested that this temperature difference at the end of the display period was used as a cue for discrimination, instead of or in addition to the cue of cooling rate. However, if this were the case, then the thresholds in the 5 °C condition would be twice as high as those in the base condition. This is because the difference in terms of time constant between two stimuli with a certain temperature difference at the end of the display period is inversely proportional to ΔT. That is, when ΔT is halved, the difference between two time constants associated with a given temperature difference at the end of the display period, doubles. Thus, if discrimination were based on temperature differences at the end of the display period, one would expect the time constant thresholds in the 5 °C condition to be twice those in the base condition. From the results in figure 5, it is clear that this is not the case. The average threshold does go up in the 5 °C condition compared to the base condition, but not by a factor of 2. In fact, for 5 of the subjects, the thresholds hardly go up (CB) or not at all (HH, KK, LB and MB). This unchanged threshold could be expected if the subjects' judgements were based on heat extraction rate: although the *absolute* temperature difference between beginning and end was halved, the *relative* difference in heat extraction rate between the two stimuli in a trial has remained the same. Therefore, it is unlikely that the cue of temperature difference at the end of the display period plays a dominant role for these subjects.

In conclusion, we can say that in a normal situation with objects at room temperature, subjects can use the rate of cooling of their finger when touching a material, and thus the material's thermal diffusivity, to discriminate between objects of the same geometry but different materials when the thermal diffusivities of those materials are at least 43 ± 13 % apart. This is important information for the design of haptic interfaces, in which thermal cues may play an important role in the identification of different materials.

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