# ThermoVR: Exploring Integrated Thermal Haptic Feedback with Head Mounted Displays


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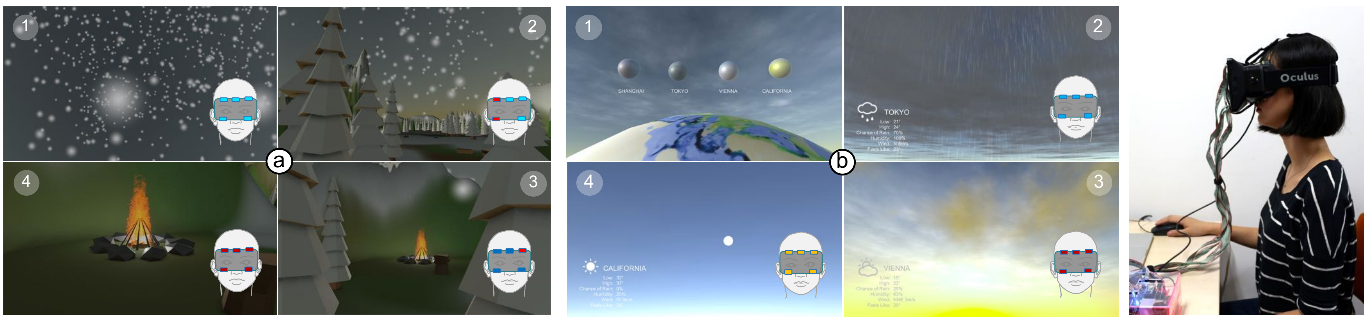


**Figure 1. ThermoVR applications (insets depict example stimulations) (a) "Where is my camp?": This game provides immersive or directional cues in the game as players try to locate their camp before it gets too cold. (a-1) Receiving immersive cold feedback in the winter night (a-2,3) Receiving directional cues as hot stimulations (a-4) Users immersively feel the warmth of the campfire; (b) "What is the weather?" Application provides thermally immersive weather feedback to let users explore the weather of different locations (b-1) Users can select the location to explore weather (b-2,3,4) Immersively explore the weather (c) User wearing the ThermoVR**


## ABSTRACT

Head Mounted Displays (HMDs) provide a promising opportunity for providing haptic feedback on the head for an enhanced immersive experience. In ThermoVR, we integrated five thermal feedback modules on the HMD to provide thermal feedback directly onto the user's face. We conducted evaluations with 15 participants using two approaches: Firstly, we provided simultaneously actuated thermal stimulations (hot and cold) as directional cues and evaluated the accuracy of recognition; secondly, we evaluated the overall immersive thermal experience that the users experience when provided with thermal feedback on the face. Results indicated that the recognition accuracy for cold stimuli were of approx. 89.5% accuracy while the accuracy for hot stimuli were 68.6%. Also, participants reported that they felt a higher level of immersion on the face when all modules were simultaneously stimulated (hot and cold). The presented applications demonstrate the ThermoVR's directional cueing and immersive experience.



## ACM Classification Keywords

H.5.2. Information Interfaces and Presentation (e.g. HCI): User Interfaces



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## Author Keywords

thermal display; thermal haptics; head mounted display


## INTRODUCTION

Head Mounted Displays (HMDs) have been on the rise as a display that lets users immerse themselves in the virtual world. Besides visual output, recent research demonstrated further enriching VR experience by adding the headset with various sensory outputs [11, 3]. This allows for improved immersion while keeping the device compact and centralized.

Haptic research, in particular, presented major driving forces toward this trend [4, 16]. De Jesus et al. [3] implemented spatial vibrotactile cues by embedding the headset with a set of vibrotactors around the head. GyroVR [5] enables simulating inertial with augmenting a flywheel on the headset. In this work, we explored adding a new dimension of feedback, thermal haptic feedback.

Thermal haptics has been independently explored on various locations, such as the wrist [6], palm [13], ear [1] for contexts such as thermal displays [9] and communication [10, 7]. As far as we know, this paper presents a first attempt at integrating an HMD with thermal haptics for spatial and immersive thermal experience.

## ThermoVR

We present ThermoVR, a thermal feedback-integrated HMD capable of presenting spatial and immersive cooling and warming sensations on users' face. By integrating five peltier modules on the facial interface of a HMD, this setup provides

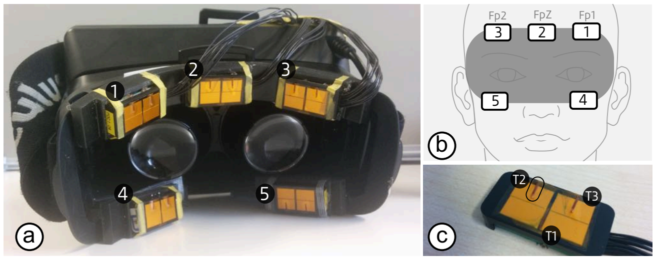


**Figure 2. (a) The Prototype System of ThermoVR that integrates five thermal modules (b) Contact locations of the thermal modules on the face (c) Close up of thermal module. T1, T2 and T3 are temperature sensors where T1 contacts the skin during use**

effective thermal feedback through direct contact between the thermal modules and the target locations on the face. Figure 1(a)-(c) demonstrates ThermoVR being used to provide thermal cues for a virtual reality game and applications.

Our main research objectives are two fold. Firstly, to identify the accuracy of perception of various thermal cues on the face (such as haptic and directional cues). Secondly, we aim to qualitatively explore the thermal immersion, i.e, if thermally stimulating the facial area can create a perception of immersive thermal experience.

## IMPLEMENTATION

The ThermoVR prototype is shown in Figure 2 (a). Five 2cm x 1.5cm thermal modules [12] were attached to the HMD using a custom 3D printed rig. Peltier modules are able to increase or decrease (heat or cool) the temperature with relatively high speeds. When ThermoVR is worn by a user, the peltier modules are in contact with the three locations (indicated in standard EEG 10-20 system[1] for standardization) on the forehead, and the area under each eye as depicted in Figure 2 (b). When the HMD is worn, these locations are in constant contact with the user's face. Each peltier module is driven by a full bridge motor controller (TA7291) and an Arduino Nano microcontroller[2] employing a closed loop PID (proportional, integral, derivative) temperature controller for accurate temperature control. The T1, T2, T3 temperature sensors (Figure 2 (c)) are used for the closed loop control. The controller is tuned to change the temperature at $\pm 3^0$C per second rate. The full setup in use is shown in Figure 1(c).

### Thermal Stimulations

ThermoVR provides two types of thermal stimuli: Hot and Cold. Starting from the skin temperature, a 'Hot' stimulation is provided by $+3^0$C and a 'Cold' stimulation is provided by a $-3^0$C within a one second for each. This typical rate of $3^0$C/s thermal stimulation is sufficient for a user to detect a thermal stimulation [8]. For the current scope of this work, if two or more thermal modules are actuated, they were actuated simultaneously. I.e, if multiple modules are actuated, the actuation starts and stops simultaneously. As an initial step towards thermal feedback on the face, we focus on single and simultaneous stimulations and do not explore temporal, i.e. stimulations that follow one after the other.

[1] https://www.trans-cranial.com/local/manuals/10_20_pos_man_v1_0_pdf.pdf

[2] https://www.arduino.cc/en/Main/ArduinoBoardNano

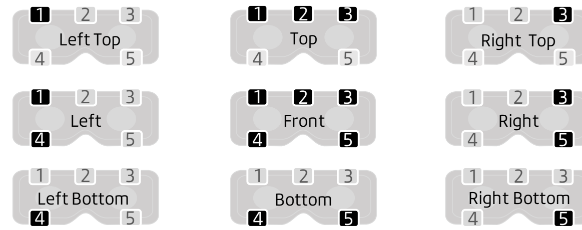


**Figure 3. Stimulation patterns for directional cues. The modules in black denote the thermally (hot or cold) stimulated modules**

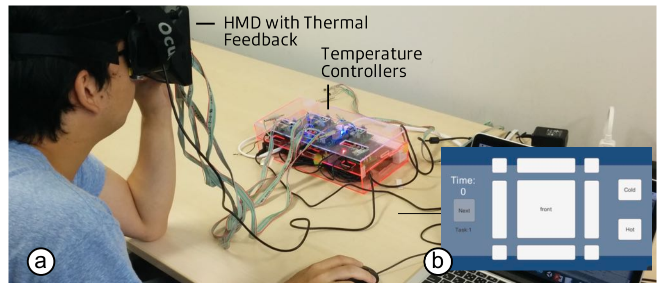


**Figure 4. The study setup (a)The evaluation setup for identifying thermal cues (b) Interface displayed on the HMD for selecting perceived cues during the evaluation**

### Stimulation Patterns

For providing directional cues, stimulation patterns were used as depicted in Figure 3. We identified 9 directional cues that are possible with the current setup: Left Up (LU), Up (U), Right Up (RU), Left (L), Front (F), Right (R), Left Down (LD), Down (D), Right Down (RD). For example to provide a 'Left' cue, modules 1 and 4 or for a 'Front' cue, all modules 1,2,3,4 and 5 would be actuated (thermal module numbers as depicted in Figure 2 (a)). Such patterns could be useful in providing 3 dimensional directional cues for an application such as navigation in a virtual reality game. For providing immersive effects, we actuated all the modules (similar to the 'Front' pattern) with hot or cold stimulations for 1s and maintained the temperature at the reached temperature for another 5s.

## EVALUATIONS

We conducted two evaluations: a quantitative study for the perception accuracy of directional cues through thermal stimulations on the face, and an informal qualitative study for identifying the thermal immersion experience of the system.

### Study 1: Perception Accuracy for Directional cues

The objective of this evaluation was to identify the accuracy of perception for directional cues that were provided as individual or multiple (simultaneous) thermal stimulations. Directional cues regularly in virtual reality and other haptic applications [3]. For this purpose, we provided two thermal levels (hot and cold) for each of the 9 directional cues repeated over five times. This resulted in 90 tasks which were randomized (9 directional cues x 2 thermal levels x 5 repetitions) during the

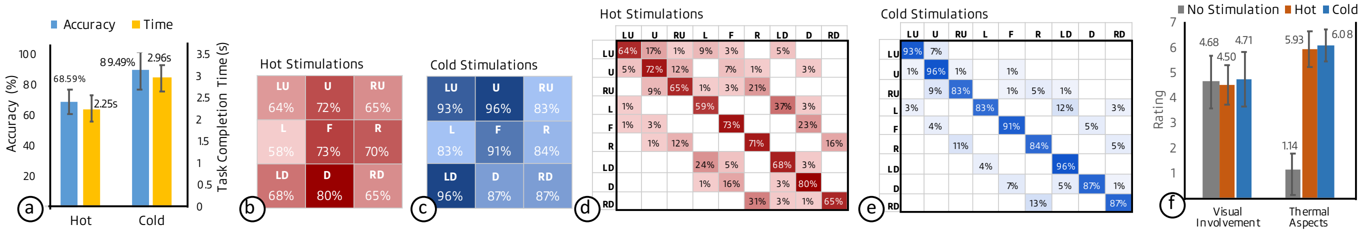


**Figure 5. Results: (L-Left, U-Up, D-Down, R-Right) (a) Perception accuracy and Average Task Completion Times for thermal cues: Hot and Cold cues; Heat map visualization of the accuracy of perception for individual cues for (b) hot and (c) cold stimulation; Confusion matrix for the (d) hot and (e) for cold stimulations (f) Qualitative study results**

study. A 15s period was provided between each task. During this period the system was brought back down to the starting skin temperature. Average starting skin temperature was 35.6$^0$C and the room temperature was 24$^0$C.

During the study, the participants wore the ThermoVR system (Figure 4 (a)) and the HMD displayed the user interface developed using Unity[3] depicted in Figure 4 (b). When users clicked 'Start', a thermal directional cue was provided. Next, users selected the perceived direction of the cue from the middle layout of the buttons, and selected if the cue was 'Hot' or 'Cold'. After completion of such a task, the 15s countdown timer was displayed, at the end of which, the users repeated the task with the next cue. Before each evaluation, the users were explained of the motivation, the system and were given 10 minutes to familiarize with the thermal cues and the interface The provided stimulation, perceived stimulation (direction, hot or cold) and cue selection time were recorded. The whole evaluation lasted approximately 40 minutes per participant.

### Study 2: Thermal Immersion Experience of ThermoVR

In this study, we explored the the thermal immersion by providing related visuals in the HMD under three conditions: hot stimulation, cold stimulation and no-stimulation. Two visuals were used: Figure 1 (b-4) as the visual that is related to the hot stimulation and, Figure 1 (b-2) for the cold. In the no-stimulation condition, same images were shown (one after the other in random order) without a thermal stimulation. All the conditions were repeated 5 times and the order was randomized. After each task, the participant answered a modified and related Sensory Factors questions of the Presence Questionnaire [14]: Q1) *How much did the visual aspects of the environment involve you?* Q2) *How much did the thermal aspects of the environment involve you?* All answers were marked from 0-7 with 7 being the 'most compelling'.

### Participants

Both evaluations were completed by 15 healthy participants (Average age 28, 9 males). All participants had previously tried or used HMDs. Each participant went through both evaluations.

## RESULTS

### Perception Accuracy for Directional cues

Figure 5(a) shows the overall accuracy for the perception of thermal directional cues. All thermal levels were perceived properly, i.e. hot stimuli were perceived as hot and cold were perceived as cold. It was observed that cold cues (M:89.49%, SD:8.03%) were perceived with higher accuracy than hot cues (M:68.59%, SD:12.62%). We noted that the average response time for cold cues (M: 2.25s) were faster in comparison to hot cues (M: 2.96s) (Figure 5(a)). Results were further analyzed using a paired t-test with $\alpha = 0.05$. Cold cues were significantly more accurate than Hot cues (t(14)=5.52, p<0.05). Regarding individual directional cues, all directions except three directions R, RU, and D also showed Cold cues being significantly more accurate. Figure 5(b)(c) indicates the perception accuracy for each cue in hot and cold conditions. Figure 5(d)(e) shows the confusion matrix that depicts which cues were misidentified.

### Thermal Immersion Experience

As shown in Figure 5(f), the study results of visual involvement, Q1, reported 4.68 (SD:0.99) in the no-stimulation condition and 4.5 (SD: 0.75) for the hot condition and , 4.71 (SD: 1.07) for the cold conditions. Q1 results were analyzed using Friedman test. There were no significant differences among the three conditions for the visual involvement ($\chi^2(2) = 0.844$, $p = 0.656$). The thermal aspects of the environment question, Q2, reported a 1.14 ($SD: 0.65$) for no-stimulation condition and 5.9 ($SD: 0.73$), 6.08 ($SD: 0.67$) respectively for the hot and cold conditions. A further analysis with Friedman test revealed that, there was a significant difference in thermal involvement ($\chi^2(2) = 22.769$, $p < 0.01$). Post hoc analysis with Wilcoxon signed-rank tests was further conducted with a Bonferroni correction applied. Median for the no-stimulation, hot and cold groups are 1, 6, 6 respectively. There is not significant difference between the hot and cold groups ($Z = -1.027$, $p = 0.305$). There is significant difference between the no-stimulation and hot groups ($Z = -3.315$, $p < 0.001$). Also, there is significant difference between the no-stimulation and cold groups ($Z = -3.306$, $p < 0.001$).

## DISCUSSION

### Results Discussion

Cold stimulations performed significantly better with above 83% accuracy for providing directional cues for head mounted displays. This is consistent with previous research that indicate that the skin is more sensitive to cold stimulations [2]. In addition, the heat stimulations on average were approximately 38$^0$C (+3$^0$C) which is above the neutral thermal zone (30-36$^0$C [8]). Above this temperature zone, the skin's thermal sensors adapt faster to repeated stimulations and can result in

[3] https://unity3d.com/

difficulty to identify the cues. Three participants reported that occasionally, the heat stimulations tendered to spread with one saying "felt like heat was spreading on the forehead, making it difficult to identify the cue".

Overall, the general participant feedback mentioned that the hot stimulations on the forehead were difficult to identify. However, for the cold stimulations, Up cue was perceived at 96% accuracy. According to the confusion matrix for the Hot stimulations (Figure 5(d)), all the cues on the forehead (Left Up, Up, Right Up) were heavily misidentified with each other and the Front cue. Most participants misidentified other cues as the Left Down cue (37%). One of the participants mentioned that the module's press against the skin made it "[feel] like a pinch" (during the hot cue) on the cheek and therefore was difficult to identify the hot cues. The cold stimulation confusion matrix (Figure 5(e)) indicated that the Right Up cue was the most difficult to understand as it was confused as Up, Front, Right, Left Down cues. However, these confusions were relatively low (1%-9%).

In the thermal immersion experience study (Figure 5(f)), participants rated visual involvement and thermal aspects for no-stimulation, hot and cold stimulations conditions. As seen through the results, the no-significance between the visual involvement (Q1) denotes that the shown visuals had a less impact on the perceived thermal stimulations. From the thermal aspects (Q2), it can be concluded that the significance between no stimulation and the hot/cold stimulation conditions indicates that the thermal stimulation significantly improved the immersion experience for the participant. Although visual aspects (especially colors) could influence thermal perception as recent research has indicated [15], the contrast in our results could be influenced by the direct facial thermal stimulation. I.e. high thermal sensitivity of the face combined with the co-located thermal feedback reported prominently high levels of thermal immersion leading to lower ratings for the visual condition. In addition, in the explanation phase (without visuals), most of the participants mentioned that the stimulations suddenly reminded them of different contexts: "It feels like the wind", "Feels like I am underwater" were some comments for the cold stimulation and "I feel like I opened the oven" was one of the comments for the hot stimulation. This has inspired us to develop few immersive applications.

### Limitations and Future Work

Introducing thermal stimulation as feedback introduces many variables for exploration such as starting temperatures, stimulation temperature ranges and temperature change rates. As a starting point, ThermoVR explores the $\pm 3^0$C from skin temperature at $3^0$C per second based on previous research [8] to identify the suitability of thermal feedback integration with HMDs. Based on the current results, we intend to explore further into these variables by investigating different temperature rates. In addition to these parameters, we wish to further investigate combination with other modalities such as vibrotactile in the future.

In the current setup we could not provide a 'Back' cue since the hair area of the head limits a good contact between the thermal modules and the skin. However, the back of the neck area is another possible location we will explore in the future for such purposes.

Some of the participants mentioned that the hard surface of the peltier modules was occasionally uncomfortable especially when during stimulations. In the next version of our prototypes, we aim to resolve this by introducing a thin soft material to transfer the thermal stimulation comfortably. In addition, two of the participants found the system to be rather heavy after prolonged use (more than 20min). We believe that this could be addressed by a more efficient design of our rig.

## APPLICATIONS

The presented applications are aimed to demonstrate the ThermoVR's directional cueing and immersive experience.

### Thermal Cues: Where's my camp?

'Where's my camp?' (Figure 1(a)) is a first-person point of view game. The environment is set in a thick forest, and the goal is for the players to find their camp before the night gets too cold. At the beginning of this game, the avatar appears in the forest, and the snowy weather makes it hard for users to directly see where the campfire is. The game provides a cold immersive thermal feedback where the temperature drops by $1^0$C every 30s. The 'heat' from the campfire is used as directional cues to find the camp. Every 15s, the user is able to request a directional cue to find the campfire. Using these cues, the player is tasked to find the camp before the feedback gets too cold.

### Thermal Immersion: What Is The Weather?

'What Is The Weather?' is an application (Figure 1(b)) we designed for enhancing virtual reality experience with thermal haptic feedback. In this application, by clicking the crystal balls in the menu scene, users can unfold specific weather information of corresponding places. A main feature of our system is that it provides not only the details of real-time weather information over the world, but also real feeling of temperature through the ThermoVR. Due to safety reasons (thermal pain threshold: approx $15^0$C and $45^0$C for cold and hot [8]) and limitations of the current prototype, the temperature range that is displayed are from 24-$40^0$C.

## CONCLUSION

ThermoVR describes a first attempt to integrate thermal feedback with HMDs. The system integrates five thermal modules that provide thermal stimulations directly onto the user's face. The evaluations conducted identified that Cold stimulations were perceived significantly better in providing directional cues. In addition, users found the system to be thermally immersive when all modules were activated with hot and cold stimulations.


## ACKNOWLEDGEMENTS

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