ThermoQuest - A Wearable Head Mounted Display to Augment Realities with Thermal Feedback

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Fig. 1. Prototype of the ThermoQuest system worn by a user experiencing cold and hot immersive virtual environments.

We present ThermoQuest, a self-contained wearable head-mounted display system for enhancing Virtual Reality experiences with temperature feedback. It's constructed with commodity hardware elements, featuring 6 Peltier elements on the rim of the headset touching the users face. We explain the design and implementation of an affordable wearable thermal VR prototype build with commodity hardware. In a user study with 15 participants, we show evidence for a significant difference in reported presence in VR between thermal VR and control conditions ($p > 0.017$) in a counterbalanced experimental setup. We end with a discussion and use cases of the presented VR prototype and similar systems.

CCS Concepts: • **Human-centered computing** → **Virtual reality**; **Interaction devices**.

Additional Key Words and Phrases: Multimodal Interfaces, Thermal Feedback, Virtual Reality

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1 INTRODUCTION

As governments and healthcare experts around the world call for changing lifestyle in response to the Covid-19 pandemic, the development and usage of remote communication and touchless technologies are rapidly becoming an essential part of the "new normal". At the same time, the absence of touch and physical contact highlights their critical importance in human life from school to hospital to care facilities. The struggle of deafblind individuals who rely on touch alone for communication especially sheds light on how critical this sense is in human communication, since they are unable to take advantage of the conventional auditory and visual telepresence technologies even as their usage is promoted under stay-at-home measures.

In our research, we are working on technologies to use feedback to the human somatosensory subsystem (i.e. pressure, temperature, texture, pain and body position) to encode, model and deliver information from computing systems in a minimally obtrusive way. In this paper we focus on thermal perception, equipping a commodity, wearable VR headset with affordable Peltier elements to provide thermal feedback.

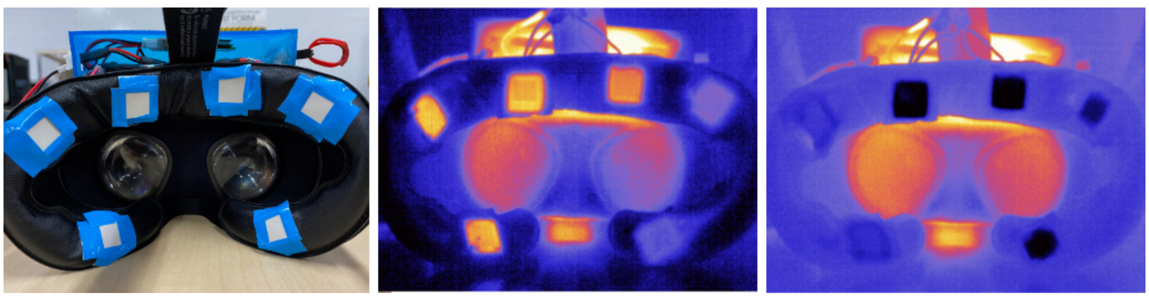

Fig. 2. Prototype of the virtual reality headset with 6 embedded Peltier elements (left) showing the thermal preview of hot actuation (middle) and cold actuation (right).

Our contributions are as follows:

- We present the design and implementation of an affordable, wearable thermal VR HMD prototype built with commodity hardware.
- We show evidence for a significant difference in reported presence in VR between thermal VR and controll conditions ($p > 0.017$) in a counterbalanced experimental setup with 15 participants.
- We end with a discussion and use cases of the presented VR prototype and similar systems.

2 RELATED WORK

Somatosensory feedback over pressure, tactile and thermal actuators is often used as an additional output channel in human computer interaction, from simulating different materials, over thermal notifications, navigation scenarios to increase presence in virtual reality environments [2, 5, 8, 14–18, 20]. For brevity, we will focus on thermal feedback related to human computer interaction and the enhancement of mixed/virtual reality applications.

Nakashige et al. presented an early work augmenting a computer mouse to enhance digital media with temperature information [8]. There are several continuations of this work, enhancing game controllers and mobile phones with thermal interactions, adding situational awareness or simple hot/cold notifications to applications [7, 19]. Also form factors evolved from interaction devices and peripherals to wearables. Peiris et al. present a bracelet with thermal feedback, evaluating perception thresholds and application cases [9]. Moving away from notifications, immersion and situational awareness, Tewell et al. explore the use of thermal feedback also for navigation tasks [16].

Presence and immersion evaluations in virtual environments are subjective and usually recorded over questionnaires. Although there is an ongoing discussion about validity and effectiveness, thermal (and other somatosensory) feedback has been shown to increase immersion [3, 4, 6, 11, 12, 14, 15, 17, 18]. Ranashinghe et al. use additional hardware setups, focusing on thermal actuation on the neck, throat and behind the ear to increase immersion simulating wind and temperature [13]. These works often apply extensive hardware setups in larger lab environments.

Close to our work, Peiris et al. present ThermoVR, a HMD connected to a computer, using some five thermal feedback prototype modules to provide hot/cold feedback on the user's face [10]. Chen et al. also present some thermal design patterns for the same type of thermal feedback prototypes [1]. Yet, these systems use thermal feedback prototypes from a specific producer. These elements are not readily available for other researchers and DIY makers. Compared to this our prototype uses off-the-shelf products and is easy to assemble for researchers and enthusiasts. We use the works as basis for our feedback design, combining the 6 actuators in 3 channels (left, front, right).

To the best of our knowledge, ThermoQuest is the first fully wearable HMD with thermal feedback using affordable commodity elements. We are also unaware of any research evaluating thermal feedback in standalone VR headsets.

3 IMPLEMENTATION

The device is designed to fit the standard Oculus Quest HMD. Peltier elements were mounted into the removable foam face interface of the HMD. In total we used 6 elements, 15x15mm in size, rated at 2A 3.7V max. 6 elements are split into 3 channels: front (2 on the forehead), left and right (1 on temple and 1 on cheek). Each of 3 groups is controlled with an Allegro A3909 H-bridge chip, allowing us to pass current through the element in either direction, providing both cold and hot sensations on the same element. Each channel is powered through a PTC fuse for safety reasons.

The feedback module is controlled by an esp32 module, acting as a Wifi Access Point (AP) with Oculus connecting to this AP directly and communicating with the thermal device over WiFi. The device is powered from a 3.7v lithium-polymer battery with another PTC fuse on the power line.

The thermal sensations were provided in repetitive pulses. For hot sensations the element was powered on for 4 seconds followed by a 6 second cool down period. For cold sensations the elements were powered on for 5 seconds and powered off for another 5 seconds. Since we did not use any cooling mechanism on the peltier elements we could not power them continuously in order to avoid overheating.

Fig. 3. Pictures from inside the VR environment showing thermally charged objects that generate cold and hot sensations. Proximity to the waterfall triggers cold feedback, while the fire produces heat.

4 METHODOLOGY

A mobile VR headset prototype capable of providing thermal feedback in short repeating pulses was created for the experiment. Additionally, an immersive virtual environment was created with Unreal Engine to facilitate the thermal feedback interactions. The experiment featured three controlled conditions. To account for the possible ordering effects, the trials between participants followed a counterbalanced order. With this study we have captured quantitative data for the self-estimated presence in virtual environment using Witmer & Singer Presence Questionnaire (version 3.0). Qualitative feedback regarding the user experience was gathered as well. The experiment was conducted in a closed room with ambient temperature set at a constant level for all the participants. The procedure of the study was as follows:

1) Informed Consent. The participant was welcomed to the study location and and was informed about the details of the procedure of the study. Then, we explained the consent form and the data protection policy which the participants were asked to read and sign.

2) Personal Data Gathering. The participant then was asked to indicate their age and sex on the digital spreadsheet.

3) Experiencing Virtual Environment. The person conducting the experiment would then select an appropriate trial category for the participant and hand over the virtual reality HMD to the participant. The experience was set up to start after a 30 second delay, providing just enough time for the user to put the headset on and get comfortable. Virtual environment featured six scenes spread across three virtual worlds. Each scene has lasted 30 seconds after which the users virtual avatar would be teleported to the new view location. Thermal feedback was provided passively as an ambient environmental cue and the user was not able to affect it in any way. Two virtual scenes were neutral and featured no thermal feedback, two scenes contained objects as temperature sources (waterfall and fireplace), and two were thematically charged with temperature (winter environment and desert environment). The user was only equipped with the VR headset and could interact with the environment though rotation and small motion based on the physical position of the headset. No other interactions were provided.

4) Filling the Questionnaire. After going through the virtual experience, the participant had filled in the 32 questions of Witmer & Singer Presence Questionnaire (version 3.0), rated on a Likert scale from 1 to 7. Additionally, they were provided a secondary questionnaire where they were asked to fill in a free form the answers to the following questions:

- What supported your feeling of immersion in the VR scene?
- What reduced your feeling of immersion in the VR scene?
- What did you like about the presented feedback?
- What did you NOT like about the presented feedback?

5) Trials with Different Conditions. The experiment was then repeated for the remaining two conditions. For example, if the first trial was without any feedback (A), the consecutive trial would contain normal thermal feedback (B) and then reversed thermal feedback (C), repeating steps (3) and (4) for each one.

5) Semi-structured Interview. After all three trials were complete, the participant was asked to elaborate on their answers to the questions in section (4) and to share their general opinion and comments regarding the overall experience, if they

Fig. 4. User wearing the prototype of mobile head-mounted display with thermal feedback.

had anything to add.

5 RESULTS

A total of 15 participants (6 male, 9 female, age 21 to 30) have taken part in the experiment.

Initial analysis of the data conducted with a Friedman test had shown that there was a statistically significant difference in the reported sense of presence depending on the type of feedback presented to the users while in VR, $x^2 = 19.600$, $p = 0.000055$. Post hoc analysis with Wilcoxon signed-rank tests was conducted with a Bonferroni correction applied, resulting in a significance level set at $p < 0.017$. Median presence evaluation levels for the no feedback, normal expected feedback and reversed unexpected feedback were 131 (104 to 174, std = 17.578), 149 (129 to 163, std = 18.019) and 119 (106 to 128, std = 20.786), respectively. There were significant differences between all three trial category pairs: no feedback and normal feedback trials ($Z = -3.238$, $p = 0.001204$), no feedback and reversed thermal feedback ($Z = -2.473$, $p = 0.013394$), normal feedback and reversed feedback ($Z = -3.409$, $p = 0.000652$).

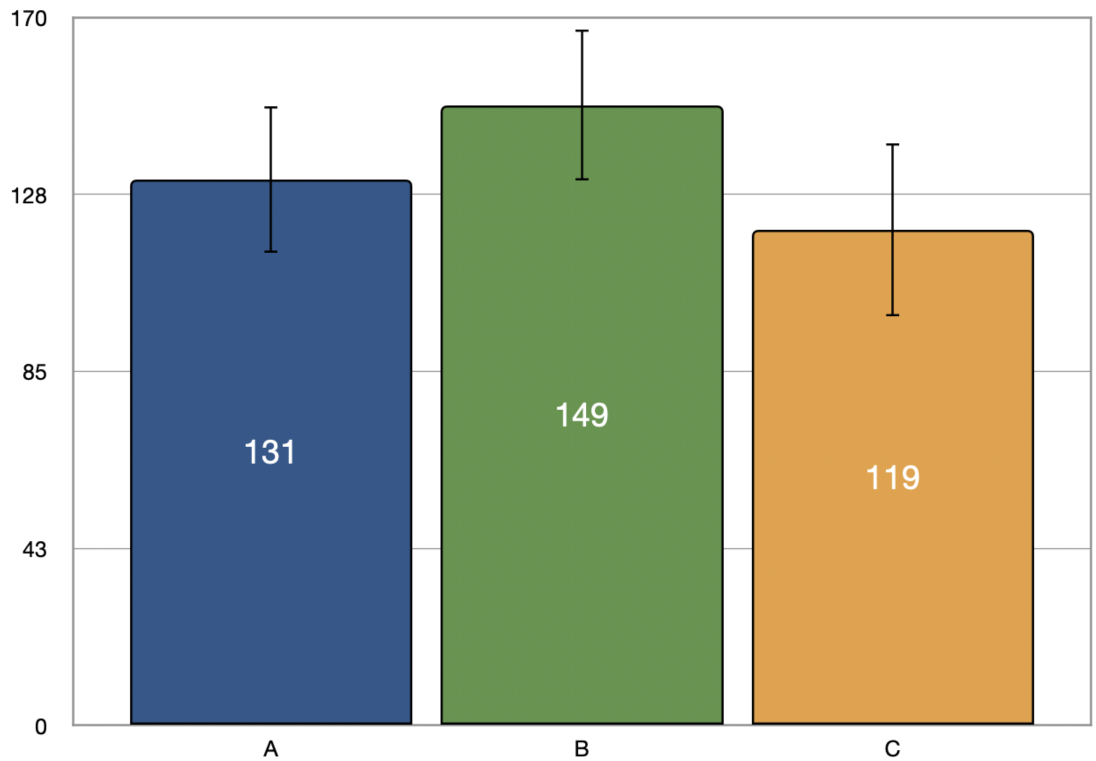

Fig. 5. Median presence scores with standard deviations for 3 experimental conditions: A - no feedback, B - expected feedback, C - unexpected feedback.

6 DISCUSSION

Statistical analysis of the W&S questionnaire suggests that regular temperature feedback was effective in increasing the sense of presence in virtual environment, while reversed thermal had feedback decreased that sense. Many users have reported that audio played a significant part in evaluating the experience. As such, one participant had said that "I can feel objects surrounding me by listening to the background sound". Some have also mentioned the aesthetic qualities of the environment and reported that the polygonal nature of the chosen style had a minor negative impact on their sense of immersion, due to being "not realistic". Others, however, enjoyed the look of the environment, claiming that "I like the sound and visual design". Some participants felt limited by the lack of interactions with the environment. As for the temperature, the following reactions were observed. Two users have reported a sense of inconsistency when perceiving "intense" warm feedback from a visually small object (fireplace). One participant had said that when feeling normal thermal feedback on the face, he felt more engaged with the experience and wished that it would be possible to interact with the environment to feel the feedback on different parts of the body, specifically hands. When asked about the unexpected feedback, the majority of participants have described it as "weird" and "uncomfortable". One had claimed that "mismatching feedback doesn't make sense and doesn't add anything positive to the experience".

Several participants have exhibited an elevated sense of alertness and the desire to "figure out what is wrong" that lasted for several seconds, before they could realize that it's just an opposite temperature setting and nothing else in the environment had changed. One explained that such disconnect "feels like it's a cue for me to look at things". This suggests a possible intentional use of the unexpected thermal feedback technique as a way of temporarily inducing the sense of unease in the experience. Several users felt that pulsating feedback, chosen due to technical limitations, was limiting and wished to feed more "even" sensation; two have expressed the desire to either have more touch-points or have the feedback provided by a consistent mechanism, where individual thermal stimuli could not be distinguished. Many users have reported that after going through trials with both normal feedback and without feedback they felt "relaxed and very peaceful", confirming the assumption of potentially using such type of experience for light recreation and alleviating stress. One user had expressed the feeling of stronger feedback intensity when switching between the polar opposite scenes from warm to cold, saying "when the situation changed from the desert to snow, the difference of the temperature is too big, so I feel even colder". Two have described the feedback as "too strong", to the point where they felt even the thermal stimuli aligned with the virtual scene have distracted them the experience. During the interview two participants have mentioned that they actually have felt more immersed with the environment featuring unexpected feedback, either because it was consistent with their life experience (such as feeling the comforting warmth in the winter), or because they felt compelled to create a sensible explanation (such as comparing warm feedback from waterfall to the heat of the hot spring). Overwhelmingly, the version of the experience featuring regular thermal feedback was referred to as "the best", with participant saying that "feedback matching the scene has a great positive impact on the immersion", "the sound and the heat changes supported my feeling" and "thermal feedback is cool".

7 CONCLUSIONS AND FUTURE WORK

The results of the experiment seem to support the original hypothesis that addition of the thermal feedback to the VR experience would elevate the sense of presence and immersion, while the use of an "unexpected" feedback would help achieve the opposite result. Additionally, it suggests potential use of the "unexpected" feedback as an intentional design technique aimed at making the user either confused, uncomfortable and more alert for the upcoming event in the scene. Lastly, it provides several directions for the future hardware design, suggesting to change the stimuli distribution to a more continuous range and to integrate a cooling module, so that the feedback could be used with a faster onset and be consistent without pulsations.

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