ThermOuch: A Wearable Thermo-Haptic Device for Inducing Pain Sensation in Virtual Reality through Thermal Grill Illusion

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Abstract

Existing research showed that unpleasant haptic feedback, such as pain, could enhance the user experience and performance in various scenarios (e.g. entertainment and training). This paper introduces ThermOuch, a wearable thermo-haptic device that leverages the thermal grill illusion (TGI) to simulate pain sensations in virtual reality (VR) without causing actual invasive/non-invasive harm. Our results of the user-perception experiments revealed that higher temperature-changing rates, particularly with increased warming, were associated with more intense pain perceived by the participants through our system. Furthermore, a higher ratio of warm-to-cool temperature transitions reduced the sensation of coldness prior to pain. Our experiments also showed that introducing an additional stimulus unit potentially heightened pain perception, and altering the spacing between stimulus units modified the perceived pain area. Lastly, 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.

CCS Concepts

• **Human-centered computing → Virtual reality**; **Haptic devices**.

Keywords

Virtual reality, Haptic devices, Thermal, Pain sensation, Thermal Grill Illusion

ACM Reference Format:
Haichen Gao, Shaoyu Cai, Yuhong Wu, and Kening Zhu. 2024. ThermOuch: A Wearable Thermo-Haptic Device for Inducing Pain Sensation in Virtual Reality through Thermal Grill Illusion. In *SIGGRAPH Asia 2024 Conference Papers (SA Conference Papers '24), December 03–06, 2024, Tokyo, Japan.* ACM, New York, NY, USA, 12 pages. https://doi.org/10.1145/3680528.3687620

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SA Conference Papers '24, December 03–06, 2024, Tokyo, Japan

ACM ISBN 979-8-4007-1131-2/24/12
https://doi.org/10.1145/3680528.3687620

1 Introduction

Many researchers have developed various haptic devices for enabling high-fidelity haptic experience [Cai et al. 2024, 2020; Choi et al. 2017; Huang et al. 2023; Tanaka et al. 2023; Zhu et al. 2019a], for different types of touch sensation in VR. Among different tactile modalities of human beings, the pain sensation is considered to be an unpleasant sensory experience possibly associated with potential or actual damage [Raja et al. 2020]. As the pain sensation induces danger or harm awareness to humans, bringing such unpleasant experiences in VR could improve safety awareness in training [Cervero 2012] and increase the experience of entertainment, enlightenment, and sociality [Benford et al. 2012; Laso 2007].To avoid applying extreme conditions directly to user's body, researchers have proposed different approaches for pain induction in VR, such as electrical muscle stimulation (EMS) [Kono et al. 2018; Lopes et al. 2015] and pseudo-haptics [Weir et al. 2012]. However, these techniques may suffer from limited application scenarios (e.g. attacking impact for EMS) and mismatching visual-haptic experience (for pseudo-haptics). Recently, Jiang et al. [2021] applied capsaicin chemical stimulant on users' skin to trigger different levels of pain sensations, but extra chemical stimulants need to be applied to remove the pain effects and may potentially harm the skin invasively. To this end, there is a need for a new haptic mechanism to induce continuous pain sensation without harming human skin, and easy for removing the pain effect in VR.

The thermal grill illusion (TGI) is an illusory phenomenon that generates a paradoxical sensation of pain through simultaneously deploying interlaced warm and cool stimuli within an innocuous temperature range [Bach et al. 2011; Craig and Bushnell 1994; Kern et al. 2008]. Compared to using chemical stimulants to generate pain sensations, TGI enables pain sensation with fast execution and removal on the skin surface without the need of micro-needling or penetrating the skin which may cause direct skin harm. To this end, TGI could be potentially applied in virtual environments to "render" pain sensation safely. However, it may not be trivial to directly apply the TGI mechanism into VR. This could be due to the uncertainty of how different system parameters (e.g., temperature-changing rates,

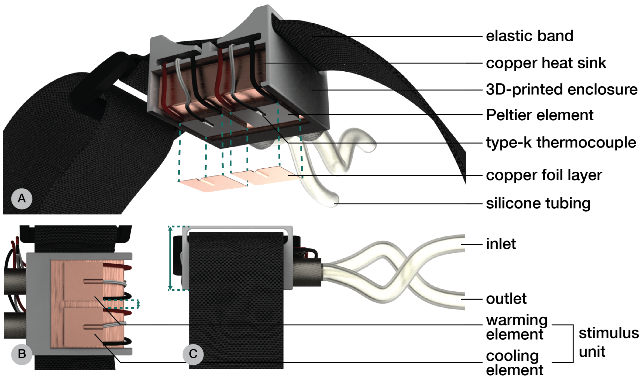


Figure 1: Detailed architecture of a single ThermOuch unit. (A) Internal components and their arrangement; (B) A bottom view highlighting a 2 mm spacing between two Peltier devices; (C) A side view showing that the maximum thickness of the unit is approximately 2 cm.

stimulated locations) may influence the perception of TGI-induced pain, hindering the scalability of its application in VR. Additionally, while the thermohaptic feedback has been extensively studied in VR research [Cai et al. 2020; Liu et al. 2021; Niijima et al. 2020; Peiris et al. 2019, 2017; Zhu et al. 2019b], it is unclear how TGI-induced pain perception may affect the VR experience.

In this paper, we propose ThermOuch (Fig.1), a wearable device with thermal feedback for creating TGI-induced pain sensation in VR. Our first user-perception experiment showed that higher temperature-changing rates led to more intense pain perception. Furthermore, a higher warm-to-cool rate ratio reduced the sensation of coldness before pain was perceived. We then deployed one more stimulus unit in our second experiment, where the results demonstrated that additional stimulus unit heightened the perception of pain, and altering the spacing between units could affect the perceived pain area. Lastly, a user study in VR showed that the ThermOuch-induced pain perceptions could significantly improve the sense of presence and the body ownership compared to no haptic feedback.

2 Related work

In this section, we discuss the relevant research on pain sensation for VR/AR and the background of thermal grill illusion.

2.1 Haptic Rendering of Pain Sensation in VR/AR

Incorporating appropriate pain sensations could enhance empathic and immersive experiences in virtual environments [Fusaro et al. 2016]. However, providing pain sensations to users poses challenges due to safety and ethical concerns. One cost-effective pain-induction approach was through pseudo-haptics. For example, BurnAR [Weir et al. 2012] allowed users to experience the illusion of heating and burning through virtual fires and smoke on their hands in augmented reality (AR). Clavelin et al. [2023] employed perceptual manipulation on pain during a simulated finger dislocation experience. However, the effectiveness of pain perception induced by pseudo-haptics may vary among individuals, as some may not feel the vision-induced pain [Eckhoff et al. 2020]. In addition, only applying visual stimuli to evoke psychological effects of pain sensation could lead to a non-matching visual-haptic experience, which may affect the user performance and immersion [Cai et al. 2024; Hochreiter et al. 2018].

Some researchers have explored haptic feedback on users' skin to generate actual pain sensations. Lopes et al. [2015] developed Impacto to create the physical impacts of hitting and being hit through EMS in VR. Similarly, Kono et al. [2018] combined EMS with visual feedback to manipulate users' eyelids and induce fear or pain. However, EMS-induced pain may be limited to instant physical impact rather than persistent pain. Besides, Niijima et al. [2020] found that users could also feel heat and pain when their sensitive body parts, such as lips or forearms, came into contact with activated Peltier devices. However, it may cause actual harm on the human skin by exceeding the pain threshold.

Considering chemical stimulants for pain sensation, previous research has demonstrated that capsaicin can induce pain and mechanical hyperalgesia on human skin [Simone et al. 1989]. Jiang et al. [2021] present Douleur , which injected capsaicin onto the skin to activate the trigeminal nerve, and incorporated an additional Peltier module to adjust the level of pain by heating or cooling the affected area. Lu et al. [2021] investigated the temporal profile of painful sensations as the skin naturally absorbs cinnamaldehyde. However, the use of chemical stimulants comes with the limitation of latency due to the dispersion of pain sensation.

While these approaches enabled pain sensation in virtual environments, they may cause actual negative effects on skin or mismatched visual and haptic experiences (for pseudo haptics). Compared to these existing efforts, ThermOuch explores the feasibility and effects of leveraging TGI, which led to on-skin pain illusion without inflicting harm to the skin, in interactive VR scenarios.

2.2 Thermal Grill Illusion

The thermal grill illusion (TGI), initially discovered in 1896, is a phenomenon where the application of alternating warm and cool stimuli to the skin leads to the illusory perception of intense heat and pain [Alrutz 1898; Craig and Bushnell 1994]. Characterized by the simultaneous presentation of these stimuli, TGI results in a unique prickling sensation combining burning heat and pain [Bach et al. 2011]. Previous studies have shown that neither the arrangement nor the number of alternating warm and cool stimuli units significantly affected TGI occurrence [Li et al. 2009]. A larger temperature range increases pain intensity through sensory summation [Leung et al. 2005]. A larger thermal stimuli area is associated with increased pain perception [Saga et al. 2022]. Harper and Hollins [2014] discovered that adaptation to the cool bars of the grill resulted in a significant reduction in pain, indicating that the sensation of coolness may contribute to the experience of TGI-induced pain. Consequently, exposure to coolness before applying the TGI could potentially lead to reduced pain sensations [Hunter et al. 2015]. Later, Patwardhan et al. [2018] showed that the larger temperature difference between heat and cold led to higher pain intensity perceived by the participants, along with shorter response time. More recently, Mitchell et al. [2024] found that the temperature-changing process periodically between hot and cold with a single Peltier module could also induce illusionary pain sensation.

Although previous research has extensively investigated TGI and its impact on pain sensation, there is a lack of exploration regarding the influence of warming and cooling rates on the pain sensation induced by TGI and how to integrate it with VR technology. Furthermore, the previous work [Hunter et al. 2015] shows that it is challenging to provide the strong intensity of simulated pain sensations induced by TGI due to the diminishing pain sensation caused by the anticipatory feeling of coolness prior. Such a challenge could potentially be addressed by combining a rapid warming rate and a slow cooling rate in *dynamic* conditions (changing the temperature while the skin is in contact with the grill). Additionally, a grounded TGI system adopted by previous researches limits further exploration of its potential application in VR, where users typically move and use gestures to interact with virtual environment. ThermOuch seeks to address these gaps by focusing on the design of wearable TGI device which was untackled in the previous works and investigating the effects of thermal feedback on TGI-induced pain sensations with varying *dynamic* signal configurations.

3 ThermOuch System Implementation

ThermOuch contains a thermoelectric stimulative system to evoke TGI-based pain, supplemented by a water-cooling regulation subsystem to stabilize the rate of temperature change.

3.1 TGI Induction Module

The cornerstone of the ThermOuch system is the Peltier-based temperature-control system for inducing thermal grill illusion. The stimulative unit is housed within a 3D-printed enclosure, with a copper heat sink. Beneath this heat sink, a pair of thermoelectric Peltier elements (12.5 × 12.5 mm, Module No.: HT16040), one for warming and the other for cooling, are situated to form an integral stimulative unit. The Peltier elements are separated by a 2 mm gap, as depicted in Fig. 1B, to reduce thermally mutual influence. A Type-K thermocouple is attached for close-loop temperature regulation. Heat sink surface in potential contact with the user's skin are covered with thermal insulation fabric to prevent unintended heat transfer. To allow comfortable wearing on the user's body, the system contains an adjustable elastic band that allows for a versatile fit across different body parts for different users. In our current prototype and experiments, we focused on the specific context of the ThermOuch device being worn on the user's forearm as it has been widely studied for TGI and obtained an average level of thermal sensitivity [Luo et al. 2020] and pain threshold [Park et al. 2019] among different body parts.

3.2 Thermal-Regulation System

The temperature-regulation system of ThermOuch ran upon a water-cooling mechanism. Originating from the inflow and outflow ports of the copper heat sink, the silicone tubes connected to a water pump and a reservoir, respectively, constituting the water-cooling circuit. The reservoir (370 milliliters), positioned atop the water pump, serves as the repository for the cooling medium, which is circulated to the heat sink as needed. The water temperature is continually monitored via a Type-K thermocouple and is maintained within the narrow range of 23 to 25 °C (room temperature) for our later experiments. The fans were activated to cool the water when the temperature exceeded 23°C detected by the Type-K thermocouple.

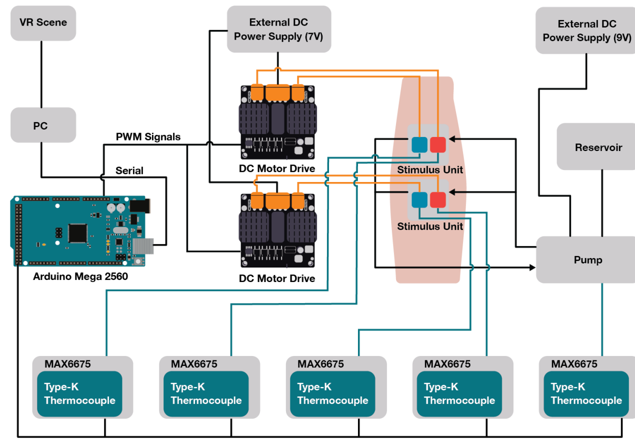


Figure 2: The system diagram of ThermOuch

The temperature-regulation system was driven an Arduino Mega 2560 which interfaced with two dual channel motor drivers (L298N BTS7960) powered by an external 9V power supply to control the Peltier elements, shown in Fig. 2. Real-time temperature monitoring was achieved via the Type-K thermocouples connected to MAX 6675 modules that provided temperature readings at a sampling frequency of 4Hz. With the thermocouple readings, the microcontroller executes a Proportional-Integral-Derivative (PID) algorithm to continuously adjust PWM signals for temperature control. Table 1 in the supplementary material shows the PID parameters of our control system. Figure 3 shows our system performance, for various rates and thermal directions. We adopted the temperature-changing rate of +/-5°C/s for temperature resetting, achieving the resetting time below 2.5s which could be useful for real-time VR application. In a VR setting, as users navigate and interact with the environment, the system detects the collision events on the avatar's forearm, and controls the ThermOuch system to trigger the corresponding thermal stimulus.

4 User-perception Experiment 1: The Perceived Intensity of Pain Sensations

In the first study, we investigated how different warming and cooling rates would affect users' perceived pain intensities through the grounded ThermOuch setup. This was to study the perception bandwidth of pain sensation enabled by our system. All the experiment protocols (including this and the latter ones) were approved by the ethics committee in our university (HU-STA-00000327).

4.1 Participants

The study recruited 12 participants(3 females and 9 males), with an average age of 28.7 years old (SD = 3.71). The average skin temperature of the forearm was 33.48°C (SD = 0.63). Furthermore, the mean length of their forearms was 23.25 cm (SD = 2.22). As they self-reported, all the participants were right-handed without any body impairment, and possessed normal thermal-perception capacity.

4.2 Apparatus

Fig. 4 illustrates the configuration of the user study environment. A participant put his/her dominant forearm on a pressure-sensing surface with load cells (GML670). We adopted a linear motion actuator (Module No.: 28T6*4-100) to control the perpendicular movement of Peltier actuators to contact the midpoint of the forearm with the constant applied normal force. During the study, the participant provided his/her subjective ratings on the stimuli using a 12-inch touch-screen laptop, with their non-dominant hand. To mitigate visual cues that may influence their perception, a black cloth is placed in between to obscure the stimulus unit from the participant's view. Additionally, to eliminate potential auditory distractions, the participant put on a pair of noise-cancelling headphones throughout the duration of the study. The environmental conditions within the study area are regulated, with the ambient temperature maintained at a constant 25°C.

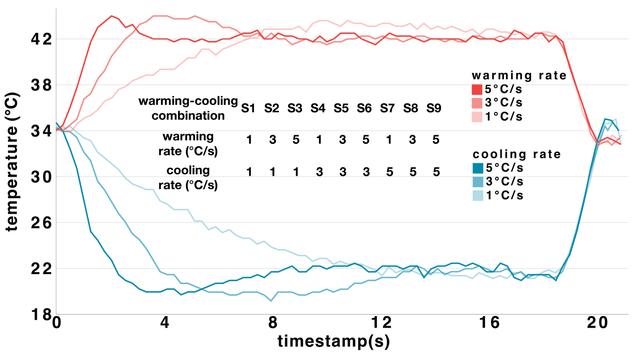


Figure 3: The step response of thermal stimuli with different temperature-changing rates (i.e., 1°C/s, 3°C/s, and 5°C/s) and thermal directions (i.e., warming and cooling) in the experiment.

Figure 4: (A) The user interface for evaluating pain intensity, coldness, and unpleasantness; (B) Setup environment where stimulus unit fully contacts the skin and halts upon a 2N increase in pressure as measured by the load cell.

4.3 Study design

A within-subjects design was adopted with the combination of warming and cooling rates as the independent variable. In this experiment, we adopted the six temperature-changing rates, three warming and three cooling. These temperature-changing configurations were chosen due to the clear distinguishability among them based on the results of the previous thermohaptic studies [Claus et al. 1987; Kenshalo et al. 1968; Nakashige et al. 2009; Pertovaara and Kojo 1985; Wilson et al. 2011]. This resulted in 3 cooling rates × 3 warming rates = 9 combinations of thermal stimuli for TGI induction, denoted as S1 to S9 shown in Figure 3. A neutral starting temperature of 34°C was chosen as this is within the defined 'natural zone' of thermal sensation [Jones and Berris 2002; Stevens 2013] and has been used in other studies [Cai et al. 2020; Stevens and Hooper 1982]. To ensure the participants' safety and comfort, the temperature range was constrained, with an upper limit of 42°C and a lower limit of 22°C which are below the thresholds for heat and cold pain [Bouhassira et al. 2005; Hardy et al. 1952; Harrison and Davis 1999]. Each participant was subjected to a total of 45 randomized trials, with the 9 combinations of warming and cooling rates, each being repeated 5 times.

We measured participants' subjective ratings of perceived coldness prior to the onset of pain sensations, the unpleasantness and the perceived pain intensities at the incipient moment of pain perception, and the perceived pain intensities at five seconds after the detection of pain sensation. Participants were asked to provide subjective ratings on an 11-point Numerical Rating Scale (NRS) ranging from 0 to 10, assessing perceived coldness prior to pain onset, initial pain intensity, and unpleasantness associated with the pain. Additionally, the detection time was logged as the time interval between the initiation of the temperature shift and the point at which participants reported the onset of pain sensation.

4.4 Procedure

Each experiment consisted of one participant and one researcher. The researcher first explained the purpose and procedure of the study to the participant, obtained their consent, and measured their skin temperature and the length of their dominant forearm. The participant was then seated at the experiment table, aligning their dominant forearm with the central position marked on a load cell located at the midpoint of the stimulus unit. The central position of the participant's forearm was determined based on the previously measured length.

Prior to the experiment trials, participants underwent a training session to familiarize themselves with the experimental process and ensure that they could perceive and tolerate the simulated pain illusion. During the training session, participants experienced two thermal stimuli: 1°C/s for cooling and warming, and 5°C/s for cooling and warming rates. These extreme temperatures were chosen to evoke mild and intense TGI sensations, respectively, providing participants with a range of thermal stimuli. The participant independently initiated each trial by pressing the "START" button on the touchscreen (Fig. 4A). A linear motion actuator then advanced the stimulus unit downward, halting upon a 2N increase in pressure as measured by the load cell, to ensure the full contact and the comfort. After attaining the 2N pressure, the stimulus unit remained at 34°C for an additional five seconds with the visual countdown on the screen, before the thermal stimulus was triggered. During the stimulus, the participant was instructed to press the "OUCH" button on the touchscreen as soon as he/she perceived a painful sensation, and he/she then rated the pain level, the coldness, and the unpleasantness respectively. The temperatures of the warming and cooling elements were logged simultaneously and maintained for five seconds. After a five-second maintenance period, the participant was prompted with "Trial Finish" on the screen to rate the current pain intensity. To end the trial, participants pressed the "MOTOR UP" and "RECORD" buttons, which retracted the stimulus unit. A 15-second interval was provided between consecutive trials to allow the skin temperature to return to its initial state and alleviate any remaining pain through self-touching of the stimulated skin area [Kammers et al. 2010].

If the participant did not report pain within 15 seconds of starting the trial, they were instructed to press the "NO PAIN" button and leave the rating sections blank. Participants were also informed that they could withdraw from the experiment at any time if they found the simulated pain sensation intolerable. Importantly, no participants chose to end their participation prematurely. The entire experimental procedure lasted approximately 1 to 1.5 hours per participant.

4.5 Results

4.5.1 More Pain with Faster Warming and Cooling. Taking the combinations of warming and cooling rates as the independent factor, we ran a Friedman Test on the participants' ratings of perceived pain intensities at the incipient moment of pain perception (Fig. 5A). The analysis revealed that the warming-cooling combination significantly affected the rated pain intensities ($\chi^2(8) = 92.583$, $p < 0.001$). We then conducted post-hoc pairwise Conover Test between each two combinations, and more details about pairwise comparison results can be found in Table 2 in our supplementary materials. In general, the participants rated more pain at the incipient moment with faster warming-cooling combinations. Additionally, with an identical sum of warming and cooling rates, a faster warming rate tends to dominate the illusion and induce more pain.

Similarly, we also found a significant effect on the perceived pain intensities five seconds after in terms of the warming-cooling combination ($\chi^2(8) = 50.126$, $p < 0.001$), depicted in Fig. 5B. We also ran Conover test on our pain intensity after 5-seconds in Table 3 in the supplementary materials. We then adopted Wilcoxon signed-rank comparison test on perceived pain intensity for incipient moment and 5-second past (Table 4 in the supplementary materials). The results indicated a significant reduction in all stimuli after five seconds compared to their initial moment, highlighting a rapid decrease in pain sensations within a relatively short time frame. The Pearson Correlation Test revealed that the rated pain intensities after five seconds was highly related to those at the incipient moment ($r(538) = 0.844$, $p < 0.001$).

4.5.2 Cold and Unpleasant Feeling Varied Across Stimuli. We collected subjective coldness and unpleasantness ratings for each stimulus during the experiment (Fig.5C&D). We expect to provide suitable pain sensations through TGI with minimum cold sensation interference. The Friedman Test on perceived coldness prior to the onset of pain sensations showed a significant difference ($\chi^2(8) = 67.747$, $p < 0.001$). Post-hoc pairwise Conover Tests revealed that a higher warm-to-cool rate ratio could result in a less intense cold sensation prior to the pain. More details could be found in Table 5 in supplementary.

Additionally, the Friedman Tests revealed that there was a significant main effect of the different warming-cooling combinations on the ratings of unpleasantness ($\chi^2(8) = 78.696$, $p < 0.001$). Post-hoc pairwise Conover Test delineated that S6 ($p < 0.001$) and S9 ($p < 0.01$), with the fastest cooling speed and the intermediate/fastest warming speed, elicited significantly higher ratings of unpleasantness in comparison to the other seven stimuli. Table 6 in our supplementary provides more details for pairwise comparisons. The Pearson Correlation Test yielded that the immediate perception of pain intensity is strongly positively associated with the response of unpleasantness ($r(538) = 0.719$, $p < 0.001$).

4.5.3 Shorter Response Time with Stronger Pain. Out of 540 trials, participants reported no pain perception in 118 instances. The average response time for each stimulus is shown in Figure 5E. For the statistical analysis, we treated the participants' response time toward these trials as 15 seconds. A repeated-measures ANOVA revealed a statistically significant influence of the different warming-cooling combinations on the participants' response time towards perceiving the pain sensation/illusion induced by our system ($F(8, 88) = 13.722$, $p < 0.001$). Table 7 in the supplementary materials shows more details about our post-hoc pairwise comparison test results for response time. In addition, Pearson Correlation Test indicated a negative relationship between detection time and the initial perceived pain intensity ($r(538) = -0.768$, $p < 0.001$), suggesting that greater pain intensity correlates with quicker detection times.

In summary, our first user-perception experiment showed that the combination of warming and cooling rates significantly influenced the participants' rated TGI-induced pain intensity. We further performed a K-means-based clustering process on the intensity ratings, and found the nine warming-cooling combinations could be divided into 3 clusters (as shown in Table 8 in the supplementary materials) with a significant difference in the intensity ratings between all clusters and no significant difference within the cluster. This suggested that our system could yield three different levels of pain illusion. Within each cluster, we selected the stimuli

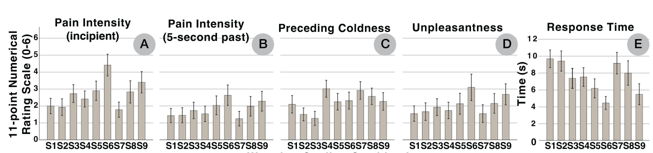


Figure 5: User perception of perceived pain intensity on incipient moment (A) and 5-second past (B), coldness prior to the incipient moment of pain (C), unpleasantness (D), and detection time (E) regarding each temperature rates combination (color-coded bins denote groupings of stimuli with identical sum of cooling and warming rates; error-bar represents a 95% of confidence interval).

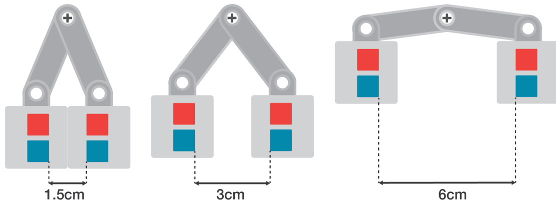


Figure 6: Adjustment of inter-stimulus distances (bottom-up view). The structure is affixed to the motion slide rail at the potion marked by the black cross.

that elicited less cold sensation, namely S2, S3, and S6, for further experiments.

5 User-perception Experiment 2: The Perceived Area of Pain Sensations

While our first experiments showed different temperature-changing rates in our system could yield different levels of pain illusion, a wearable design may contain multiple stimulating units to support dynamic TGI patterns. In the second study, we investigated how the thermal signals from two spatially distributed warming-cooling units on user's forearm may affect the perceived pain area and intensity.

5.1 Participants

The study recruited 12 right-handed participants (9 males, 3 females) from a local university with the similar criteria (i.e. normal limb functionality and thermal sensation) as the first experiment. To avoid potential biases or learning effects, none of the participants had been involved in the preceding experiment.

5.2 Apparatus

The experimental setup for the second user study was analogous to that of the first experiment. There was an additional stimulus unit affixed alongside the original unit on the end effector of the linear motion actuator. To accommodate the experimental need for adjustable inter-unit distances, each unit was attached to the end of a pair of pin-jointed beams, as depicted in Fig. 6.

5.3 Study Design

We adopted a within-subjects design, with three independent variables: the distance between the two stimulus units, the combination of warming and cooling rates, and the actuation sequence of the stimulative units. Considering the two-point-discrimination (2PD) threshold for pain sensation on the forearm [Mancini et al. 2014], we chose 1.5cm, 3cm, and 6cm for the possible values of the distance between the two stimulus units. The two stimulating units were attached symmetrically according to the midpoint of the forearm. As mentioned above, we selected S2, S3, and S6 for the stimuli combinations. Last but not least, we considered three actuation sequences: the activation of the distal stimulus unit followed by the proximal unit (denoted as S_{down}), vice versa (denoted as S_{up}), and the simultaneous activation of both units (denoted as S_{none}). The duration of each stimulus is detailed in Table 9 in the supplementary materials. For S_{up} and S_{down}, the subsequent stimulus would start once the prior one achieved its maximum temperature differential of 20°C, established between 42°C and 22°C. Meanwhile, the prior stimulus maintained this maximum temperature differential. The stimuli stopped when the subsequent stimulus also attains its maximum temperature differential. For S_{none}, both stimulating units were activated at the same time, and stopped when both reached the maximum temperature differential. Each participant completed a total of 81 trials (3 distances × 3 warming-cooling combinations × 3 actuation sequences × 3 repetitions). The presentation order of the distances was counterbalanced using a Latin square design. Within each block, the sequence of stimulus presentations was randomized. The dependent variables measured in each trial included the participants' subjective ratings of perceived pain intensity, the accuracy of identifying the lateral motion direction of the pain sensation, and the pixel count in the user-drawn pain area.

5.4 Procedure

We followed the similar procedure of "Introduction – PreQuestionnaire – Training – Testing" in the first user study. During the training session, participants were exposed to randomized stimuli under the inter-unit distance of 3cm and tried as much as possible until he/she reported him/herself to be familiar with the experimental procedure. After each trial, the screen displayed the graphical user interface (Fig. 7) for the participant to rate the perceived pain intensity from 0 to 10, indicate the lateral direction of pain (i.e. DOWN, UP, or NONE), and draw the perceived pain area.

There was a 15-second break between two consecutive trials, and a 5-minute break after each condition of inter-unit distance. The entire experiment spanned approximately 2 to 2.5 hours per participant.

5.5 Results

5.5.1 Larger Pain Area with Longer Unit Distance. The size of the perceived pain area was determined by the number of pixels of the participant-drawn image. A multi-factorial repeated-measured ANOVA revealed a statistically significant effect of the inter-unit

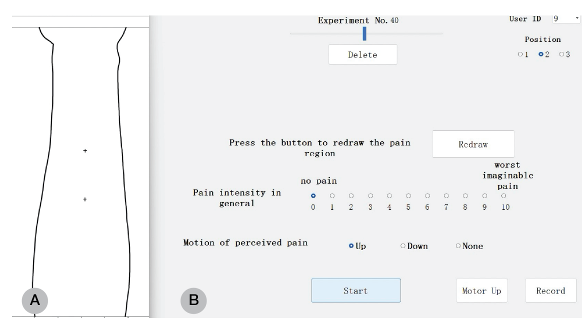


Figure 7: (A) The pop-up window for drawing perceived pain area during stimulation period, featuring a pair of cross marks that indicate the approximate locations of the two stimulus units. (B) Main window for evaluating generally perceived pain intensity and the directional movement of pain sensation.

distance on the size of the perceived pain area (F(2,22) = 16.252, p < 0.001, η_p^2 = 0.317). Post-hoc pairwise comparisons (Fig. 8A) further disclosed that the distance of 6cm yielded significantly larger pain area compared to the settings of 3cm and 1.5cm (p < 0.001). Furthermore, the warming-cooling condition also exerted a significant effect on the perceived pain area (F(2,22) = 14.999, p < 0.001, η_p^2 = 0.3). The post-hoc test (Fig. 8B) revealed that S3 triggered significantly larger pain area than S2 (p = 0.025) and S6 (p < 0.001). Additionally, S2 elicited significantly more expansive pain area than S6 (p = 0.022). There was no significant effect on the perceived pain area in terms of the actuation sequences. Fig.9 showed the heat maps of the participants’ drawings for different warming-cooling combinations and inter-unit distances for the condition of the simultaneous activation for both units (S_{none}).

5.5.2 Distant/Sequence not Affecting Perceived Pain Intensity. A multi-factorial repeated-measures ANOVA on the response results after Aligned Rank Transform (ART) [Wobbrock et al. 2011] showed that a significant main effect of the selected combination of warming and cooling rates on the ratings for general pain intensity (F(2,22) = 4, p = 0.023, η_p^2 = 0.103). The post-hoc pairwise comparison revealed that S3 engendered significantly higher pain intensity compared with S2 (p = 0.034). Meanwhile, S6 was associated with a pain intensity that was only marginally higher than that of S2 (p = 0.054), and no significant difference was found between the pain intensity ratings of S6 and S3, as shown in Fig.8C. There was no significant effect of either inter-stimulus distance or actuation sequence on the ratings of perceived pain intensity.

5.5.3 Low Accuracy for Detecting Lateral Motion Direction. In overall, the participants achieved a low accuracy in identifying the lateral motion direction of the illusory pain (i.e., 42.90 % (SD=23.66%) for 1.5cm, 44.45% (SD=18.37%) for 3cm, and 55.56% (SD=10.76%) for 6cm). Specifically, with the distance settings of 1.5cm and 3cm, most trials were identified as non-directional stimuli, while the identification accuracy increased with the inter-unit distance of 6cm, as illustrated in Fig.8D. This could be due to the low spatial acuity of thermal perception [Jones and Berris 2002; Stevens 2013].

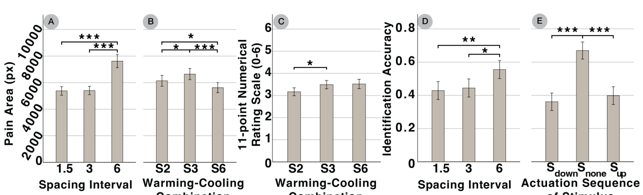


Figure 8: User perceived average pain area relative to spacing interval (A) and temperature rates combination (B); Overall pain intensity during stimulation period (C); The identification rate of the lateral motion direction of pain sensation relative to spacing interval (D) and the stimulus activation sequences (E) (error-bar represents a 95% of confidence interval; * p <= .05; **p <= .01; ***p <= .001)

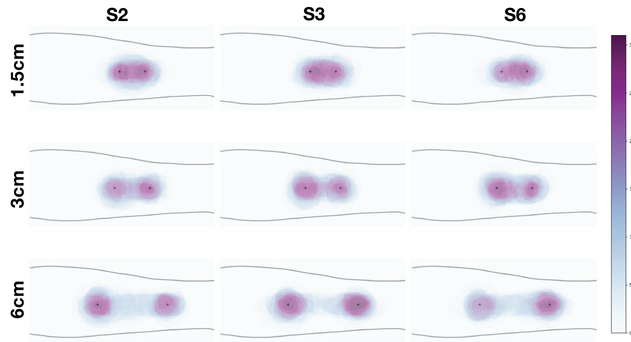


Figure 9: Aggregated results of the pain areas drawn by all participants under the S_{none} condition. The color gradient represents the degree of overlap in responses, ranging from 0 (no overlap) to 30 (complete overlap by all participants).

6 User-Perception Experiment 3: User Experience with ThermOuch in VR

Building upon the empirical findings from the first and the second experiments, we conducted the third user study to investigate the integration of ThermOuch in VR and how it may influence user’s sense of presence, body ownership, and emotional conditions reflected in their biosignals in immersive VR.

6.1 Participants

We recruited 12 participants (8 males, 4 females) for this experiment, with an average age of 26.4 (SD = 3.83), all right-handed with normal limb functionality. All of them did not attend the previous experiments. All participants had prior experience with VR, but only two had encountered it in combination with haptic feedback on skin.

6.2 Apparatus

The ThermOuch system used in the second experiment was deployed to provide the TGI feedback on the user’s forearm. We developed a VR application containing two scenes using Unity3D engine, version 2020.3.40f1. The application used an HTC Vive Pro HMD and a pair of HTC Vive handheld controllers for interacting with virtual objects in the scene. We also collect users’ heart rate (HR), electrocardiography (ECG) and electrodermal activity (EDA) signals through BITalino[1] toolkit. The electrodes were adhered to the recommended positions in the literature [van Dooren et al. 2012; Wang et al. 2013], as illustrated in Fig. 10C, ensuring accurate biosignal measurement while minimizing potential signal disturbance during engaging in VR activities. The biosignal data thus collected were continuously monitored and subsequently archived using the OpenSignals software[2] on a PC.

[1] https://www.pluxbiosignals.com/pages/bitalino
[2] https://support.pluxbiosignals.com/knowledge-base/introducing-opensignals-revolution/

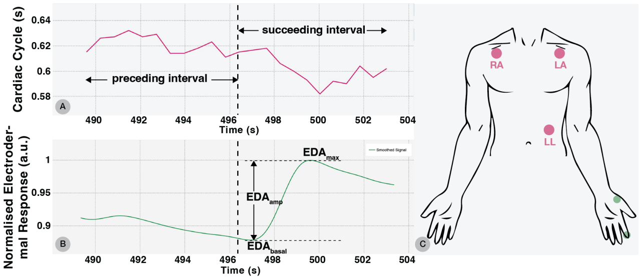


Figure 10: In a 14-second window centered around each timestamp, the change in heart rate is measured by comparing the average cardiac cycle before and after the stimulus (A). The change in EDA values is measured within the same window by subtracting EDA_{basal} from EDA_{max} (C). It shows a three-lead ECG placement (pink) and a two-lead EDA placement (green).

6.3 Study Design

The experiment was constructed with a within-subjects design. We create three different conditions in VR scenes: wearing ThermOuch with temperature maintained at an idle state (i.e., 34°C, denoted as TO_{idle}), wearing ThermOuch with the TGI-based haptic stimuli corresponding to the VR visual contents (denoted as TO_{corr}), wearing ThermOuch with randomized TGI-based haptic stimuli (denoted as TO_{rand}) wherein all correlated stimuli excluded. We selected inter-unit distances of 6cm and 1.5cm, and comprised them with S2, S3, S6 to form six distinct stimuli. To preserve the sense of presence in VR and mitigate the potential disruption of immersion due to mid-experiment changes in inter-stimulus spacing, we designed two separate VR scenes, jungle navigation and dragon fighting. In one scene, participants were tasked with navigating to a campfire by following a stone path. The other scene presented a fiercer event where participants were required to defend themselves against a dragon and subsequently retaliate using a bow and arrow. Each pain-triggering event in the two scenes was tailored around the profile of corresponding stimuli, as detailed in Fig. 11.

The dependent variables were the sense of presence and body ownership within the VR, which were evaluated through questionnaire with selected haptic-related items from [Witmer and Singer 1998] and [Roth and Latoschik 2020] respectively. Moreover, variations in biosignals between pre- and post-stimulus, were also analyzed to study how the participant responded to the interaction in real time.

6.4 Procedure

In the third user experiment, we followed a similar procedure as the first two. Participants were introduced to the experiment, put on the ThermOuch system, VR HMD, and biosignal sensors with the researcher's assistance. They learned how to interact with the virtual environment using handheld controllers.The participant then engaged in three testing conditions, counterbalanced using a Latin square design, with each representing one of the three aforementioned haptic conditions. Within each sub-session, the presentation sequence of the two scenes was randomized. During the VR interactions, any incidents of pain sensation triggers were annotated by the experimenter with timestamps in the OpenSignals software. After each sub-session, participants removed the HMD and completed a touchscreen questionnaire using a 7-point Likert scale. The study ended with a semi-structured interview, allowing for a more nuanced exploration of the participant's experience. Overall, the experiment took around 45 minutes per participant.

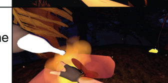
Scene	Event	VR First-Person Perspective	Warming-Cooling Combination (intensity-area)	Distance (spot-area)
jungle navigation	poked by pointed leaf		S6(acute-small)	1.5(single-small)
	scratched by serrated leaf		S3(acute-large)	1.5(single-small)
	applying medicine to the wound		S2(mild-medium)	1.5(single-small)
defense and retaliation against the dragon	defending fireball strike with an arm shield		S6(acute-small)	6(multi-large)
	blocking falling rocks		S3(acute-large)	6(multi-large)
	triggering old injury while drawing		S2(mild-medium)	6(multi-large)

Figure 11: Six events and their corresponding stimulus features

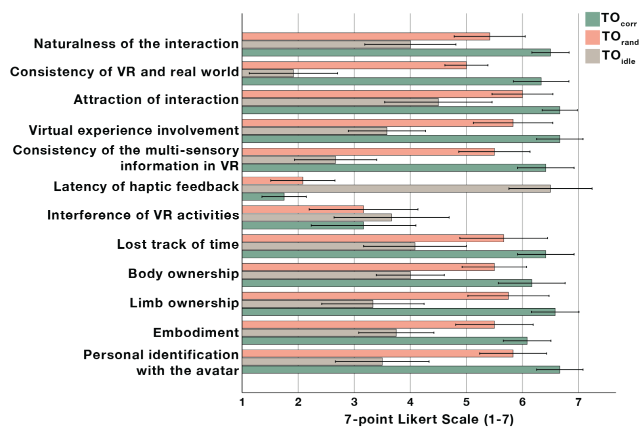


Figure 12: Questionnaire responses on the user experience.

6.5 Results

6.5.1 Subjective Ratings of Presence and Ownership. The rating of the sense of presence and body ownership within VR was depicted in Fig. 12. The Friedman Test analysis revealed that the stimulation mode significantly influenced the naturalness of the interaction ($\chi^2(2)$= 19.581, p < 0.001), consistency of VR and real world ($\chi^2(2)$ = 22.136, p < 0.001), attraction of interaction ($\chi^2(2)$ = 15.548, p < 0.001), experience involvement ($\chi^2(2)$ = 20.333, p < 0.001), consistency of the multi-sensory information in VR ($\chi^2(2) = 21.565$, $p < 0.001$), latency of haptic feedback ($\chi^2(2) = 21.333$, $p < 0.001$), lost track of time ($\chi^2(2) = 18.865$, $p < 0.001$). Post-hoc Conover's test revealed that the stimulation mode TO_{corr} and TO_{rand} outperformed the TO_{idle} across most measured dimensions, with the exception of the latency of haptic feedback. Furthermore, TO_{corr} marginally outperformed TO_{rand} in naturalness of the interaction ($p = 0.051$) and consistency of VR and real world ($p = 0.054$).

Additionally, the Friedman test revealed a significant effect of the stimulation mode on the ratings of body ownership ($\chi^2(2) = 16.233$, $p < 0.001$), limb ownership ($\chi^2(2) = 21.273$, $p < 0.001$), embodiment ($\chi^2(2) = 18.878$, $p < 0.001$), personal identification with the Avatar ($\chi^2(2) = 21.571$, $p < 0.001$). A subsequent post-hoc Conover's test revealed that the conditions TO_{corr} and TO_{rand} were superior to the TO_{idle} in cultivating a sense of ownership across all measured dimensions. There was no significant difference was discerned between the TO_{corr} and TO_{rand}.

6.5.2 Biosignals. We observed obvious changes in heart rate and EDA data in response to the stimulus, as shown in Fig. 10A&B. We compared the collected heart rate (Fig. 13A) and EDA (Fig. 13B) data within a 7-second interval preceding and succeeding each logged timestamp of the onset of event. The repeated-measured ANOVA revealed that the type of stimulation mode significantly impacted the heart rate variation (F(2,18) = 7.142, $p = 0.005$, $\eta_p^2 = 0.442$). Further analysis through post-hoc testing revealed that the average heart rate increased significantly under both stimulation mode TO_{corr} ($p = 0.005$) and TO_{rand} ($p = 0.048$) compared to TO_{idle}. No significant effect was detected between the stimulation mode and the event type, implying that the observed heart rate changes were consistent across different VR events within each stimulation condition.

For EDA_{amp} data, we first adopted a 0-35Hz bandpass filter to the collected EDA_{amp} signals to remove high-frequency noise [Chen et al. 2015]. Four participants' data were excluded due to the flat plateau EDA_{amp} signals, which may be caused by the sweat from palms. The repeated-measured ANOVA showed that the type of simulation mode had a significant impact on the EDA_{amp} values (F(2,14) = 11.593, $p = 0.001$, $\eta_p^2 = 0.623$). Post-hoc comparisons revealed a significant higher EDA_{amp} under the correlated simulation mode TO_{corr} than TO_{rand} ($p = 0.027$) and TO_{idle} ($p < 0.001$).

6.5.3 Qualitative Feedback. We interviewed the participants to gather their feedback after the experiment. Compared to TO_{idel}, the conditions simulating pain sensations improve the sense of presence and immersion in the virtual environment. However, most of them could not specify a superior between TO_{corr} and TO_{rand}. For example, P10 stated, "I may notice the discrepancy of pain areas if I focus on it." P8 felt that somatosensory localization of pain, experienced when being cut by a leaf in TO_{corr}, was more aligned with the concurrent visual cues, and the pain intensity from the cut was more intense than when applying medicine to the wound, which met his expectations. Regarding the haptic feedback in the designed events, six participants mentioned the event of using a shield to block fireballs as being notably realistic. "[...] because in that event the fireball is inherently hot, and the rendered stimulus spreads out, which very much resembles the impact of

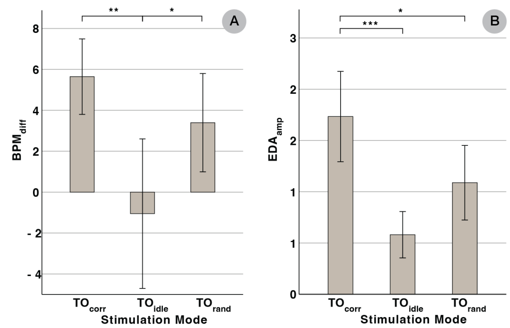


Figure 13: Average variation of heart rate (A) and electrodermal response (B) in response to three stimulation modes. (error-bar represents a 95% of confidence interval; * $p <= .05$; ** $p <= .01$; *** $p <= .001$)

being struck," said P9. Additionally, the event of applying medicine to a wound and the pain felt in the arm during archery received positive feedback. P2 commented, "The whole medicine application was very much in line with expectations. It started off with a cool feeling, just like when you first dab on some ointment, right? Then came this spreading kind of pain that kicked in, telling me the stuff was working. Gave me a pretty rich, detailed kind of sensation." P11 noted, "The pain during archery seemed to remind me that the damage from the recent rockfall wasn't just make-believe. It even affected how I handled things afterwards." The events involving blocking falling rocks and being pricked by pointed leaves did not receive positive feedback. "In my mind, the impression of being hit by a rock still includes some pressure and a scraping sensation," said P11. "A diffuse, spreading pain doesn't quite match the sharpness of being pricked by leaves. However, having experienced the prick, I found myself wanting to avoid similar plants on my path," P6 explained. When asked about noticeable delays in haptic feedback, 10 out of 12 participants reported perceiving little to no latency. The other two participants reported a slight delay, but it did not detract from the overall experience. P3 commented, "Actually, it's not bad, especially for virtual environments, because your focus is definitely on other things." P10 added, "There's a tiny bit, maybe, in the second scene where timely feedback is relatively crucial. But with something like a leaf cut, it's pretty reasonable to how you might not check the wound on your skin until you notice the pain from a real-life accidental cut."

7 Discussion

The first user study provides insights into how pain illusions respond to dynamically changing thermal stimuli. The results indicated that the temperature-changing rate combination significantly influenced the perceived pain intensity. Specifically, the participants experienced lower pain intensity with faster cooling rates, even when the total rate changes (i.e., the sum of warming and cooling rates) were identical. This aligns with previous research showing that the increased frequency of cold sensations reduces pain perception in the context of TGI [Harper and Hollins 2014]. The findings suggested that pain intensity can be augmented more energy-efficiently by raising the ratio of warm-to-cool rates rather than merely increasing total rate change. Given that cooling-stimulus Peltier devices inherently produce excess heat that must be efficiently dissipated, a lower dependency on the cooling rate can significantly reduce the heat generated. This reduction could contribute to the development of a more compact air-cooling system, enabling the design of wearable TGI devices to be more lightweight and untethered. Meanwhile, altering the ratio also affected the perception of coldness preceding the pain, with a higher warm-to-cool rate ratio leading to a less intense cold sensation. This can be beneficial in scenarios requiring increased pain intensity without a preceding cold sensation. A carefully managed ratio could also provide more nuanced pain sensation, especially in situations where coldness is required before rendering pain sensation, such as simulating the touch of sharp edges. We observed that there were 22.4% of the trials without receiving the response of pain sensation, spanning all temperature rate combinations and participants. These pain-free trials were predominantly concentrated among three individuals with attenuated responses, echoing with previous research [Bouhassira et al. 2005; Harper and Hollins 2014], suggesting that some individuals may have an inherent insensitivity to TGI.

The second user perception experiment demonstrates that the spatial-temporal parameters (i.e., the distance, the temperature-changing rate, and the activation sequence) of thermal stimuli units have significant effects on the perceived pain area and intensity. By increasing the distance between thermal stimuli units from 3cm to 6cm, we found that the perceived pain area significantly expanded. In terms of temperature-changing rate combination, S3 induced stronger pain and covered the largest perceived pain area. However, the participants did not discern a significant difference in pain intensity between S3 and S6. This divergence from the results of the first user study may be attributed to the evaluation based on overall pain intensity rather than specific moments. In addition, compared to the first experiment, the second one observed fewer pain-free trials: none for S2 and S3, and only 2.8% for S_{none} at a 1.5 cm spacing interval. The results indicate that an enlarged area of stimulation enhances the perception rate of TGI, especially for mild pain sensations. The participants could more accurately perceive the direction of lateral motion with a 6cm spacing interval (~70%), but the overall identification rate was not high. We suspected that the selected distances were not available for clear lateral motion detection as they were too close. Previous research has observed that TGI stimuli can produce a pain sensation up to distances of 30cm [Defrin et al. 2008], which creates ambiguity in direction determination. Additionally, our results of two-units TGI-based pain sensation indicated the possibility of integrating the array of TGI-triggering units into the wearable form factors dynamic pain patterns in VR.

By integrating the ThermOuch system with VR, we assessed its impact on user experience in terms of sense of presence, ownership, and stress level. Compared to the condition without haptic feedback TO_{idle}, correlated configurations TO_{corr} and random configurations TO_{rand} significantly enhanced the sense of presence and ownership. While comparing TO_{corr} and TO_{rand}, we didn't observe significant difference between these two conditions in terms of presence and body ownership in VR. Existing psychophysical research indicates that simultaneous visual and tactile stimuli can enhance the sense of ownership towards virtual body parts, while the specific type of tactile stimuli (i.e. noxious and non-noxious, more and less pain), may not significantly affect this sense of ownership [Capelari et al. 2009]. Users' ratings on the sense of presence were based on their subjective understanding of the pain sensations anticipated from VR pain-triggering events. However, scenarios like blocking falling rocks or defending fireball attacks from a dragon, were imaginary experiences that most people have not encountered in their real lives. These were different from the existing VR haptic research (e.g. temperature/vibration-based material identification in VR), meaning users may not have a real-world "ground truth" of pain as a reference for their ratings of in-VR realism. This may lead to similar sense of presence ratings between TO_{rand} and TO_{corr}. Notably, the psychological signals evoked by TO_{corr} yielded higher levels in terms of stressful experience compared to the randomised TO_{rand}, allowing more intensive skin conductance response (SCR), such as sweating. Existing research showed that the SCR level could be positively correlated to the effectiveness of fear learning which is crucial for survival and danger avoidance [Staib et al. 2015]. To this end, our system with corresponding visual and TGI-based pain stimuli could be potentially applied to the scenario of safety-related training and education in VR. In our interview, participants suggested several potential applications for ThermOuch. In entertainment, such as VR gaming and 4D cinema, it could heighten tension and excitement, thereby enhancing immersion. In medical education, it could train healthcare professionals about pain management and foster empathy towards patients. It could also be applied in training of hazardous settings, like firefighting or military operations, to enhance skill acquisition. Another potential application is wearing the TGI modules on other body parts, such as foot, chest, and back, to stimulate whole-body experience.

8 Limitations

We identified and summarized a few limitations for the current ThermOuch system. First, there is a subset of individuals is insensitive to TGI, limiting ThermOuch's utility as a haptic interface for pain feedback. Although our second user study resulted in the improvement with enhanced stimuli, more comprehensive testing across broader demographics, ethnic backgrounds, and skin sites should be considered for further validation. We also noticed that the perceived pain intensity decreased within five seconds post-onset, suggesting that the ThermOuch system may not be ideal for simulating intensive pain over a prolonged duration. Additionally, our future work will study how ThermOuch may perform in generation pain sensation for other body parts which may obtain different thermal and pain sensitivity. Last but not least, the current device relies on a water-cooling system to cool the Peltier devices, which constrains user mobility. Potential advancements could explore portable cooling technologies or redesign the system to improve cooling efficiency and user comfort.

9 Conclusion

In this paper, we proposed ThermOuch, a wearable thermo-haptic device to induce pain sensation through thermal grill illusion (TGI) without causing actual harm and requiring invasive procedures in

VR. Through three user-perception experiments, we first demonstrated that controlling the warming and cooling rates of the stimulus unit enables to modulate the level of pain intensity. Then, we introduced an extra stimulus unit to explore pain perception performance in terms of perceived area, pain intensity and lateral motion effects. Lastly, our third user study for VR experience revealed that ThermOuch significantly enhanced the sense of presence and ownership. Looking ahead, we envision broader applications where ThermOuch could contribute to a safer, more empathetic, and engaging interaction experience.

Acknowledgments

This research was partially supported by the Centre for Applied Computing and Interactive Media (ACIM) of School of Creative Media, City University of Hong Kong. This work was also partially supported by the National Natural Science Foundation of China (Project No. 62172346), and the Innovation and Technology Fund (Project No. ITS/106/22).

References

Sydney Alrutz. 1898. On the temperature-senses. *Mind* 7, 25 (1898), 141–144.

Patrick Bach, Susanne Becker, Dieter Kleinböhl, and Rupert Hölzl. 2011. The thermal grill illusion and what is painful about it. *Neuroscience letters* 505, 1 (2011), 31–35.

Steve Benford, Chris Greenhalgh, Gabriella Giannachi, Brendan Walker, Joe Marshall, and Tom Rodden. 2012. Uncomfortable interactions. In *Proceedings of the sigchi conference on human factors in computing systems*. 2005–2014.

Didier Bouhassira, Delphine Kern, Jean Rouaud, Emilie Pelle-Lancien, and Françoise Morain. 2005. Investigation of the paradoxical painful sensation ('illusion of pain') produced by a thermal grill. *Pain* 114, 1-2 (2005), 160–167.

Shaoyu Cai, Zhenlin Chen, Haichen Gao, Ya Huang, Qi Zhang, Xinge Yu, and Kening Zhu. 2024. ViboPneumo: A Vibratory-Pneumatic Finger-Worn Haptic Device for Altering Perceived Texture Roughness in Mixed Reality. *IEEE Transactions on Visualization and Computer Graphics* (2024).

Shaoyu Cai, Pingchuan Ke, Takuji Narumi, and Kening Zhu. 2020. ThermAirGlove: A Pneumatic Glove for Thermal Perception and Material Identification in Virtual Reality. In *2020 IEEE Conference on Virtual Reality and 3D User Interfaces (VR)*. IEEE, 248–257.

Edla DP Capelari, Carlos Uribe, and Joaquim P Brasil-Neto. 2009. Feeling pain in the rubber hand: integration of visual, proprioceptive, and painful stimuli. *Perception* 38, 1 (2009), 92–99.

Fernando Cervero. 2012. *Understanding pain: exploring the perception of pain.* Mit Press.

Weixuan Chen, Natasha Jaques, Sara Taylor, Akane Sano, Szymon Fedor, and Rosalind W Picard. 2015. Wavelet-based motion artifact removal for electrodermal activity. In *2015 37th Annual International Conference of the IEEE Engineering in Medicine and Biology Society (EMBC)*. IEEE, 6223–6226.

Inrak Choi, Heather Culbertson, Mark R Miller, Alex Olwal, and Sean Follmer. 2017. Grabity: A wearable haptic interface for simulating weight and grasping in virtual reality. In *Proc of UIST'17*. ACM, 119–130.

D Claus, MJ Hilz, I Hummer, and B Neundörfer. 1987. Methods of measurement of thermal thresholds. *Acta neurologica scandinavica* 76, 4 (1987), 288–296.

Gaëlle Clavelin, Mickael Bouhier, Wen-Jie Tseng, and Jan Gugenheimer. 2023. Exploring the Perception of Pain in Virtual Reality through Perceptual Manipulations. In *Extended Abstracts of the 2023 CHI Conference on Human Factors in Computing Systems*. 1–7.

AD Craig and MC Bushnell. 1994. The thermal grill illusion: unmasking the burn of cold pain. *Science* 265, 5169 (1994), 252–255.

Ruth Defrin, Anat Benstein-Sheraizin, Adva Bezalel, Ofira Mantzur, and Lars Arendt-Nielsen. 2008. The spatial characteristics of the painful thermal grill illusion. *Pain* 138, 3 (2008), 577–586.

Daniel Eckhoff, Alvaro Cassinelli, Tuo Liu, and Christian Sandor. 2020. Psychophysical effects of experiencing burning hands in augmented reality. In *International Conference on Virtual Reality and Augmented Reality*. Springer, 83–95.

Martina Fusaro, Gaetano Tieri, and Salvatore Maria Aglioti. 2016. Seeing pain and pleasure on self and others: behavioral and psychophysiological reactivity in immersive virtual reality. *Journal of neurophysiology* 116, 6 (2016), 2656–2662.

James D Hardy, Harold G Wolff, and Helen Goodell. 1952. Pricking pain threshold in different body areas. *Proceedings of the Society for Experimental Biology and Medicine* 80, 3 (1952), 425–427.

Daniel E Harper and Mark Hollins. 2014. Coolness both underlies and protects against the painfulness of the thermal grill illusion. *PAIN®* 155, 4 (2014), 801–807.

Joel LK Harrison and Karen D Davis. 1999. Cold-evoked pain varies with skin type and cooling rate: a psychophysical study in humans. *Pain* 83, 2 (1999), 123–135.

Jason Hochreiter, Salam Daher, Gerd Bruder, and Greg Welch. 2018. Cognitive and touch performance effects of mismatched 3D physical and visual perceptions. In *2018 IEEE Conference on Virtual Reality and 3D User Interfaces (VR)*. IEEE, 1–386.

Ya Huang, Jingkun Zhou, Pingchuan Ke, Xu Guo, Chun Ki Yiu, Kuanming Yao, Shaoyu Cai, Dengfeng Li, Yu Zhou, Jian Li, et al. 2023. A skin-integrated multimodal haptic interface for immersive tactile feedback. *Nature Electronics* 6, 12 (2023), 1020–1031.

J Hunter, R Dranga, M Van Wyk, and JO Dostrovsky. 2015. Unique influence of stimulus duration and stimulation site (glabrous vs. hairy skin) on the thermal grill-induced percept. *European journal of pain* 19, 2 (2015), 202–215.

Chutian Jiang, Yanjun Chen, Mingming Fan, Liuping Wang, Luyao Shen, Nianlong Li, Wei Sun, Yu Zhang, Feng Tian, and Teng Han. 2021. Douleur: creating pain sensation with chemical stimulant to enhance user experience in virtual reality. *Proceedings of the ACM on Interactive, Mobile, Wearable and Ubiquitous Technologies* 5, 2 (2021), 1–26.

Lynette A Jones and Michal Berris. 2002. The psychophysics of temperature perception and thermal-interface design. In *Proceedings 10th symposium on haptic interfaces for virtual environment and teleoperator systems. HAPTICS 2002*. IEEE, 137–142.

Marjolein PM Kammers, Frédérique de Vignemont, and Patrick Haggard. 2010. Cooling the thermal grill illusion through self-touch. *Current Biology* 20, 20 (2010), 1819–1822.

Dan R Kenshalo, Charles E Holmes, and Paul B Wood. 1968. Warm and cool thresholds as a function of rate of stimulus temperature change. *Perception & Psychophysics* 3, 2 (1968), 81–84.

Delphine Kern, Frédéric Plantevin, and Didier Bouhassira. 2008. Effects of morphine on the experimental illusion of pain produced by a thermal grill. *Pain* 139, 3 (2008), 653–659.

Michinari Kono, Takashi Miyaki, and Jun Rekimoto. 2018. In-pulse: inducing fear and pain in virtual experiences. In *Proceedings of the 24th ACM Symposium on Virtual Reality Software and Technology*. 1–5.

Pau Waelder Laso. 2007. Games of Pain: Pain as Haptic Stimulation in Computer-Game—Based Media Art. *Leonardo* 40, 3 (2007), 238–242.

Albert Y Leung, Mark S Wallace, Gery Schulteis, and Tony L Yaksh. 2005. Qualitative and quantitative characterization of the thermal grill. *Pain* 116, 1-2 (2005), 26–32.

Xi Li, Laura Petrini, Li Wang, R Defrin, and Lars Arendt-Nielsen. 2009. The importance of stimulus parameters for the experience of the thermal grill illusion. *Neurophysiologie Clinique/Clinical Neurophysiology* 39, 6 (2009), 275–282.

Yuhu Liu, Satoshi Nishikawa, Young Ah Seong, Ryuma Niiyama, and Yasuo Kuniyoshi. 2021. ThermoCaress: A wearable haptic device with illusory moving thermal stimulation. In *Proceedings of the 2021 CHI Conference on Human Factors in Computing Systems*. 1–12.

Pedro Lopes, Alexandra Ion, and Patrick Baudisch. 2015. Impacto: Simulating physical impact by combining tactile stimulation with electrical muscle stimulation. In *Proceedings of the 28th annual ACM symposium on user interface software & technology*. 11–19.

Jasmine Lu, Ziwei Liu, Jas Brooks, and Pedro Lopes. 2021. Chemical haptics: Rendering haptic sensations via topical stimulants. In *The 34th Annual ACM Symposium on User Interface Software and Technology*. 239–257.

Maohui Luo, Zhe Wang, Hui Zhang, Edward Arens, Davide Filingeri, Ling Jin, Ali Ghahramani, Wenhua Chen, Yingdong He, and Binghui Si. 2020. High-density thermal sensitivity maps of the human body. *Building and environment* 167 (2020), 106435.

Flavia Mancini, Armando Bauleo, Jonathan Cole, Fausta Lui, Carlo A Porro, Patrick Haggard, and Gian Domenico Iannetti. 2014. Whole-body mapping of spatial acuity for pain and touch. *Annals of neurology* 75, 6 (2014), 917–924.

Alexandra G Mitchell, Jesper Fischer Ehmsen, Małgorzata Basińska, Arthur S Courtin, Rebecca A Böhme, Camila Sardeto Deolindo, Micah G Allen, Kristian Sandberg, and Francesca Fardo. 2024. Thermal contrast enhancement predicts paradoxical heat sensation. *Communications Psychology* 2, 1 (2024), 37.

Mutsuhiro Nakashige, Minoru Kobayashi, Yuriko Suzuki, Hidekazu Tamaki, and Suguru Higashino. 2009. " Hiya-Atsu" media: augmenting digital media with temperature. In *CHI'09 Extended Abstracts on Human Factors in Computing Systems*. 3181–3186.

Arinobu Niijima, Toki Takeda, Takafumi Mukouchi, and Takashi Satou. 2020. Thermalbitdisplay: Haptic display providing thermal feedback perceived differently depending on body parts. In *Extended Abstracts of the 2020 CHI Conference on Human Factors in Computing Systems*. 1–8.

Moon Young Park, Doyeon Han, Jung Ho Lim, Min Kyung Shin, Young Rok Han, Dong Hwan Kim, Sungsoo Rhim, and Kyung Sook Kim. 2019. Assessment of pressure pain thresholds in collisions with collaborative robots. *PloS one* 14, 5 (2019), e0215890.

Shriniwas Patwardhan, Anzu Kawazoe, David Kerr, Masashi Nakatani, and Yon Visell. 2018. Too hot, too fast! Using the thermal grill illusion to explore dynamic thermal perception. In *2018 IEEE Haptics Symposium (HAPTICS)*. IEEE, 145–150.

Roshan Lalitha Peiris, Yuan-Ling Feng, Liwei Chan, and Kouta Minamizawa. 2019. Thermalbracelet: Exploring thermal haptic feedback around the wrist. In *Proceedings* *of the 2019 CHI Conference on Human Factors in Computing Systems*. 1–11.

Roshan Lalintha Peiris, Wei Peng, Zikun Chen, Liwei Chan, and Kouta Minamizawa. 2017. Thermovr: Exploring integrated thermal haptic feedback with head mounted displays. In *Proceedings of the 2017 CHI Conference on Human Factors in Computing Systems*. 5452–5456.

Antti Pertovaara and Ilpo Kojo. 1985. Influence of the rate of temperature change on thermal thresholds in man. *Experimental Neurology* 87, 3 (1985), 439–445.

Srinivasa N Raja, Daniel B Carr, Milton Cohen, Nanna B Finnerup, Herta Flor, Stephen Gibson, Francis Keefe, Jeffrey S Mogil, Matthias Ringkamp, Kathleen A Sluka, et al. 2020. The revised IASP definition of pain: Concepts, challenges, and compromises. *Pain* 161, 9 (2020), 1976.

Daniel Roth and Marc Erich Latoschik. 2020. Construction of the virtual embodiment questionnaire (veq). *IEEE Transactions on Visualization and Computer Graphics* 26, 12 (2020), 3546–3556.

Satoshi Saga, Ryotaro Kimoto, and Kaede Kaguchi. 2022. Spatiotemporal Thermal Control Effects on Thermal Grill Illusion. *Sensors* 23, 1 (2022), 414.

Donald A Simone, Thomas K Baumann, and Robert H LaMotte. 1989. Dose-dependent pain and mechanical hyperalgesia in humans after intradermal injection of capsaicin. *Pain* 38, 1 (1989), 99–107.

Matthias Staib, Giuseppe Castegnetti, and Dominik R Bach. 2015. Optimising a model-based approach to inferring fear learning from skin conductance responses. *Journal of neuroscience methods* 255 (2015), 131–138.

Joseph C Stevens. 2013. Thermal sensibility. In *The psychology of touch*. Psychology Press, 73–102.

Joseph C Stevens and Janet E Hooper. 1982. How skin and object temperature influence touch sensation. *Perception & psychophysics* 32 (1982), 282–285.

Yudai Tanaka, Alan Shen, Andy Kong, and Pedro Lopes. 2023. Full-hand Electro-Tactile Feedback without Obstructing Palmar Side of Hand. In *Proceedings of the 2023 CHI Conference on Human Factors in Computing Systems*. 1–15.

Marieke van Dooren, Joris H Janssen, et al. 2012. Emotional sweating across the body: Comparing 16 different skin conductance measurement locations. *Physiology & behavior* 106, 2 (2012), 298–304.

Yishan Wang, Ralf Wunderlich, and Stefan Heinen. 2013. Design and evaluation of a novel wireless reconstructed 3-lead ECG monitoring system. In *2013 IEEE Biomedical Circuits and Systems Conference (BioCAS)*. IEEE, 362–365.

Peter Weir, Christian Sandor, Matt Swoboda, Thanh Nguyen, Ulrich Eck, Gerhard Reitmayr, and Arindam Dey. 2012. BurnAR: Feel the heat. In *2012 IEEE International Symposium on Mixed and Augmented Reality (ISMAR)*. IEEE, 331–332.

Graham Wilson, Martin Halvey, Stephen A Brewster, and Stephen A Hughes. 2011. Some like it hot: thermal feedback for mobile devices. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*. 2555–2564.

Bob G Witmer and Michael J Singer. 1998. Measuring presence in virtual environments: A presence questionnaire. *Presence* 7, 3 (1998), 225–240.

Jacob O Wobbrock, Leah Findlater, Darren Gergle, and James J Higgins. 2011. The aligned rank transform for nonparametric factorial analyses using only anova procedures. In *Proceedings of the SIGCHI conference on human factors in computing systems*. 143–146.

Kening Zhu, Taizhou Chen, Feng Han, and Yi-Shiun Wu. 2019a. HapTwist: creating interactive haptic proxies in virtual reality using low-cost twistable artefacts. In *Proc of CHI'19*. ACM, 693.

Kening Zhu, Simon Perrault, Taizhou Chen, Shaoyu Cai, and Roshan Lalintha Peiris. 2019b. A sense of ice and fire: Exploring thermal feedback with multiple thermoelectric-cooling elements on a smart ring. *International Journal of Human-Computer Studies* 130 (2019), 234–247.

Received 20 February 2007; revised 12 March 2009; accepted 5 June 2009