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A Compact Thermal Grill Illusion Presentation System for Psychophysiological and Engineering Studies

Kazuma Kotera and Atsutoshi Ikeda, *Member,IEEE*

Abstract— **The Thermal Grill Illusion (TGI), a perceptual phenomenon arising from the central integration of spatially interlaced warm and cold stimuli, provides a unique window into the psychological and physiological processes underlying pain perception and central sensitization. While previous studies have primarily explored TGI using large-area thermal arrays, the mechanisms by which TGI can be elicited within a narrow contact area and the relationship between illusory sensations and heat transfer dynamics at the skin interface remain largely unexplored. To address this gap, we developed a compact, smartphone-controlled device capable of delivering precisely regulated, localized TGI stimuli via Peltier elements and copper contact plates. The system incorporates high-accuracy thermistor calibration using the Steinhart–Hart equation and PID-based temperature control within ± 1 deg, enabling reproducible manipulation of thermal gradients. Experiments with 17 healthy participants assessed two temperature ranges (20–35 deg, 18–42 deg) applied to the palm and upper arm, demonstrating that greater temperature disparities yield stronger perceptions of warmth and burning, and that site-specific differences emerge under smaller disparities. By enabling controlled induction of TGI in confined regions, this device provides a versatile research tool for investigating the interplay between thermal perception, skin heat transfer, and nociceptive processing—offering a foundation for both basic psychophysiological research and future clinical applications.**

I. INTRODUCTION

Chronic pain is a complex condition with multifactorial aetiology, which renders its evaluation and treatment particularly challenging in clinical practice. Among the various types of pain, nociplastic pain—which is not associated with apparent tissue damage or inflammation—is especially difficult to assess using conventional imaging or biomarkers. Recent studies have indicated that central sensitization plays a pivotal role in the development and persistence of such pain.

In this context, the phenomenon known as the Thermal Grill Illusion (TGI) has emerged as a promising, non-invasive method for evaluating central sensitization. TGI arises from central integration of warm and cold stimuli, and both the illusion and cold-induced burning pain can be explained by a shared neural mechanism [1]. It is not merely a sensation of pain but a complex perceptual experience that lies between heat and pain, making it particularly useful for studying hypersensitivity in chronic pain. The illusion evokes distinct perceptual qualities that differ from those induced by single-temperature stimuli [2].

Furthermore, Karmakar et al. proposed an analytical model based on the disinhibition theory to predict TGI pain intensity, demonstrating through experiments and simulations that greater temperature differences produce stronger perceived pain [3]. Complementing this, Patwardhan et al. reported that the perceptual response time to TGI decreases with increasing stimulus intensity, which they explained using a tissue heating model [4].

Importantly, Osumi et al. showed that TGI-induced pain shares similar qualities with central neuropathic pain, suggesting that the mechanism of TGI is more closely related to central, rather than peripheral, neuropathic pain. This highlights the potential clinical value of TGI, as pain quality can help distinguish between central and peripheral pain mechanisms [5]. Furthermore, in a study related to the central nervous system, there is a report that compared the sensations elicited by a wide range of temperature differentials between the warm and cold bars of a thermal grill applied to the hand among patients with fibromyalgia, patients with irritable bowel syndrome, and healthy controls [6]. The results showed that the percentage of TGIP responses, as well as the intensity and unpleasantness of TGIP, were significantly greater in patients than in controls. These findings reinforce the interpretation of TGI as a reflection of thermal signal integration and pain perception within the central nervous system—positioning it as a valuable proxy for evaluating central sensitization in clinical settings.

Despite its scientific significance, the TGI has been mainly explored in experimental psychology and neuroscience, and its practical applications in medical or occupational health settings remain limited. In addition, most existing studies have employed relatively large contact areas, leaving the spatial scale at which the TGI can be reliably elicited unclear. Table I summarizes representative device configurations reported in prior studies. When the contact area becomes smaller, the amount of heat transferred to the skin also decreases, potentially reducing the likelihood of illusion induction. Thus, whether the TGI can be evoked through highly localized, small-area stimulation—and if so, under what thermal conditions—remains an open and fundamental question

Moreover, recently, devices have been developed to present thermal stimuli. For example, ThermoScratch is a device that uses the TGI to create the sensation of scratching the skin without actual physical contact [7]. By leveraging this illusion, it can help alleviate itch without causing damage

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Kazuma Kotera is with the Graduate School of Science and Engineering, Kindai University, Osaka, Japan 2533330331f@kindai.ac.jp
Atsutoshi Ikeda is with the Graduate School of Science and Engineering, Kindai University, Osaka, Japan, ikeda@emat.kindai.ac.jp

TABLE I
REPRESENTATIVE DEVICE CONFIGURATIONS IN PREVIOUS TGI STUDIES.

Study	Warm/Cold Bar Width (mm)	TGI Area (mm)	Number of Bars
Karmakar et al.[3]	5	80 × 55	4
Patwardhan et al.[4]	6	150 × 66	6
Osumi et al.[5]	5	200 × 99	8
This study	2	20 × 14	4

to the skin.

Moreover, Gao et al. proposed ThermOuch, a wearable thermo-haptic device that leverages the TGI to simulate pain sensations in virtual reality (VR) without causing actual invasive or non-invasive harm [8]. The user study in VR demonstrated that ThermOuch significantly enhanced the sense of presence and body ownership for the participants, as well as elevated their biosignal-indicated arousal levels.

However, these devices primarily focus on stimulus presentation, and systematic studies investigating how TGI is perceived in small contact areas or how heat transfer dynamics influence illusory sensations are still lacking.

Accordingly, there is an urgent need for the development of simple, portable, and reproducible devices capable of delivering controlled TGI stimuli for clinical evaluation.

In this study, we propose a prototype device, Pain Compass, designed to induce TGI through localized warm and cold stimulation.Our goal is to investigate the conditions under which the thermal grill illusion occurs, particularly whether it can be induced locally in narrow regions. If so, we aim to determine how warm and cold stimuli should be presented and how thermal transfer at the skin interface contributes to the illusion.

We report on the feasibility of reliably eliciting TGI using this system, discuss the associated technical challenges, and explore the experimental parameters necessary to establish a quantifiable and repeatable evaluation method based on TGI.

II. DESIGN AND DEVELOPMENT OF TGI DEVICE

A. Hardware Overview

The proposed device's appearance is illustrated in Fig. 1. The dimensions of the device are $76 \times 60 \times 105$ mm in width x depth x height, with a weight of $262\ g$. The proposed device is powered by an AC adapter ($5\ V$, $1\ A$)

The device is controlled by an Arduino NANO 33 BLE (Arduino), and the low and high temperatures of the TGI are provided by two Peltier elements (Z-MAX Co. Ltd.). Each Peltier element is governed by an amplification process of the DA output of the Arduino, facilitated by a MOSFET module. The temperature control of the Peltier elements is described in detail in the following subsection. The Peltier elements on the low temperature side of the TGI are cooled by a cooling fan and a heat sink to prevent heat from remaining inside the device. The integration of all electronic components, with the exception of the power supply and the stimulus presentation element of the TGI, will be accomplished through the

Fig. 1. Device overview

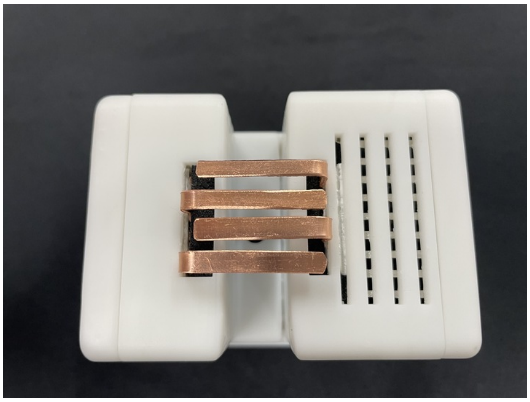

Fig. 2. Contact area

implementation of a case created by a 3D printer. The cover of the device are fixed with hooks and the cover can be easily removed. Therefore, the contact area for presenting various thermal sensations can be easily modified to allow testing with different shapes and hot–cold arrangements. The power connector and LED lamps are located on the side of the case. The status of the proposed device is indicated by the LED lamps.

The figure shows the contact area of the proposed device. The contact area was fabricated by machining a copper sheet with a thickness of $1\ mm$. Copper was selected because of its high thermal conductivity, which allows efficient heat transfer during the experiment. The high-temperature and low-temperature presenting sections are arranged in an alternating sequence. The dimensions of the presenting part are approximately $2\ mm$ in width and $20\ mm$ in length. The separation between the high and low temperature presentation sections was calibrated to be $2\ mm$, taking into account the spatial density of warm and cold spots on human skin.

B. Thermal control architecture

The temperature of the Peltier element is regulated through the utilization of an Arduino. The temperature of the TGI stimulus presentation unit is measured by fixing a thermistor to a copper plate. For an NTC thermistor with resistance R_0 [Ω] at a reference temperature T_0 [K], the resistance R [Ω]

at temperature T [K] can be expressed as:

$$R = R_0 \exp\left[B\left(\frac{1}{T} - \frac{1}{T_0}\right)\right] \quad (1)$$

where B is the so-called B-constant, which is specific to each thermistor. As a more precise alternative to Eq. (1), the Steinhart–Hart equation is often used to describe the resistance–temperature relationship:

$$\frac{1}{T} = a + b\ln(R) + c(\ln(R))^3 \quad (2)$$

where T is the absolute temperature, R is the thermistor resistance, and a, b, c are material-specific constants. In this study, the Steinhart–Hart equation was adopted since measurement accuracy was of particular importance.

The thermistors were positioned within the low and high temperature presentation sections, and the model parameters were determined through preliminary experiments. The output of the thermistors is received by the AD input of the Arduino, and the temperature of the Peltier element is controlled by a PID controller. An indicator lamp is illuminated when the temperature deviates within ± 1 deg of the target value. The target temperatures for the low and high temperature presentation sections are set using a smartphone application. In this study, we used *nRF Connect for Mobile*, a smartphone application developed by Nordic Semiconductor, to communicate with the Arduino Nano via BLE. This application allows users to scan for and connect to BLE devices, as well as transmit data such as target temperatures to the Arduino.

On the smartphone screen, this device can be detected under the name“ThermalGrillIllusion”. Once the connection to the device is established, the screen transitions to the one shown in Fig. 3. Temperature settings can be configured in the areas labeled *hot* and *cool*, where the respective target temperatures are set. In the section labeled *ON/OFF*, entering 1 starts temperature control, while entering 0 stops it.

The developed electrical circuit is shown in Fig. 4

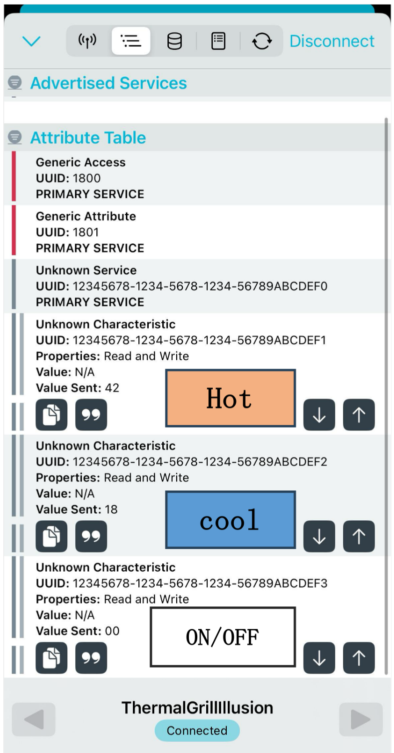

Fig. 3. Device operation screen

Fig. 4. Circuit

III. Fundamental Experiments on Temperature Control

Accurate temperature control is critical to the operation of the thermal illusion device, as the effectiveness of the illusion depends heavily on precise and stable thermal feedback. This feedback is provided by thermistors, which continuously monitor the temperature of the contact surfaces. Even small deviations in temperature readings can lead to significant discrepancies between the intended and actual thermal stimuli, potentially weakening or altering the perceived illusion.

However, thermistor outputs are inherently nonlinear with respect to temperature, and factors such as manufacturing tolerances, self-heating effects, and environmental conditions can introduce measurement errors. To enhance the accuracy of temperature sensing, we characterized the thermistors' behavior through experimental calibration. Using the collected resistance–temperature data, we applied the Steinhart–Hart equation, a well-established model for thermistor response, to obtain precise calibration parameters.

The device uses two thermistors: one for measuring higher temperatures and another for lower ranges. Each thermistor was placed in water in a vacuum-insulated tumbler along with a digital thermometer. The beaker was sealed to prevent heat loss. Measurements were taken at 5 deg intervals from 5 deg to 80 deg, with the resistance recorded three times at each point. Water was chosen for its high thermal capacity and ability to maintain stable temperatures.

Using the measured data, we estimated the Steinhart-Hart parameters using the least squares method. These parameters were then used to evaluate the temperature control performance of the device. The system was tested with two temperature ranges: a smaller difference ($20 - 35$ deg) and a larger difference ($18 - 42$ deg), corresponding to the conditions of user experiments. A PID controller was implemented to

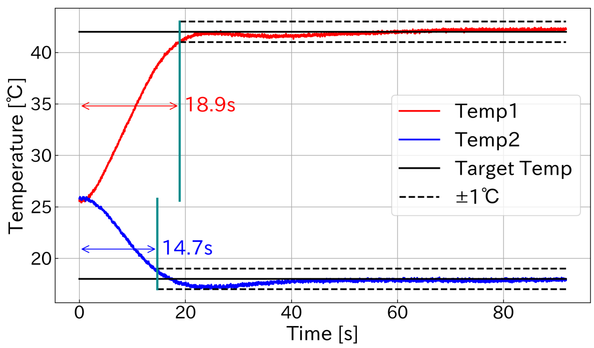

Fig. 5. Temperature response with PID control

maintain the temperature within ± 1 deg of the target by using appropriate proportional, integral, and derivative gains. As shown in Fig. 5, for the $18-42$ deg condition, both Temp1 (heating) and Temp2 (cooling) reached the steady-state error band within approximately 20 s. After reaching the band, both temperatures remained stable within the ± 1 deg tolerance, demonstrating the controller's ability to achieve short settling times and maintain high steady-state accuracy.

IV. Experiment: Validation of Localized Thermal Grill Illusion Induction

A. Experimental Overview

To verify whether the developed pain illusion presentation device could effectively induce the TGI, we conducted experiments with 17 healthy male participants aged 21–25 years in our laboratory. This study was approved by the Institutional Ethics Committee of Kindai University. It specifically investigates the illusion caused by differences between warm and cold stimuli. Since instability in body temperature may affect participants' perception of the illusion, all participants were acclimated to a 24 deg (± 0.5 deg) environment for 15 minutes prior to testing to ensure a consistent baseline body temperature.

The TGI stimuli were applied to two distinct body parts: the thenar eminence of the palm and the upper arm. The thenar eminence was specifically selected because it has a high density of thermoreceptors, resulting in heightened thermal sensitivity. In contrast, the upper arm, known for its relatively lower thermal sensitivity due to fewer thermoreceptors and thicker skin, was also tested to investigate whether the illusion could be induced in less sensitive regions of the body . Two temperature ranges were tested: a smaller difference ($20-35$ deg) and a larger difference ($18-42$ deg).

During the test, participants closed their eyes to avoid bias and exposed both arms. Stimuli were applied randomly to either side of the thenar eminence or upper arm using the device(Fig. 6). Each stimulus lasted up to 5 seconds, with a maximum of three trials per condition to prevent adaptation. After each stimulus, participants rated the perceived intensity of "warmth," "burning sensation," and "discomfort" on a 0 to 10 scale, where 0 meant "no sensation" and 10 indicated "maximum imaginable pain." The "burning sensation" was described as a stinging or tingling pain, while "discomfort" was defined as throbbing or lingering pain.

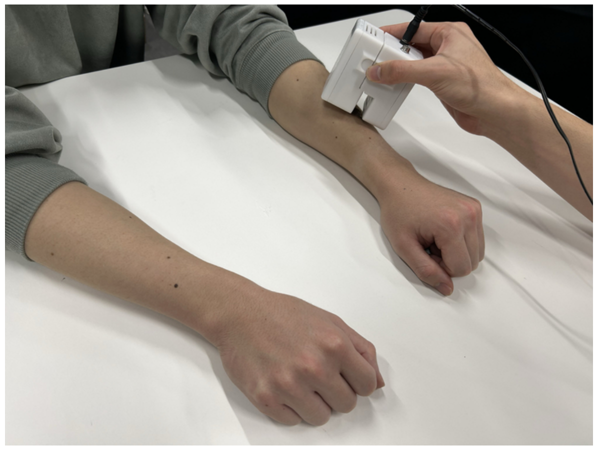

Fig. 6. Experimental setup

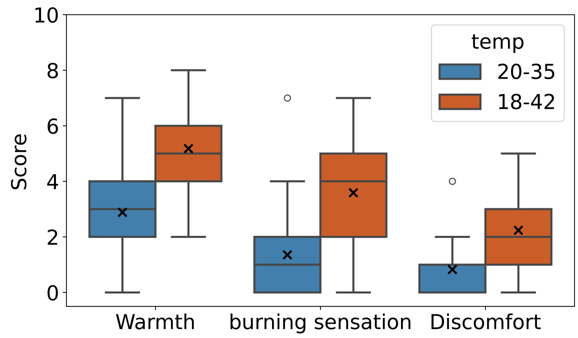

Fig. 7. Results palm

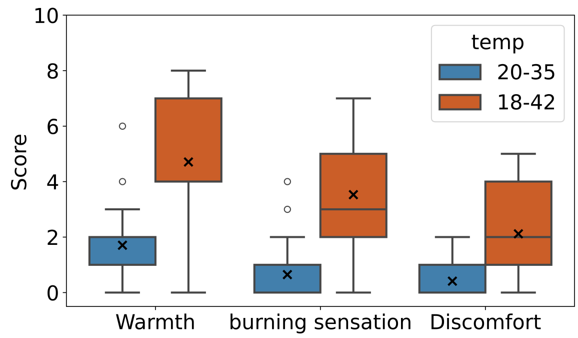

Fig. 8. Results upper arm

B. Experimental Results

Fig. 7 and 8 show box plots summarizing the results for the thenar eminence and upper arm, respectively. The vertical axis represents the subjective score (0–10), and the horizontal axis includes the three metrics: "warmth," "burning sensation," and "discomfort." Dots represent outliers and cross marks indicate the mean score. Fig. 7 shows box plots of subjective ratings for the thenar eminence (palm) under two thermal conditions: a smaller temperature difference ($20-35$ deg) and a larger temperature difference ($18-42$ deg). Each plot represents three perceptual dimensions:

TABLE II

PAIRED T-TEST RESULTS BETWEEN TEMPERATURE CONDITIONS.

Region	Section	t-value	p-value
Palm	Warmth	5.73	< 0.001
	Burning Sensation	4.44	< 0.001
	Discomfort	3.51	< 0.002
Arm	Warmth	5.05	< 0.001
	Burning Sensation	5.53	< 0.001
	Discomfort	5.01	< 0.001

TABLE III

WILCOXON SIGNED-RANK TEST RESULTS BETWEEN STIMULATION SITES.

Temperature Range	Section	z-value	p-value
20–35 deg	Warmth	83	< 0.05
	Burning Sensation	33	< 0.05
	Discomfort	24	$n.s.$
18–42 deg	Warmth	65.5	$n.s.$
	Burning Sensation	63	$n.s.$
	Discomfort	48	$n.s.$

Warmth, Burning Sensation, and Discomfort. The vertical axis indicates the subjective rating scale (0–10), where 0 represents "no sensation" and 10 denotes "maximum imaginable pain." Colored boxes represent interquartile ranges (IQR), horizontal lines within the boxes show the medians, and whiskers extend to 1.5 × IQR. Outliers are displayed as dots, and mean values are marked with cross symbols. For both "Warmth" and "Burning Sensation," the larger temperature difference ($18 - 42\ deg$) elicited significantly higher scores than the smaller one, confirming the hypothesis that greater thermal disparity intensifies the illusion. A smaller but still significant difference was observed for "Discomfort."

Fig. 8 presents the corresponding box plots for the upper arm under the same two thermal conditions ($20 - 35\ deg$ and $18 - 42\ deg$). Similar to Fig. 7, the vertical axis represents subjective intensity ratings (0–10), and the three perceptual categories—Warmth, Burning Sensation, and Discomfort—are plotted along the horizontal axis. The plots indicate that all three perceptual dimensions were rated higher under the $18 - 42\ deg$ condition compared to the $20 - 35\ deg$ condition. However, the differences between the two conditions were slightly smaller than those observed for the palm. Notably, the "Discomfort" scores showed no statistically significant differences between the palm and upper arm, regardless of temperature condition, suggesting regional variation in thermal sensitivity may not strongly influence this specific perception.

To statistically evaluate the effect of temperature differences, we performed one-tailed paired t-tests. The null hypothesis stated that "there is no difference in score due to temperature range," while the alternative hypothesis claimed "a greater temperature difference leads to higher scores." Before conducting the t-tests, the Shapiro-Wilk test was used to confirm normality of the score differences. All p-values were greater than 0.05, indicating that the data followed a normal distribution. Thus, the assumptions for the t-tests were satisfied.

Table II summarizes the results of the t-tests. For all metrics, significant increases in perceived intensity were observed under the larger temperature difference condition ($p < 0.001$), supporting the hypothesis that greater temperature disparity intensifies the TGI.

To examine the effect of stimulation site, we compared scores between palm and arm under each temperature condition using the one-tailed Wilcoxon signed-rank test (due to non-normal distribution in some comparisons). Table III presents the results. A significant difference was observed only in the $20 - 35\ deg$ condition for "warmth" and "burning sensation," where the palm produced higher scores.

V. DISCUSSION

The results of this study clearly demonstrate that a larger temperature difference ranging from approximately $18 - 42\ deg$ induces a significantly stronger and more vivid thermal grill illusion (TGI) compared to a smaller temperature difference in the range of $20 - 35\ deg$. This finding aligns well with previous research literature, which consistently shows that the intensity and clarity of the TGI are positively correlated with the magnitude of the thermal disparity presented. The larger the contrast between warm and cold stimuli, the more robust the illusory sensations experienced by participants. These results confirm that the developed device is capable of reliably inducing TGI even with localized thermal stimuli.

Furthermore, when comparing the effects of stimulation applied at different body sites, it was observed that the palm exhibited significantly higher illusion scores than the upper arm under the small temperature difference condition. This suggests that body regions with a higher density of thermal receptors and mechanoreceptors, such as the thenar eminence of the palm, are more sensitive to subtle thermal differences and thus more susceptible to experiencing the thermal illusion. However, under the high temperature difference condition, this site-specific difference disappeared. Both the palm and the upper arm showed similarly strong illusion scores. This lack of difference in the high temperature condition could be explained by the fact that the intense thermal stimuli provided at both sites were sufficiently strong to overwhelm the sensory system, thereby masking more subtle perceptual differences that are apparent only under less extreme conditions.

Notably, no significant differences were found between the palm and the arm for the sensation described as "discomfort," regardless of the temperature condition applied during the experiment. This lack of difference could be explained by the distinct physiological properties and conduction velocities of the nerve fibers involved in transmitting these sensations. The "burning sensation" is typically conveyed by fast-conducting $A\delta$ fibers, which allow rapid and well-localized pain perception. In contrast, "discomfort" is thought to be mediated primarily by slower-conducting C fibers. Because of these differences, when a strong "burning" stimulus activates the fast $A\delta$ fibers, the more slowly developing signals from C fibers that produce discomfort may be masked or overshadowed. This temporal difference in signal transmission can lead to the reduction of variability in discomfort perception across different stimulation sites such as the palm and the arm.

Overall, the experiment supports the conclusion that localized thermal stimulation using the developed device is sufficient to induce TGI, with perceptual strength modulated by temperature difference and stimulation site.

VI. Conclusion

The spatial conditions under which the Thermal Grill Illusion (TGI) can be elicited, particularly whether it can occur in small areas, how warm and cold stimuli should be delivered in such cases, and how heat transfer occurs at the skin surface during stimulation, have not yet been elucidated. Therefore, we present a study on the development and validation of a compact, smartphone-controlled device capable of locally inducing the TGI using precisely regulated Peltier-based warm and cold stimulation. Experiments with 17 participants confirmed that the device can reliably elicit TGI, with perceptual strength strongly influenced by the temperature difference between stimuli. Notably, larger temperature disparities ($18 - 42\ deg$) consistently produced more intense sensations of warmth and burning than smaller disparities ($20 - 35\ deg$), aligning with previous findings on TGI mechanisms.

These results demonstrate the potential of the proposed system as a reproducible tool for assessing nociplastic pain and central sensitization in both research and clinical contexts. The device's portability and controllability make it suitable for standardized evaluations beyond laboratory settings.

Future work will investigate how variations in the geometry of the contact area influence perceptual differences, examining different shapes, sizes, and thermal arrangements to better understand their effects on the thermal grill illusion. Additionally, thermography will be employed to measure both skin and contact surface temperatures during stimulation, providing detailed spatial and temporal temperature profiles. This approach will help clarify how heat is transferred between the device and the skin, and how these thermal dynamics contribute to the triggering of the illusion under different physical configurations.

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