

Thermosensory reversal effect quantified

Wouter M. Bergmann Tiest *, Astrid M.L. Kappers

Helmholtz Institute, Utrecht University, Princetonplein 5, 3584 CC Utrecht, The Netherlands

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Abstract

At room temperature, some materials feel colder than others due to differences in thermal conductivity, heat capacity and geometry. When the ambient temperature is well above skin temperature, the roles of ‘cold’ and ‘warm’ materials are reversed. In this paper, this effect is quantified by measuring discrimination thresholds for subjective coldness at different ambient temperatures using stimuli of different thicknesses. The reversal point was found to be at 34 °C, somewhat above skin temperature. At this reversal point, discrimination is quite impossible. At room temperature, subjects were able to discriminate between stimuli of different thickness based on subjective coldness, showing that the sense of touch, unlike vision, can penetrate solid objects. Furthermore, somewhat surprisingly, at ambient temperatures well below normal room temperature, discrimination is worse than at room temperature.

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1. Introduction

Objects made of different materials that are all at the same temperature, can still feel thermally different. For instance, wood generally feels warmer than metal, even though both materials are at room temperature. This effect is caused by differences in the thermal properties of these materials. Katz (1925) noted that when a subject is asked to order materials from ‘colder’ to ‘warmer’, the ordering is reversed at high temperatures (50 °C) compared to room temperature. For example, a copper sample that felt colder than a wood sample at room temperature, will feel *warmer* than the same wood sample when both are felt at a high temperature. This is in keeping with the idea that the subjective coldness of materials is determined by the heat flow from the observer’s hand to the material. If this heat flow is reversed, as is the case when the material is hotter than the

observer’s hand, the subjective coldness is also reversed. This interesting reversal effect has until now received little attention.

The subjective coldness, i.e. how cold an object feels to an observer, is determined by the thermal conductivity and heat capacity of the material and by the object’s geometry. A high thermal conductivity allows heat extracted from the finger to spread quickly to other parts of the object, thus enabling the object to extract heat from the finger faster. A high heat capacity means that the object does not warm up very much from outside heat, which enables it to continue extracting heat from the finger. In other words, it does not ‘saturate’ as fast. The geometry of the object also plays an important role: a thick bar can conduct heat away from the finger more easily than a thin foil.

Subjective coldness must be distinguished from the perception of temperature or temperature differences. Although both subjective coldness and temperature perception are mediated by thermal receptors in the skin, the subjective coldness depends on the amount of heat per time unit that is conducted away from or towards the skin, while

* Corresponding author. Tel.: +31 30 253 7715; fax: +31 30 252 2664.
E-mail address: W.M.BergmannTiest@phys.uu.nl (W.M. Bergmann Tiest).

temperature perception is registered more directly. The temperature discrimination threshold, i.e. the just noticeable difference (JND) between surfaces that are physically at different temperatures, has been studied extensively (e.g., Johnson, Darian-Smith, & LaMotte, 1973; Kenshalo, Holmes, & Wood, 1968; Stevens & Choo, 1998). However, there have been few experiments measuring discrimination between materials that are at equal temperatures: the discrimination threshold for subjective coldness. In Dyck, Curtis, Bushek, and Offord (1974); Jones et al. (2003) and Ho and Jones (2006), the capacity for subjective coldness discrimination was assessed using a few different materials. Dyck et al. (1974) had chosen the geometries of their stimuli in such a way that each differed by a factor of 10 in heat transfer rate from the next. Using this coarse scale, an upper and lower limit for the discrimination threshold could be established: with a difference of a factor of 10 in heat transfer rate, the percentage correct was $61 \pm 11\%$ (chance level 50%), while with a difference of a factor of 100, this was $83 \pm 9\%$. Jones et al. (2003) estimated a discrimination threshold in terms of thermal conductivity and heat capacity, but their stimulus set did not allow for a very precise number to be calculated. In later work, the discrimination threshold in terms of contact coefficient, defined as the square root of the product of thermal conductivity, density and heat capacity (Businger & Buettner, 1961), was estimated to be a factor of three or lower (Ho & Jones, 2006). The difficulty with using different materials for these discrimination experiments, is that the materials differ in more than one parameter (heat capacity, thermal conductivity, and density), and a desired systematic spacing in these parameters might not be available. Some materials might be too close in thermal parameters, while others differ too greatly. Therefore, it is difficult to narrow down the threshold value using different materials.

The effect of heat extraction from touching an object can also be simulated using artificial heat extraction, often by means of a Peltier element (Bergmann Tiest & Kappers, submitted for publication; Caldwell & Gosney, 1993; Ho et al., 2004; Ino et al., 1993; Yamamoto, Cros, Hashimoto, & Higuchi, 2004). In this way, the desired systematic spacing can be made available. In an experiment in which systematically varying heat extraction profiles were displayed to subjects' fingers, the discrimination threshold (JND) for heat transfer was determined to be 40% of the stimulus intensity (Bergmann Tiest & Kappers, submitted for publication). However, all these studies were performed at room temperature, so that the dependence of the threshold on ambient temperature was not determined.

For these reasons, it was considered worthwhile to rigorously quantify the subjective coldness discrimination threshold at different ambient temperatures, and to see how strong the reversal effect was. To this end, discrimination thresholds were measured at four temperatures using a two-alternative forced-choice method. In order to stay as close as possible to an everyday context, real stimuli and not artificial heat extraction were used. To avoid the diffi-

culties with the spacing of the thermal parameters associated with using different materials, we decided to provide different thermal experiences by varying the *geometry* of the stimuli instead of the material.

2. Method

2.1. Subjects

Six subjects were paid for their participation. They ranged in age between 22 and 25 years and were all right-handed according to Coren's test (Coren, 1993).

2.2. Materials

It is difficult to find different materials that have thermal properties varying in a systematic way, but by using different thicknesses, a systematically varying range of heat extraction rates can be attained. The stimuli were $100 \times 100 \text{ mm}^2$ blocks of aluminium that varied in thickness between 1 and 9 mm. Heat is conducted better in a thicker stimulus, enabling it to spread through the material faster. A thicker stimulus also has a higher total heat capacity, allowing it to absorb more heat before warming up noticeably. The two effects combine to effect different heat transfer rates upon touch for stimuli with different thicknesses. There were eight test stimuli (1, 2, 3, 4, 6, 7, 8 and 9 mm). Each test stimulus was paired with its own reference stimulus of 5 mm. If a single reference stimulus had been used with all test stimuli, the reference stimulus would have been touched more often and warm up more than the test stimulus, biasing the sensation. By having eight duplicates of the reference stimulus, this problem was prevented. Each stimulus was mounted on another of a complementary thickness with insulating foam spacers, i.e. the 1 mm was on top of the 9 mm, 2 mm on top of 8 mm, etc. In this way, the height of the touched surface was equal for all stimuli, as was the mass. Thus, height cues and inertia cues (when a stimulus was accidentally moved during exploration) were eliminated.

To provide different ambient temperatures, a temperature-controlled box was designed and built. On one side, it had a transparent hatch which allowed the experimenter to manipulate the stimuli and observe the subject's hand. On the other side, there was a hole covered by rubber flaps through which the subject could insert his or her hand to feel the stimuli. The stimuli were placed on a plastic grid that allowed free circulation of air. The temperature was read out using an electronic thermometer (Dallas Semiconductor DS600). The cooling and warming were done with a Peltier element (Campingaz Powerbox 24 l) connected to a computer-controlled power supply (Delta E 015-20). The temperature was regulated by a software PID controller. A fan provided circulation of air in the box. The air temperature could be regulated within 0.1°C of the desired temperature. Since the stimuli were inside the box at all times, it is unlikely that their temperature would depart significantly from the set temperature.

A second temperature-controlled box ensured that the subject's hand was at the same temperature for every trial. It was kept at 30 °C, approximately skin temperature. The box had an opening to stick the hand through and contained a block of aluminium to rest it on.

2.3. Procedure

For each subject, the experiment was divided into four sessions of about an hour. In each session, one of four ambient temperatures (10, 20, 30 and 40 °C) was used. A session consisted of 80 two-alternative forced-choice trials, 10 repetitions for each test stimulus. The order was randomized and the left/right placing of the stimuli was counter-balanced. All stimuli were in the temperature-controlled box during the entire duration of a session, and were thus always at the same temperature within one session. Before the start of each session, the subject's skin temperature was measured by holding the probe of a digital thermometer between thumb and forefinger. Before the first and between trials, the hand was put in the box which was kept at 30 °C, approximately skin temperature. For each trial, the subject took his or her hand out of this box and felt the stimuli in the other. Each pair of stimuli consisted of a test and a reference. The subject could explore their surfaces freely and was asked to report which one felt the coldest. In order to stay as close as possible to a 'natural' situation, subjects could use their fingers or their whole hand. There was no time limit, and subjects could go back and forth between test and reference as often as they preferred. Free exploration like this ensures that subjects have the opportunity to perform at an optimum level, so that the measured thresholds truly represent the limit of their capabilities. The experimenter could observe the subject's movements through the transparent hatch. The subject responded either verbally ('left' or 'right') or by pointing at or tapping the stimulus that felt the coldest. After responding, the subject replaced his or her hand in the other box and the experimenter prepared the next trial.

2.4. Analysis

The data were plotted as the number of times that the test stimulus was perceived as the coldest as a function of its thickness. An example is shown in Fig. 1. At stimulus temperatures below skin temperature, discrimination is easy when the test stimulus is much thinner than the reference (left-hand side of the graph), and subjects hardly ever choose the test stimulus as the 'coldest'. Similarly, when the test stimulus is much thicker than the reference (right-hand side), subjects almost always choose the test stimulus. In between, with the thicknesses closer together, discrimination is more difficult and the scores approach chance level (5). In this way, the characteristic shape of the psychometric curve arises. Conversely, when the stimulus temperature is higher than skin temperature, the thinnest stimulus will

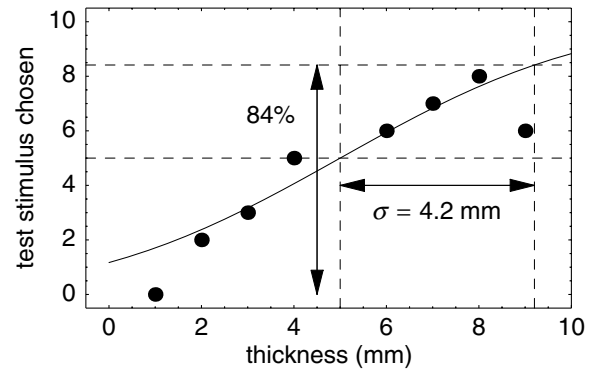


Fig. 1. Example of a discrimination threshold measurement for a single subject at an ambient temperature of 20 °C. The dots represent the number of times the test stimulus was perceived colder than the 5 mm reference. The solid line is a fit of a cumulative Gaussian function to the data.

feel the 'coldest' and the shape of the curve is mirrored. A cumulative Gaussian function of the form

$$f(d) = 5\text{erf}\left(\frac{d - d_0}{\sqrt{2}\sigma}\right) + 5$$

was fitted to the data, where d_0 is the reference thickness of 5 mm. This function gives a reasonable fit to the data, taken into account the fact that the stimulus range is quite limited, and therefore does not always extend far into the 'wings' of the function. The width (σ) of the cumulative Gaussian, corresponding to the 84% level, is a measure of the discrimination threshold. Note that σ can also be negative, in which case the function is mirrored. A higher absolute value of the threshold means a worse performance in discrimination. Because we would like to assess discrimination performance as a function of temperature, we report here the *inverse* threshold value (σ^{-1}). For this quantity, a higher absolute value is better. An inverse threshold of zero means that discrimination was not possible at all. Negative values indicate a reversal of the 'cold' and 'warm' sensations.

3. Results

The results are shown in Fig. 2, averaged over subjects. A considerable inter-subject variability was present, as indicated by the error bars in the figure. A repeated-measures ANOVA shows that there is an effect of temperature ($F_{3,15} = 10.5$, $p = 0.001$). Discrimination is best at 20 °C, approximately room temperature. At the highest temperature, 40 °C, the subjective coldness has reversed: the 'coldest' stimulus at room temperature now feels the 'warmest'. If we interpolate, the reversal point is found to lie at 34 °C. This is lower than core body temperature; the relation to body and skin temperature is discussed below. At the lowest temperature, 10 °C, the discrimination performance is somewhat reduced compared to room temperature, although this difference is not significant (Bonferroni-corrected two-tailed t -test, $t = 1.5$, $p = 0.6$).

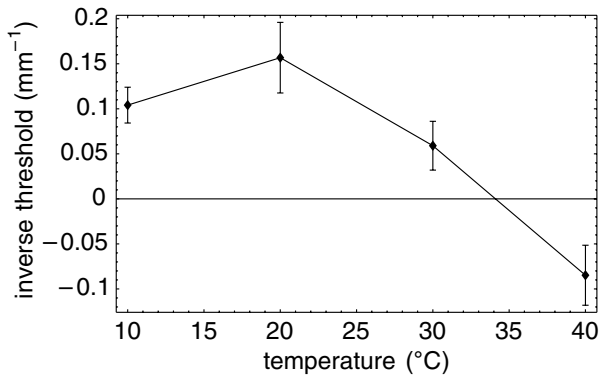


Fig. 2. Inverse thresholds averaged over all subjects at four reference temperatures. The error bars indicate the standard error of the sample mean.

The average skin temperature was 29 ± 3 °C. There was no significant correlation between the individual skin temperatures and the individual reversal temperatures ($p = 0.17$).

4. Discussion and conclusions

As can be seen in Fig. 2, for room temperature (20 °C) and warmer, the subjects' ability to discriminate subjective coldness seems directly related to the temperature difference between hand and object. Because the heat transfer rate, i.e. the amount of heat transferred per second, depends on the temperature difference, the discrimination performance is related to the heat transfer rate. Indeed, when the direction of the heat flow reverses, so does the subjective coldness. The reversal point of 34 °C lies a few degrees higher than the average skin temperature (29 ± 3 °C). It seems that the reference temperature for deciding the direction of heat flow is an intermediate between skin temperature and body temperature (37 °C). This is understandable given the fact that the thermal receptors are located below the skin surface. Although the correlation between the individual reversal points and the individual skin temperatures was not significant, this may be due to the limited accuracy of the determination of the individual reversal points. We may speculate that with a group of subjects with a higher average skin temperature, also a higher reversal point would be found.

Based on the heat transfer rate, one might expect the best discrimination performance at 10 °C, the largest temperature difference between hand and stimulus. The reduction in performance that is observed instead may be ascribed to the reduced sensitivity of the thermal receptors in the skin at this low temperature. Even though this temperature is still within the range of temperatures encountered in everyday life, it has been observed that the perceived thermal intensity function starts levelling off at this temperature (Greenspan, Roy, Caldwell, & Farooq, 2003). It is not surprising that this reduced sensitivity for thermal intensity should coincide with the reduced sensitiv-

ity for subjective coldness, as observed in the present experiment. The lowest temperature may for some subjects approach the range of noxious cold. It has been shown that in this range, the ability to detect temperature changes is significantly worse than in the innocuous range, suggesting that the noxious temperatures are mediated by a different set of receptors (Morin & Bushnell, 1998). This is in line with the reduced sensitivity effect found in the present experiment. Due to the trade-off between the heat transfer rate effect and the reduced sensitivity effect, there must be a point of optimum performance between 10 and 30 °C. From this optimum point, performance decreases by about 7%/°C, passing through the point of no possible discrimination at 34 °C, and then increasing again with the same rate, albeit with a reversed notion of subjective coldness.

For comparison with other experiments and general usefulness, it is better to express the thresholds in terms of physical parameters instead of units that depend on the specific stimulus set. In Dyck et al. (1974), the chosen quantity was the heat transfer rate averaged over the first 0.5 s after touching, in watts. We have used a numerical simulation to relate the stimulus thickness in our experiment to the initial heat transfer rate, given the thermal properties of the material (aluminium). This simulation involved modeling the stimulus as consisting of many small elements, the so-called finite element modeling (FEM) method. Each element has its own temperature. Each time step in the simulation, the amount of heat that is exchanged between all neighbouring elements is calculated. In this way, the heat flow within the stimulus and between the finger and the stimulus is determined. The result is a description of the heat transfer rate between finger and stimulus as a function of time. In this way, the heat transfer rate as a function of time can be calculated for every stimulus used in this experiment. The value of the heat transfer rate at a given moment in time after contact is made, can be used as the value associated with that stimulus. More details of the model are given in Bergmann Tiest (in press). The modeled heat transfer rate depends not only on the material and the geometry of the object, but also on the thermal contact resistance between the fingers and the stimulus. This factor is not accurately known, since it can vary a lot with the contact surface area, humidity, texture, applied pressure etc. Therefore, it is difficult to provide absolute numbers for the heat transfer rates. However, because the thermal contact resistance will be very similar for all stimuli in the present experiment, it is possible to calculate *relative* numbers for the differences between stimuli. For instance, changing the stimulus thickness from 5 to 6 mm yields an increase of about 6% in heat transfer rate, independent of the assumed thermal contact resistance. Based on this conversion, the threshold at 20 °C in the present experiment is equivalent to a difference in heat transfer rate of 36%. This means that at this temperature, a difference in initial heat transfer rate of at least 0.36 times the reference rate is necessary for successful discrimination. This is very well comparable to the number of 40% that

was found in Bergmann Tiest and Kappers (submitted for publication) with artificial heat extraction. This suggests that artificial heat extraction is a good approximation of the real process. The number reported here represents an improvement in accuracy with respect to the experiment by Dyck et al. (1974), which only had stimuli that differed by a factor of 10 from each other. The thresholds at the other temperatures are 54%, 95% and 66% for 10, 30 and 40 °C, respectively.

If anything, this experiment shows that subjects are able to discriminate between objects of different thickness by just touching their surface. Although this was not a thickness discrimination task, subjects could feel a difference based on the subjective coldness of the material. One could say that in this respect, the sense of touch is able to penetrate the surface of the material and ‘look’ deeper. This illustrates one area where touch outperforms vision, which is generally thought of as the dominant sense.

In conclusion, we have quantified the thermosensory reversal effect with a reversal temperature of 34 °C and performance increasing from there by 7%/°C in either direction. Below room temperature, a reduced sensitivity effect starts occurring, causing a drop in performance.

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