Studying the influence of contact force on thermal perception at the fingertip

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Abstract. This paper investigates the influence of contact force applied to the human's fingertip on the perception of hot and cold temperatures, studying how variations in contact force may affect the sensitivity of cutaneous thermoreceptors or their interpretation. A psychophysical experiment involved 18 participants exposed to cold (20 °C) and hot (38 °C) thermal stimuli at varying contact forces, ranging from gentle (0.5 N) to firm (3.5 N) touch. Results show a tendency to overestimate hot temperatures (hot feels hotter than it really is) and underestimate cold temperatures (cold feels colder than it really is) as the contact force increases. This result might be linked to the increase in the fingertip contact area that occurs as the contact force between the fingertip and the plate delivering the stimuli grows.

Keywords: Thermal feedback, Contact force, Haptic perception, Fingertip haptics

1 Introduction

Thermal feedback can be used to augment real and virtual interactions, by conveying information on the environment or as affective touch [5,8,12,13]. Peltier cells are the most common devices used in that regard, as they are compact, can display a wide range of temperatures from hot to cold, and are easy to control. However, they present significant flaws, one of them being their slow dynamics [8]. While their technical efficiency can always be improved, the use of thermal illusions is another way of attaining a target sensation faster or with less energy [8,9]. Indeed, thermal perception hinges on spatial [18] and temporal [10] thresholds of the human skin receptors [14], which can be manipulated through haptic devices to modulate thermal sensations [9]. Notable examples include the thermal grill illusion, demonstrated by Thunberg in 1896 [15]; interlaced together, innocuous warm and cool stimuli feel painfully burning. Another prominent thermal illusion is the Thaler, or temperature-weight illusion by Weber et al. in 1846 [17], in which colder objects felt heavier than neutral ones.

In this paper, we seek to evaluate the potential of contact force to modulate thermal perception. Galie et al. [2,3] studied the increase of the contact area of the skin when increasing the force applied on it through a plate. They found that between 0 N and 4 N, the contact area increased following a logarithmic trend. They also noted that the thermal sensitivity of participants' fingers was negatively affected by a prolonged increase in the contact force. Dou et al. [1] also observed that an increase in contact force led to an increase in the heat flux of materials. To our knowledge, no work has been carried out on the influence of contact force on thermal perception. However, some studies evaluated the reverse: the effect of thermal feedback on the perception of contact force or stiffness [2,4]. In this respect, Gallo et al. [4] found an increase in stiffness perception and precision when felt in combination with warm thermal feedback, significantly higher than with cold feedback. With these observations in mind, we hypothesize that thermal perception is modulated by the contact force.

This work aims to evaluate the influence of contact force on thermal perception, and if such force is effective to enhance both warm and cold thermal perception. A psychophysical experiment was carried out, where participants repeatedly compared pairs of stimuli combining force and thermal feedback. Two thermal conditions were studied: hot, at 38 °C, and cold, at 20 °C. Participants reported which stimuli in the pair felt hotter or colder, depending on the thermal condition. Our primary hypothesis is that an increase in contact force will heighten thermal perception: hot will feel hotter, cold will feel colder.

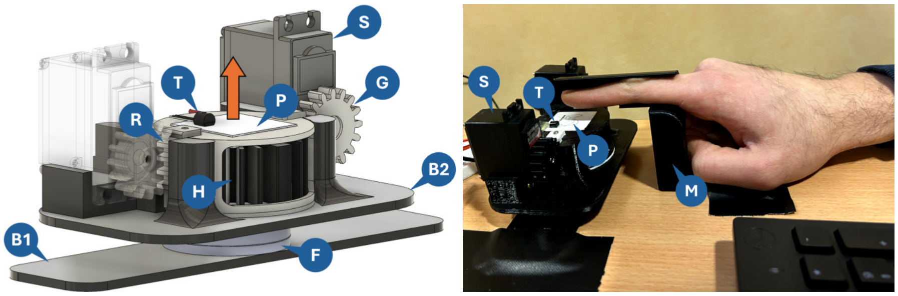
2 Methods

2.1 Experimental Setup

Device. We designed a 1-degree-of-freedom (1-DoF) haptic interface able to provide different temperatures and contact forces stimuli to a user's fingertip. The device is shown in Fig. 1a; it includes a flat plate moving upwards and downwards, towards and away from the fingertip. It houses a 3×3 cm Peltier cell (**P** in Fig. 1, model GM250-71-14-16) powered with a 5.3 V power supply and maximum current absorbed of 1.1 A, a temperature sensor (**T**, LM35) with a sensitivity of 10 mV/°C, and a heat sink (**H**, SK57720SA). The Peltier cell is located on the upper part of the plate, contacting the user's fingertip during the interaction. The temperature sensor is attached to one of the cell's corners to not interfere with the finger-platform interaction. To ensure precise temperature measurements, we assessed any discrepancies between the temperature at the center and the temperature at the corner of the cell. The heat sink is located in the lower part of the moving plate to absorb the heat produced by the Peltier cell. Moreover, a fan is located outside the device (not shown in Fig.1), pointing towards the heat sink, to increase dissipation without providing any additional undesirable stimuli to the user.

The moving plate is actuated by two servomotors (**S**, HS-625MG) through two racks (**R**) and gears (**G**), enabling the platform to move up and down with respect to the grounding base **B1**. On the sides of the moving plate, two racks (**R**) are securely attached using screws. The maximum stroke of the moving plate is 15 mm. All these components are mounted on a fixed floating base (**B2**). To register the force exerted by the plate on the user's fingertip, we installed a triaxial high-precision force and torque sensor (**F**, ATI Nano43), with a resolution of 0.002 N and 0.025 N mm, respectively. Finally, a fingertip mount (**M** in Fig.1b) enables a comfortable fingertip positioning and a controlled interaction force. The setup is firmly attached to a table with two clamps. The structure of the device is 3D-printed in ABS on a Raise3D N2 Plus printer.

We implemented a closed-loop PID-based force and temperature control using the data registered by the force and temperature sensors.



(a) 3D CAD model of the device. (b) Picture of the setup.

Fig. 1: Experimental setup. A 1-DoF platform housing a Peltier element provides different temperature and pressure stimuli to the user's fingertip.

2.2 Experimental Protocol and Measures

Participants. Eighteen participants took part in the study (16 males, 2 females), aged between 23 and 36 years old ($M=27.06$, $SD=3.27$). All participants had no known hand or finger impairment. They all gave written informed consent and did not receive any form of compensation.

Procedure. During the experiment, the room's heating system was set to maintain a temperature of 24°C. Participants sat before the setup and placed their right index finger inside the finger mount, as shown in Fig. 1b. Then, the experimenter carefully ensured that the finger pulp was placed right above the center of the Peltier element to guarantee a good contact interaction. Finally, the device and finger mount were secured to the table through two clamps to avoid undesired movements during the experiment.

The experiment included two blocks, "hot" and "cold", featuring interactions when the Peltier element on the plate had a temperature of 38 °C and 20 °C, respectively. We chose these two temperatures as they stand equally distant from the standard temperature of our fingertips, which Vergara et al. reported to be in the range [28, 30]°C [16]. In particular, a pilot test aimed to identify temperatures that produced both hot and cold sensations with comparable intensity. Results indicated that 38 °C felt as hot as 20 °C felt cold. Within each block, participants carried out 48 comparisons of two subsequent force stimuli at the given temperature (38 °C or 20 °C), comparing the reference force vs. a test force. For this experiment, we considered 2 N as the reference force and [0.5, 1.0, 1.5, 2.5, 3.0, 3.5] N as the test forces to apply at the fingertip. The range of forces was inspired from Galie et al.'s work on the influence of force on the contact area of skin [2]. Each test/reference couple was compared 4 times within each block, resulting in 8 repetitions for each tested force. Participants had no information about the rendered sensations (e.g., they did not know that the temperature within each block was the same). For each comparison, the device makes contact with the user's fingertip for 2 s, then breaks contact for 4 s, and again makes contact for 2 s (see the video). These timings were chosen to enable the user to remember the two stimuli while giving time to the fingertip to return to its rest temperature before the second interaction [7]. After each comparison, participants responded to "Which contact felt hotter?" during the hot block and "Which contact felt colder?" during the cold block. Throughout the experiment, participants could answer this question by pressing "1" or "2" on the keyboard with their left hand for the first or second feedback. Participants took a 1-minute break every 24 comparisons. The order in which the blocks were presented and the order in which the reference and test forces were applied were counterbalanced. The order in which the comparisons were presented within each block was randomized. The duration of the experiment depended on the participants' responsiveness in providing answers. Considering this factor, the experiment lasted approximately 45 minutes.

Throughout the experiment, we recorded the target and measured forces/tem-peratures for each interaction, as well as the users' response and response time for each comparison.

According to the literature, increasing contact pressure on the fingertip leads to an expanded contact surface between the skin and the interacting device (up to a certain level) [2]. With this in mind, our main hypothesis was that: Increased contact force exacerbates temperature perception (hot feels hotter than it really is, and cold feels colder than it really is) (**H**).

3 Analysis and Results

Following the data collection from the experiment, we removed trials in which the difference between target and registered forces/temperatures in the reference or comparison stimuli surpassed three standard deviations (73 out of 1728 trials), i.e., trials in which the system failed to reach the target stimulus level. We also removed data from two participants. For the first one, the temperature sensor partially detached from the Peltier cell during the experiment, leading to an unpredictable (and unknown) level of applied temperature. The second participant did not understand the comparative question for the feedback couples, leading to random, uninformative answers for studying the considered hypotheses. After this step, the data from 16 participants (1462 trials) was analyzed with regard to our hypotheses. The difference between target and registered forces/temperatures (i.e., the error in delivering the stimuli) were $M = 0.12$ N, $SD = 0.19$ N and $M = 0.00$ °C, $SD = 0.08$ °C, respectively.

Then, we computed for each user, feedback couple, and thermal condition the percentage of answers where the reference stimulus (2 N) was selected as being colder/warmer (see Fig. 2). A general linear mixed model analysis was performed, considering the *percentage* as the dependent variable, the comparison force and the temperature condition as within-subject variables, and the user as a random factor. The results showed only a significant effect on force ($F_{4.12,61.81} = 17.62$, $p < 0.001$, $\eta_P^2 = 0.54$), but not on the temperature condition ($F_{1,15} = 0.33$, $p = 0.86$, $\eta_P^2 = 0.002$) nor on their interaction ($F_{3.69,55.29} = 0.66$, $p = 0.61$, $\eta_P^2 = 0.04$). Figure 2 summarizes the results of the post-hoc tests. A line between two force levels means a significant difference ($p < 0.05$, t-tests with Bonferroni correction). We observe that the percentage of answers - wherein the reference stimulus was selected as being warmer/colder - was higher when the compared forces were smaller, and this effect does not change with the considered temperatures.

Finally we fitted a psychometric function for each user, to compute the point of subjective equality (PSE) ($M = 0.22$, $SD = 0.87$) and the just-noticeable differences (JND) ($M = -2.04$, $SD = 1.86$). Similarly to the previous results, there were no significant differences between hot/cold conditions for the PSE ($t(15) = -0.47$ $p = 0.65$) and the JND ($t(15) = 0.05$ $p = 0.96$), thus only the global PSE and JND are reported.

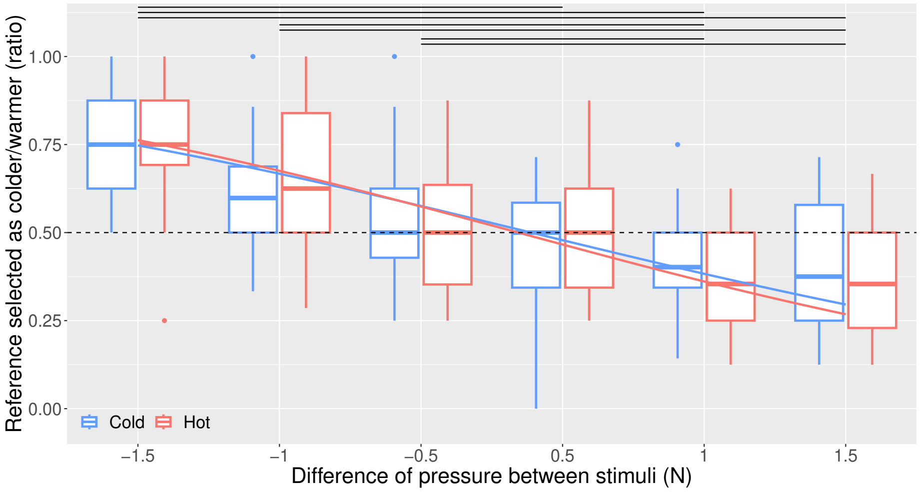


Fig. 2: Box-plot showing the ratio of the trials wherein the reference stimulus (2 N) was considered colder/warmer. The lines on the top represent significant differences between force conditions ($p < 0.05$). The difference between temperature conditions was not significant. The colored oblique lines represent the binomial regression model using measured forces.

4 Discussion and Conclusion

We explored the impact of contact force at the fingertip on the perception of hot and cold temperatures. We conducted an empirical study to compare the perceived temperature of a moving plate by applying different forces at their index fingertips. Results show a tendency to overestimate hot temperatures and to underestimate cold temperatures with increasing contact force, supporting **H**. In other words, the hot plate felt hotter as the force increased; similarly, the cold plate felt colder as the force increased. This exacerbation of the temperature perception seems stronger at lower forces (<2.5 N), e.g., results at 3 N (+1) vs. 3.5 N (+1.5) show no difference, while results 0.5 N (−1.5) vs. 1 N (−1) show a statistically significant difference. In addition to the change of pressure, this trend may be also associated with the concurrent increase in fingertip contact area as the force between the fingertip and the plate rises. Indeed, Galie and Jones [3] identified a logarithmic trend between contact force and contact area on the fingertips, with a fast increase of the contact area for low forces (<2 N) and close-to-zero increase when applying high forces (>3 N). Our study mostly addresses the former range, considering forces from 0.5 N to 3.5 N. Moreover, as stated by Jay et al. [6], pressure-induced changes in skin temperature perception might be associated to changes in blood flow. Thus, additional experiments are needed to analyze this temperature vs. force relationship at higher forces to further verify the relationship between thermal perception and contact area. For example, a potential approach to prevent the increase in contact area with the application of rising forces could be to utilize Peltier cells smaller than the fingertip.

At the end of the experiment, participants provided feedback on their strategy. The majority of the participants were surprised upon discovering that the temperature remained constant within a block, while only one speculated that only pressure changed during the comparisons. Finally, in this work, we only considered two reference temperatures and short sustained contacts (2 s) from when we reached the target contact force, meaning that higher forces were also applied for a (very slightly) longer time; these variables might impact the relationship between temperature and contact force. For example, we expect the behavior to vary depending on which set of thermal receptors are activated [7,11]. Similarly, the local shape of the end-effector at the contact point – a flat surface in our case – might change the way the temperature is delivered and, therefore, its interpretation. These observations leave a substantial space for further experimentation and application in relevant scenarios.

Indeed, these (and previous) results on the topic pave the way for the development of new thermal devices, in which the target thermal sensation can be modulated by controlling the actual temperature of the end-effector *as well as* the pressure it applies on the skin. As Peltier cells have slow dynamics, it is promising to be able to rapidly modulate the perceived temperature through pressure variation.

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