Too Hot, too Fast! Using the Thermal Grill Illusion to Explore Dynamic Thermal Perception

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Abstract— **Thermal perception is important in the experience of touching real objects, and thermal display devices are of growing interest for applications in virtual reality, medicine, and wearable technologies. In this paper, we designed a new thermal display, and investigated the perception of spatially varying thermal stimuli, including the thermal grill illusion. The latter is a perceptual effect in which a burning sensation is elicited in response to touching a surface composed of spatially juxtaposed warm and cool areas. Using a computer controlled thermal display, we present experiments in which we measured temporal correlates of the perception of spatially inhomogeneous stimuli, or thermal grills. We assessed the intensity of responses elicited by thermal grill stimuli with different temperature settings, and measured the response time until the onset of burning sensations. We found that thermal grills elicited highly stereotyped responses. The experimental results also indicated that as the temperature difference increases, the intensity increases monotonically, while the response time decreases monotonically. Consequently, perceived intensity was inversely correlated with response time. Under current physiological explanations, responses to thermal stimuli depend on tissue heating, neural processing, and the spatial distribution (or juxtaposition) of surface temperatures. The results of this study could help to inform models accounting for these factors, enabling new applications of the thermal grill illusion.**

I. Introduction

Thermal cues play important roles in the haptic perception of objects [1], especially in material discrimination [2]. Thermal feedback is also of increasing interest in several application domains, including virtual reality, where thermal feedback is needed in order to enable realistic experiences of touch contact between the skin and simulated objects. Several applications of skin-interfaced thermal displays have also been proposed in medicine and wearable computing [3] [4]. However, the systematic engineering and application of thermal displays is relatively recent, and both technologies [5] and knowledge of human factors [6] are improving.

Thermal touch involves the perception of the temperature or material properties through the exchange of heat between the skin and touched objects. The exchange is often dynamic, as thermal contacts and temperatures evolve in time, and spatially dependent, when different locations of skin are in different states of contact with materials or temperatures that may also vary spatially. The normal temperature of human skin in homeostasis is between 31°C and 35°C. Temperatures are perceived as warm ($31 - 35$°C), painfully hot (> 45°C), cool ($31 - 35$°C), or painfully cold (< 15°C), based on interactions between distinct populations of thermoreceptive afferents innervating the skin [7], as well as nociceptive afferents associated with painful temperatures [8], [9]. As in other perceptual modalities, thermal perception involves the spatiotemporal integration of sensory signals, including input from both cold and warm thermoreceptors. Spatial summation is especially pronounced, and a larger area of stimulation leads to greater intensity of sensation. The time to respond to a thermal stimulus decreases with intensity, but for moderate temperatures response times are relatively slow, evidencing significant temporal integration. While not fully understood, the perceptual integration of thermal signals in space or time, and their interaction with other tactile modalities (such as nociception) has been found to give rise to several distinct perceptual effects.

In this work, using a newly developed thermal display, we investigated one such effect, the thermal grill illusion, and assessed its ability to rapidly elicit intense sensations. The thermal grill illusion (TGI) was discovered by Torsten Thunberg (1896), who reported that innocuous warm and cool stimuli applied simultaneously to the skin by means of interlocking spiral tubes elicited burning sensations like those that accompany cold pain [10]. The illusion can be experienced by using shapes other than spiral tubes – alternating bars, checkerboard patterns, or grids. The thermal grill illusion does not change greatly with the number of stimuli or their spacing [11].

The thermal grill does not expose the skin to temperatures that are noxious or, in isolation, uncomfortable. Touching only the cold or hot bars individually thus elicits little discomfort, whereas an unambiguous and often rapid burning sensation is elicited when touching warm and cool bars with skin areas that are nearby, or that are represented proximally in the somatosensory system [12] [13].

Current physiological explanations ascribe the thermal grill illusion to interactions between different thermally sensitive afferent pathways in early somatosensory processing. When touching the cold terminal of a thermal grill, normal discharge from coolness sensitive Aδ afferent fibers is suppressed due to the spatial summation of inputs that signal warmth in nearby skin regions [14]. In the absence of these nearby warm inputs, the Aδ inputs inhibit the activity

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of polymodal C-nociceptive afferent fibers, which otherwise cause burning sensations at only noxious cold temperatures ($< 15°$ C). When Aδ input is suppressed by input from nearby warm regions, a burning sensation occurs at merely cool ($< 24°$ C) temperatures. Brain imaging studies reveal that the thermal grill and the noxious hot and cold stimuli produce similar patterns of activation in the anterior cingulate cortex, whereas the warm and cool components of the thermal grill do not [15].

The intensity of the burning sensation evoked by the TGI increases with the magnitude of the temperature difference between warm and cool bars [16], indicating that it is not a digital phenomenon. TGI stimuli are felt by warm and cold thermoreceptive afferents within skin tissues, and the time course of response is determined by the dynamics of tissue heating and neural processing, including propagation times to the central nervous system. Response times for hot or cold stimuli in isolation decrease at extremes of temperature [6]. In comparison, thermal grill stimuli elicit rapid and intense responses even at moderate (warm and cool) temperatures. The physics governing tissue heating due to uniform or spatially varying (thermal grill) stimuli is based on the time-dependent bioheat equation,

$$\rho c \frac{\partial T}{\partial t} = k \nabla^2 T + \omega \rho_b c_b (T_a - T) + q_{met} + q_{ext} \quad (1)$$

Here, $T = T(x, y, z, t)$ is the temperature of skin tissues at point $p = (x, y, z)$ and time t, k is the effective thermal conductivity of skin, ρ and ρ_b are the density of skin tissue and blood, ω is the blood perfusion rate, T_a is the blood temperature, and q_{met} and q_{ext} capture tissue heating due to metabolic and external sources. Within this model, the tissue temperature in response to thermal touch is given by the solution with boundary condition $T^*(x, y, 0, t)$ consisting of the temperature of the thermal grill at the skin surface $z = 0$, in the case of thermal grill stimuli, or the constant temperature $T^*(x, y, 0, t) = T_0$ of the touched surface, for homogeneous thermal stimuli [1].

As mentioned above, thermal grill stimuli are believed to engage thinly myelinated Aδ fibers, with conduction velocities of 2 to 30 m/s, and unmyelinated C fibers, whose conduction velocities are slower (2 m/s or less), and the engagement of each differs from those involved in purely hot or cold stimuli [17], [18]. This may partly explain why temporal properties of thermal grill induced percepts differ from those induced by either cool or warm stimuli in isolation [19]. Studies that have recorded participant responses during the course of application, through intensity ratings or temperature matching tasks, indicate that thermal grill percepts are time-dependent [20].

Further insight into temporal factors affecting TGI percepts could elucidate contributions of tissue heating and neural processing to thermal perception. This information would also be valuable for the design of devices that use the TGI alone or in combination with other modalities. However, there has been no prior quantitative assessment of response times to the onset of burning sensations in response to static thermal grill stimuli, as we provide here, or their relation to perceived intensity.

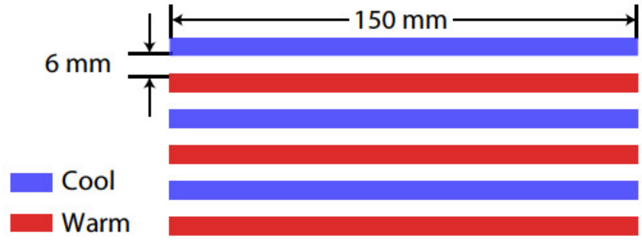

Fig. 1: Thermal grill display concept. Dimensions correspond to those used in our device. The warm bars feel warm, the cool bars feel cool, but for a suitable difference in temperature between the two, the spatial pattern of alternating warm and cool bars (thermal grill) elicits a cold burning sensation.

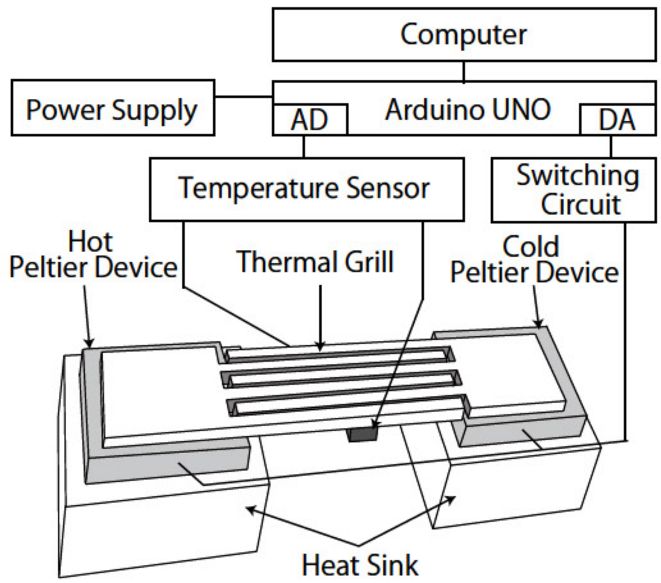

Fig. 2: Thermal grill display device. Peltier thermoelectric pumps are electronically controlled independently for each of two sets of grill elements. A microcontroller sends control signals to the Peltier elements and reads signals from the temperature sensors. Heat sinks allow the thermoelectric device to operate relative to room temperature. Temperature sensors are affixed to the bottom of the touched portion of the grill. The temperature of the top surface of the device was calibrated in order to ensure that the specified temperature is felt by the skin on contact with the device.

To investigate thermal display via the TGI, and time-dependent properties of the perception of the latter, we developed a new thermal grill display device capable of presenting a range of thermal grill temperatures under computer control. In a psychophysical experiment, we measured response time and perceived intensity as participants felt thermal grills, and analyzed the results to quantify aspects of the perception of these stimuli.

II. Thermal Grill Display Design

We designed a new thermal display device for presenting thermal grill stimuli in order to assess factors reflecting how they are perceived, and to explore the use of these stimuli in new human-computer interfaces. The device is comprised of a thermal grill surface, with electrothermal apparatus, controller, sensors, and computer. The thermal grill surface is made of aluminum bars, each having dimensions $6 \times 6 \times 15$ mm. A total of 6 such bars are used. They are separated by 6 mm and arranged in an alternating pattern. In typical operation, half of the bars are heated from one side and the remaining half are cooled from the other side.

The heating and cooling is done using Peltier devices (TEC1-12706 Thermoelectric Peltier Cooler 12 Volt, 92 Watt), semiconductor thermoelectric heat pumps that move heat heat from one side to another when an electric potential is applied across their terminals, causing one side to heat and the other to cool. An opposing side is maintained close to room temperature via a heat sink to ensure efficient operation. We employed two heat sinks to ensure that the Peltier elements could be positioned away from the touched grill area, which ensured that the warm and cool elements remained well decoupled. The temperature of the grill elements is monitored using surface temperature sensors that are attached to the bottom side of one hot and one cold element in the array, nearest to the touched interface, ensuring that the measured temperature reflects what is felt at the surface.

In order to validate the performance of the device, we measured the temperature on the top surface of the device using a thermal imaging camera and calibrated the temperature sensors to this value, ensuring that the specified temperature that is felt by the skin on contact with the device was within approximately $\pm 1^{\circ}$ C of the specified temperature. The temperature control loop and sensor monitoring (sample frequency 100 Hz) is performed via a microcontroller (Arduino Uno, Arduino SRL, Italy), and commanded by desktop computer via serial communication. When a new temperature is commanded, it takes approximately one minute for a stable target temperature to be reached (we allowed for three minutes in the experiment below).

III. Psychophysical Experiment

We designed a psychophysical experiment to apply this display, and to investigate the dynamics of thermal perception in the thermal grill illusion – and in particular the relation between the intensity of the sensations that it produced and the time that it took for these sensations to be elicited. In it, we assessed both intensity and reaction time, and analyzed the results to determine how they were related to the temperatures of the warm and cool bars.

A. Apparatus

The apparatus consisted of the thermal grill display device described in the previous section. We measured the response times during using an electronic sensor (switch), which recorded when the surface was touched and released by the hand of the participant. The ambient temperature during the experiment was climate controlled within a range from 20 and 22°C. The experiment was run under computer control using Python-based psychophysics software (Psychopy, University of Nottingham, UK), which selected the stimuli, commanded the thermal grill display, displayed the graphical user interface, and recorded participant responses.

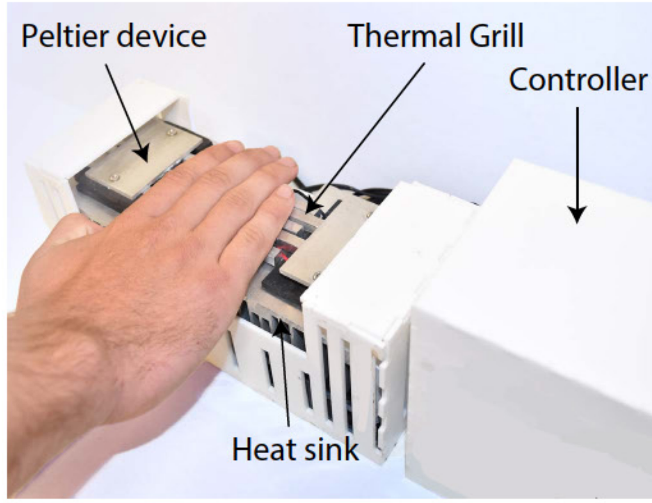

Fig. 3: The thermoelectric haptic device used for the experiment. The participant kept their hand on the thermal grill and their responses were recorded.

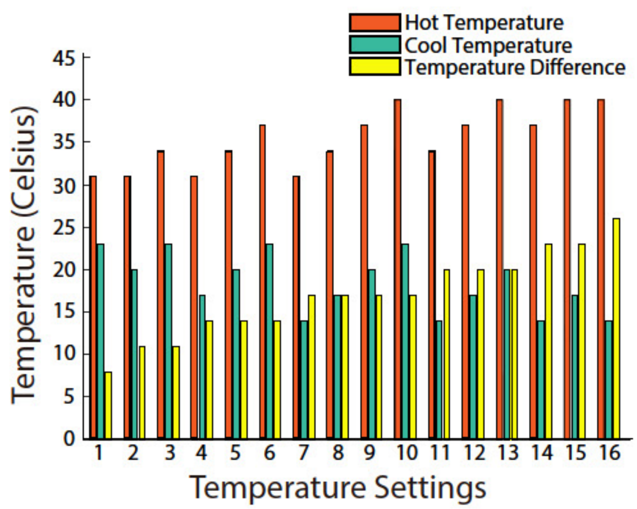

Fig. 4: Temperature Settings for the thermal grill used in the study. Hot temperatures were varied between 31 to 40°C and cold temperatures were varied between 14 to 23°C. Four combinations each for hot and cold temperatures give 16 thermal grill settings.

B. Methods and Stimuli

During the experiment, subjects felt the thermal grill at various temperature settings, consisting of the temperature of warm and cool elements, see Figure 4). Their response time and perceived intensity was recorded. The temperature settings of the thermal grill were changed between trials. There were a total of 16 temperature combinations (Figure 4).

These temperature combinations were chosen to be well within the limits of thermal pain, so as that the individual elements were not perceived to be painful. The participants felt the thermal grill at the minimum and maximum settings prior to the experiment, in order to remove individual bias towards rating the perceived intensity.

C. Participants

A total of 10 participants volunteered for the experiment, five were female and five male, with ages ranging from 22 to 29 years old. Participants were compensated with $10 for their time. Participants reported no condition affecting normal use or sensation in the hands. All reported being right-hand dominant. All subjects gave informed consent. The experiments were approved and conducted according to the human subjects research policies of the University of California, Santa Barbara. Prior to the experiment, participants completed a short survey collecting anonymous demographic and screening information.

D. Procedure

Prior to the experiment, participants were asked to touch the thermal grill at the maximum and minimum temperature differential, and then rate the intensity of each trial accordingly. The total duration for each participant was 1 hour including a three minute break time between each temperature setting. This break time also enabled the thermal grill to reach a stable temperature.

The experiment was conducted in a quiet environment to limit distractions. Participants were seated at a desk equipped with a computer interface and the thermal grill. Participants completed a brief guided training phase before they proceeded to the main part of the experiment, during which they felt the thermal grill at the minimum (smallest temperature difference) and maximum (largest temperature difference) settings, and were informed that these corresponded to the least and most intense stimuli. During each trial, participants placed their palm flat on the grill. Participants were instructed to remove their hand from the display as soon as they felt a burning sensation similar to the one that they felt for the largest temperature difference stimulus, which they felt during the acclimation phase (see Methods and Stimuli). The response time was given by the time between initial contact and the removal of the hand, as recorded by the switch. If they did not respond within 10 seconds, participants were prompted to remove their hand from the display. Participants then rated the intensity using a continuous slider, ranging from 0 (least intense) to 1 (most intense). Subsequent trials proceeded similarly. We proceeded with three trials at each temperature setting, in succession, since no delay was required between them, and this permitted significantly more data to be collected, and averaged responses from the three. Different temperature settings were presented in random order. There were a total of 16 such settings in the experiment. The procedure was computer automated, and provided automated prompts as to when the thermal grill should be felt in each experimental condition.

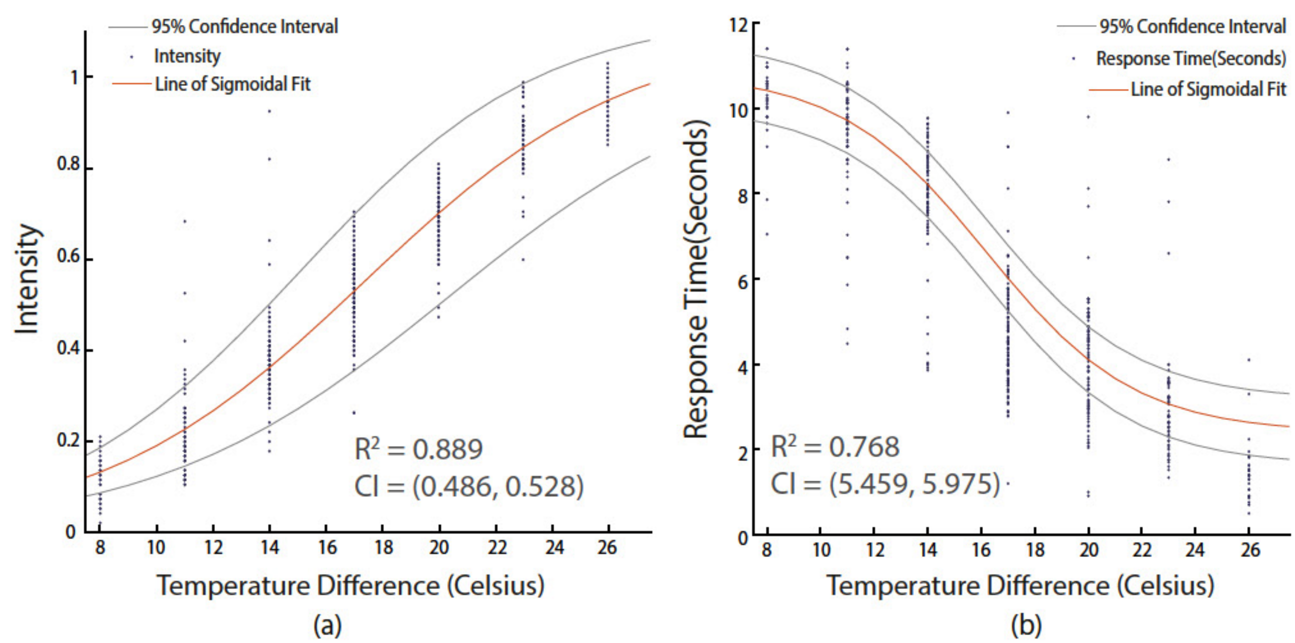

Fig. 5: Perceived intensity and response time to thermal grill stimuli, data from all subjects and all trials in the experiment. The horizontal axis represents the temperature differential of the thermal grill. The vertical axis represents perceived intensity, from 0-1, on a scale rated according to extremal settings felt before the experiment. The perceived intensity shows a sigmoidal relationship with the temperature differential. (b) As in (a), except that the vertical axis represents the response time in seconds.

IV. Results

Intensity increased, on average, monotonically with the temperature difference between warm and cool elements (Fig. 5a). The relationship between intensity and temperature difference was sigmoidal in shape. Fitting intensity I as a function of temperature difference ΔT with a sigmoidal function $I(\Delta T) = a(b + e^{-c\Delta T})^{-1} + d$ indicated a positive effect of temperature difference on intensity ($p < 0.01$). The R^2 value for the fit was 0.89. Differentiating this fitting function revealed that the maximum rate of increase in perceived intensity occurred at temperature difference ΔT =17° C.

On average, response time τ decreased monotonically with temperature difference (Fig. 5b). We modeled the relationship via a sigmoidal function $\tau(\Delta T) = a(b+ce^{-d\Delta T})^{-1}+f$ and determined that the relationship was significant ($p < 0.01$) and that the R^2 value was 0.768. From the data, at the highest temperature difference, the response time was fastest. At the lowest temperature differences, the results reflect a mix of trials in which participants withdrew their hand based on what they felt and others in which they were prompted to do so after 10 seconds had elapsed. Nonetheless, a decrease in response time is seen with increasing temperature at these levels. Here too, the rate of decrease was fastest near 17° C. For each increase in ΔT by one degree, the response time decreased by 0.506 seconds, on average.

Across all temperature differences used in the experiment, there was, on average, a decrease in response time with intensity (Fig. 6). The relationship was approximately linear, and a linear fit yielded an R^2 value of 0.673. The lowest uncertainty was for the highest temperature differences (ΔT = 26° C), for which all data points clustered around a mean response time of approximately 1.5 seconds and an intensity of 0.9.

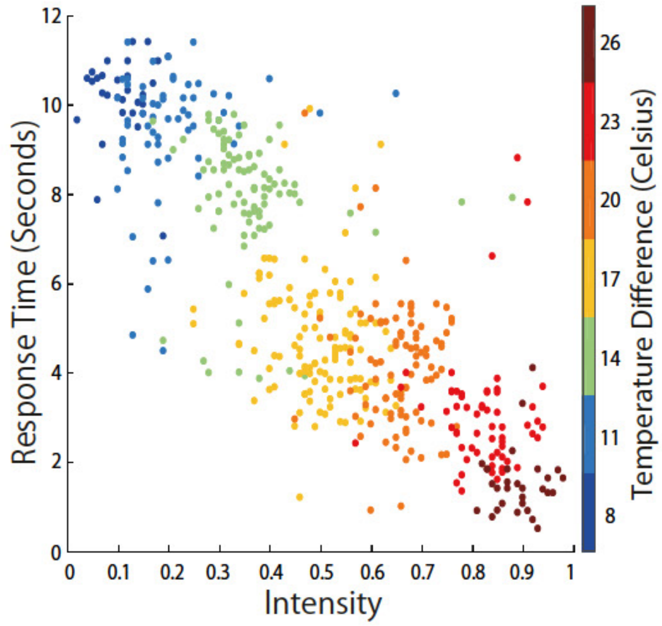

Fig. 6: Response Time vs Perceived Intensity for the entire experimental data. Response time time varies inversely with the perceived intensity, with an approximately linear relationship. Positions along this relationship were approximately organized according to temperature differential.

V. Discussion

The results (Figure 5a,b) indicate that as the temperature difference ΔT between the warm and cool bars increased, the perceived intensity increased, on average, while the response time decreased. This suggests that the thermal grill illusion is not a digital phenomenon, and that there is a proportional effect of temperature difference on both intensity and response time, for temperatures in the range studied here. This is also consistent with prior observations [16], that the strength of the thermal grill illusion depends on the cold-warm differential rather than the individual cool and warm temperatures. The sigmoidal functions that we fit to the data may, in principle, be used in order to predict the intensity and response time to thermal grill stimuli as the temperature difference is varied, but the results likely also depend on factors including the surface area of contact [21]. Nonetheless, we expect qualitatively similar results to hold for thermal grill displays of different dimensions or configuration.

At the highest temperature differences (23 to 26° C), response times were short, generally between 300 ms and 2.5 s. Participants feeling these stimuli responded very quickly after they placed their hand on the display. The response times are remarkably short. For comparison, the conduction velocity for C fiber afferents averages less than about 2 m/s, which is too slow to account for the observed response times. Conduction speeds for $A\delta$ afferents are faster, up to 30 m/s. The results may be consistent with the possibility that disinhibiting activity in first order $A\delta$ fibers reaches the central nervous system where it disinhibits temporally retrograde C fiber activity, but further research is needed. The variability in intensity and response time were smallest (excluding limiting effects on response time measurements, see above). The ratings and response times varied little among the entire participant population, underlining the robustness of this effect.

VI. Conclusion

Thermal perception is important in the experience of touching real objects, and thermal display devices are of growing interest for applications in virtual reality, medicine, and wearable technologies. In this study, we designed a new thermal display, and used it to investigate the perception the thermal grill illusion. We assessed the intensity of responses elicited by thermal grills with different temperature settings, and measured the response time until the onset of thermal grill sensations. We found that thermal grills elicited highly stereotyped responses. As the temperature difference increases, the intensity increases monotonically, while the response time decreases monotonically. Consequently, perceived intensity was inversely correlated with response time. Under current physiological explanations, responses to thermal stimuli depend on tissue heating, neural processing, and the spatial distribution (or juxtaposition) of surface temperatures. The results of this study could help to inform models accounting for these factors. Furthermore, this study has quantified the relation between display parameters and perceptual parameters. This could provided basic information needed to apply the thermal grill illusion in new application areas of human-computer interaction, VR, and medicine.

There are several areas of potential improvement of this study. The measurement method and analysis assumed that subjects would remove their hand due to discomfort at some finite time, whereas this was not necessarily true at the lowest temperatures. Ideally, we would like to present all 48 stimuli in random order, but the slow heating time of the contact surface limits this in the interst of time. A more detailed model of the TGI should account for the minimum temperature needed to elicit a TGI sensation at any temperature. More significantly, further research and theoretical analysis is needed about the relevance of different afferent pathways, and tissue heating, to the perception of the TGI. This could lead to a computational model of thermoreception accounting for the thermal grill illusion, something that we hope to address in future work.

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