Ethermal – Lightweight Thermal Feedback for VR Games

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***Abstract*—One of the major benefits of virtual reality (VR) lies in its ability to create a heightened sense of presence through visual and auditory modalities. To further enhance presence, research has investigated various ways to allow for tactile perception of objects in virtual environments. Among the different dimensions of tactile perception, thermal feedback is less explored, especially in the context of games which renders many existing approaches impractical due to their interference with game controllers. In this paper, we present *Ethermal* – a thermal feedback solution – designed to a) convey temperature information through the player's hands while b) still permitting the use of standard VR game controllers. An evaluation with 10 players, using the device in a custom-made virtual environment to demonstrate different use cases of thermal feedback, suggests that an increased feel of general and spatial presence and experienced realism can be achieved even with simple technological means.**

***Index Terms*—virtual reality, games, thermal feedback, user study, presence**

I. Introduction

One of the major benefits of virtual reality (VR) lies in its ability to offer increased presence. Presence as defined by Lee [1] is the *psychological state in which virtual objects are experienced as actual objects in either sensory or no sensory ways*, also often referred to as *the sense of being there* [2], [3]. Sometimes, a distinction between three types of presence is made (cf. [1], [4]). Physical presence (or spatial presence) describes the feeling that virtual objects behave like real ones and that the virtual world feels rather like a "place" than a picture or video. Social presence, captures the feeling that one is interacting with real people instead of virtual characters. Lastly, self presence encapsulates the impression to be one's own virtual representation.

Among these, this paper focuses on physical presence. While much work has been devoted to making virtual objects look and sound believable, tactile feedback is comparatively less developed. Okamoto et al. [5] identified five dimensions of tactile perception of humans based on a literature review of studies covering tactile dimensionality of physical properties of materials. These dimensions are: macro and fine roughness, warmness (warm/cold), hardness (hard/soft), and friction (moist/dry and sticky/slippery). While several approaches for haptic feedback for texture recognition have been proposed (e.g., [6]–[8]) the other dimensions have received less attention. In this work, we focus on offering feedback on warmness.

With the ability to provide thermal feedback we see a variety of applications within VR games to enhance player experience. In games such as *Skyrim VR* [9] the player could feel the heat of a fireball spell or feel the cold of *Skyrim's* climate when stepping outside from a cozy inn. In the VR game *Half-Life: Alyx* [10], the player could be able to feel the cold metal of the crowbar or the warmth of a cup of coffee. In shooting games such as *Pavlov VR* [11] players could be able to feel the barrel of their gun heating up from repeated firing.

Existing approaches to thermal feedback are, however, often too technologically complex, too clumsy, or are not designed to be used in conjunction with a controller to be applicable for VR games. Although HMDs like the Oculus Quest 1 and 2 offer hand tracking as a replacement for controllers, only a limited number of games uses this feature. One of the main advantages that controllers have over hand tracking is the addition of buttons and thumbsticks. The thumbstick that the player can use to walk around in the virtual world becomes especially important when the digital world exceeds the boundaries of the user's physical play space.

In this paper, we thus present *Ethermal* – thermal feedback gloves that were designed specifically for use with games. Our aim was to create a cheap and easy-to-assemble system only using off-the-shelf technology while still offering satisfying thermal feedback and remaining versatile in its use. To assess *Ethermal* we conducted a user study with 10 participants using the gloves within a custom-made virtual environment to showcase different ways of thermal feedback. Results show that the system led to an increased feeling of presence, despite its low-key approach. In summary, our contributions are:

- A design for a low-cost thermal feedback device, specifically for use together with VR controllers
- An evaluation of the device, indicating an increased sense of presence despite being technologically simple
- A discussion of the potential use cases of thermal feedback in game-like settings and potential downsides

II. Related Work

Studies have shown that the use of haptic feedback in VR experiences can increase presence. Lee et al. [12] found that *haptic feedback was a higher contributing factor to the improvement in performance and presence than image resolution and stereoscopy*. This was reinforced by the studies of Kim et al. [13] and Kreimeier et al. [14] which both indicated that vibrotactile feedback provided greater presence than only hand tracking without any kind of haptic feedback. To further enhance presence, a substantial number of solutions has been suggested for force and texture perception in VR (e.g., [8], [15], [16]). Although work on thermal feedback solutions in VR is increasing, there is still ample room for development in this area. Generally, these can be divided into on-body solutions (i.e. wearables) and solutions which use external devices placed in a room. Belonging to the latter are, for instance, *encounter type* haptic approaches [17], where a grounded robotic arm is used to place a physical proxy at the location of a virtual object. Such solutions, however, require the setup and placement of additional devices in the room which makes them impractical for playing games at home. As such and to keep the review concise we focus on wearable solutions in the following.

Cai et al. [18] proposed *ThermAirGlove*, a glove that uses inflatable airbags on the fingers to provide thermal feedback. The evaluation of *ThermAirGlove* showed that it can support material identification and significantly improves presence compared to a situation without thermal feedback. Although they have shown that it is possible to enhance presence using thermal feedback, their design was only focused on hand tracking and did not incorporate controllers. The glove also needed to be tethered to a large air chamber, making it impractical for consumer VR. Kim et al. [19] presented a glove that combines motion sensing with thermal feedback. The glove contains four thermoelectric devices attached to the palm and three fingers. Our system, in contrast, is envisioned to be used with existing controllers and thus the thermal feedback elements should not interfere with grabbing the controller. Another wearable system capable of providing thermal feedback in VR is *Hapballoon* [20], a device worn on the fingertips of the index finger and thumb and providing force, warmth, and vibration feedback. The device can inflate two balloons to provide force feedback and uses a Peltier element for temperature feedback. However, the required air compressor and the fact that it cannot be used with controllers makes it impractical for most VR games. No evaluation of the device has been reported. *Tegway* showcased a VR headset able to provide thermal feedback on the forehead [21]. Likewise, Peiris et al. [22] integrated multiple Peltier elements directly in the VR headset, concluding that the hot/cold stimulations provided by it improved the immersive experience. While temperature stimulation on the forehead is well suited for experiencing phenomenons such as the weather and proximity to fire, it is not the best placement for enhancing material perception. Günther et al. [23] presented another thermal feedback system to be used in conjunction with VR, where temperature sensations are created by liquids flowing through tubes attached to different body parts. Ragozin et al. [24] developed a VR horror game, making use of a custom-made wearable system consisting of several modules and which exhibits cold and warm sensations using multiple Peltier elements. They anecdotally report positive user experience, especially with respect to cold sensations. Soucy et al. [25], in contrast, attached a Peltier element and a heat sink to a wrist-band. A separate communication module was attached to the users forearm. Niijima et al. [26] used Peltier elements attached to a ring to provide variable thermal feedback depending on the parts of the body touching the device. This means that the ring has to be actively touched by the user which may be distracting in a gaming context.

These wearables show the potential of thermal feedback in VR application scenarios and for improving the sense of presence but are either technologically involved or were not designed with the concurrent use of game controllers in mind.

III. ETHERMAL

With a focus on enhancing presence in VR gaming environments through thermal feedback the design should satisfy two main requirements. First, for the approach to be useful for current VR games, it should not affect the use and features of a standard VR controller (i.e. spatial tracking of the controllers in six degrees of freedom; access to thumb buttons, joystick, index finger trigger, and "grab" button/capacitive touch sensor(s); wireless connectivity; and comfortable shape). Second, the design should offer thermal feedback on the hands, as our goal is to allow users to feel the temperature of the item that they are holding or interacting with.

To satisfy these requirements, we considered three approaches. First, a completely new controller could be developed that has thermal feedback build into it. However, this would cause high development effort and some headsets such as the ones from *Oculus* can only track their own controllers. Secondly, we considered to develop a cover for current controllers. This way, the users can keep using their own controllers. However, the controller would become bulkier, as all the components have to be attached to it. As such we focused on a glove-like wearable device. With this approach, the majority of the electronics can be positioned on the back of the hand. This also makes it independent from a specific VR controller. Moreover, in cases where the VR headset supports hand tracking it could also be used without a controller.

In terms of player experience, the gloves were developed with three main ways to enhance presence and game experience in VR games in mind:

❶ Inviting exploration of the virtual world by simulating thermal changes in the environment

❷ Enhancing interactions by acting upon handheld items

❸ Supporting novel game interactions that would not be possible without thermal feedback

To appropriately place the thermal feedback element, we experimented with different locations. Initially, the glove should provide feedback on the fingertips of the ring and little finger as well as the palm of the hand. Although the ring and little finger are not used for button input with the *Oculus Touch* or *HTC Vive* controllers, they are considered by the *Valve* index controllers[1] as those track all individual fingers. Having

[1]https://store.steampowered.com/app/1059550/Valve_Index_Controllers/ Accessed: May, 2022

Fig. 1: *Ethermal* Gloves Prototype

a thermoelectric element on the fingertips would thus interfere with this for which reason we have not pursued this idea further. Informal tests by the researchers also showed that placing the elements on the wrist felt a bit too sensitive and thus caused an unpleasant feeling. Moreover, the feedback on the wrist also did not match the feeling of holding a cold or warm object as was the case when placing the thermal element on the back of the hand. Finally, we opted for the base of the thumb (i.e. thenar eminence) as location for the thermal element as it also has high thermal sensitivity [27], registering temperature changes from 0.20°C for warming and 0.11°C for cooling [28]. The location also provided a good feeling of holding a hot or cold object without interfering with the controller, and was shown to be the most sensitive in terms of the number of stimuli detected compared to locations on the fingertips, the forearm, and upper arm [28], [29].

A. Technical Implementation

The final prototype is shown in Figure 1. For thermal feedback we use thermoelectric Peltier elements. Since the heat flow reverses when the current is flipped, Peltier elements can be used for both cooling and heating [30]. The Peltier element was positioned at the thenar eminence on the palmar side of each hand. It is held to the hand by a 3D printed frame and elastic straps that can be adjusted to fit different hand sizes. Each glove contains one 15mm $\times$ 30mm Peltier element with a heatsink of the same size which is driven by its own electronic speed controller (ESC) for individual control. The used Peltier elements each have a maximum current draw of 1.4A at 5V. ESCs are commonly used in remote controlled cars as they allow to easily control brushed motors that should be able to modulate their speed and spin forwards and backwards. In our case, forwards and backwards corresponds to heating up and cooling down. Both ESCs are powered by the same 5V/3A phone charger and are connected to an Arduino Uno which, in turn, is connected to the PC. The wires connecting the gloves with the ESCs are three meters long to not constrain the movement of the user.

The open-loop system can provide either a hot or a cold pulse to either hand. When the Arduino receives a signal to activate cold or hot for the left or right hand the corresponding function is triggered. The ESCs can be controlled through 50Hz pulse-width modulation signals, with pulse widths ranging from 1,000 to 2,000 microseconds. In this case, 2,000 means maximum cold, 1,500 means off, and 1,000 means maximum hot. The cold pulse lasts 3.1 seconds and lowers the temperature by approximately 2°C, starting off at full power and then dropping steeply before fading out to simulate the thermal response when touching a cold object [28]. The hot pulse raises the temperature by approximately 2°C and lasts for a shorter two seconds to allow for a three second cooldown period to prevent overheating. While a pulse is active, it can not be overwritten by the same pulse. However, it can be overwritten by the opposite pulse.

IV. Evaluation

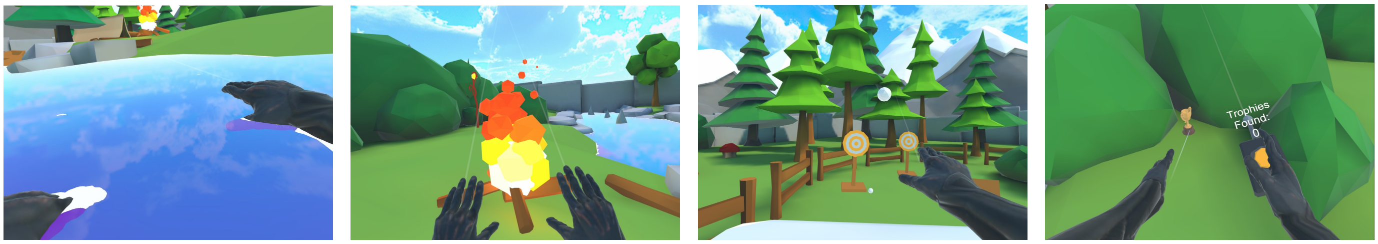
To evaluate the prototype we conducted a user study, approved by the university's ethics review board, to explore 1) if the prototype is able to significantly increase presence; 2) if people prefer thermal feedback over visual cues; 3) what kind of interactions are preferred; 4) for which (game) interactions they would like to use it for; and 5) if people liked the location of the thermal feedback. For that purpose, a dedicated virtual environment supporting two conditions was created:

Thermal: In the thermal condition, the environment included four different objects providing warm and cold feedback. Three supported environmental cues while one was directly integrated into a game mechanic.

Non-Thermal: In the non-thermal condition, the environmental objects did not provide any thermal feedback while for the game-related one color cues were used instead.

A. Virtual Environment

The virtual environment was created with the *Unity 3D Engine* [31] and uses the *OpenXR Plugin* [32] to accommodate a wide variety of HMDs and was influenced by the ones used by Peiris et al. [22] and Soucy et al. [25] in their studies. Visually we opted for a low-poly style and ensured that it is able to run on a laptop at 72 frames per second to alleviate cybersickness which is more likely to occur with low framerates (see, e.g., [33]). To populate the environment, several free packages from the *Unity Asset Store* were used. The environment was designed for a room-scale setup. The player could move through the environment using their legs as well as the thumbstick on the left *Oculus Touch* controller and was able to look around by moving their head or using the thumbstick on the right *Oculus Touch* controller. Sounds that matched the player's surroundings were played through the HMD speakers. Players could use either hand to pick up objects by pressing the grip button with their middle finger and could interact with specific objects (detailed below) using the trigger button located at their index fingers. Interactions did not have vibrotactile feedback. In the thermal condition, the environment contained four different interactable objects



(a) A river emitting cold thermal feedback when wading through it.

(b) A campfire emitting warmth in near proximity.

(c) Snowballs can be picked up and thrown and provide cold feedback while being held.

(d) *Hot & Cold* game with the player holding the remote control-like *Trophy Finder*.

Fig. 2: Objects which offer thermal feedback within the virtual environment.

that provided thermal feedback aimed at evaluating *Ethermal's* potential for enhancing player experience in the three ways (❶,❷,❸) outlined in Section III. These elements were: a river, a campfire, snowballs, and a remote-like device that could be used for a *Hot & Cold* game.

River ❶: The river (cf. Figure 2a) is the first thermal feedback interaction that the player encounters. Once the player enters the river, cold feedback is provided by the glove.
Campfire ❶: When a player is close to the campfire (see Figure 2b) the device becomes warm to simulate the act of warming hands at a fire.
Snowballs ❷: Unlike the previous two objects, the snowballs (cf. Figure 2c) can be picked up by the player. Once grabbed, the glove becomes colder to simulate the cold snow. There are a total of six snowballs that can be thrown at three targets at different distances.
Hot & Cold Game ❸: The *Hot & Cold* game was inspired by the classic children game of the same name, where the players have to find a hidden object and closeness is indicated through verbal feedback of *getting warmer* or *getting colder*. In our case the player has to find three trophies hidden around the map. To start the game, the player has to pick up the *Trophy Finder* – a remote control-like device – from a table. When the player pushes the button of the *Trophy Finder* (cf. Figure 2d), it calculates the distance to the active trophy, and leads the player towards it using thermal feedback. If the player moved away from the trophy, cold feedback is provided, otherwise warm feedback. When the player finds the trophy, it can be picked up and the next trophy is activated. The game ended when all three trophies were found. In the non-thermal condition, feedback was provided through colors. If a player was closer to the trophy compared to the last time they pressed the button, the button would turn red; if they were further away, the button would turn blue (the colors were chosen due to their common association with hot and cold). Both conditions used different locations for the trophies to counteract learning effects.

B. Measures

We collected post-experience interview data and subjective self-report measures using the system usability scale (SUS) and the Igroup Presence Questionnaire (IPQ):

Usability To assess the usability of the device in a VR gaming setting, the system usability scale (SUS) [34] was employed as a quick and established instrument being acknowledged to have excellent psychometric properties [35]. The SUS was administered for the thermal condition only.
Presence While various scales exist to measure presence we opted for the Igroup Presence Questionnaire (IPQ) [36] as it has a dedicated subscale for SPATIAL PRESENCE. Schwind et al. [37] also recommend the IPQ to measure presence as other questionnaires are either less reliable or take significantly longer to complete. Apart from SPATIAL PRESENCE, the IPQ contains two further subscales focused on INVOLVEMENT and EXPERIENCED REALISM. In particular, SPATIAL PRESENCE is defined – following [38] – as *the sense of being physically present in the VE*, INVOLVEMENT as *measuring the attention devoted to the VE and the involvement experienced*, and EXPERIENCED REALISM as *measuring the subjective experience of realism in the VE*. These subscales consist of four items each. Moreover, the IPQ contains one item which directly measures the general *sense of being there*. Each item is rated on a 7-point Likert scale which anchors vary from question to question.

C. Procedure

As HMD an *Oculus Quest 1* was used. It was connected via a USB 3.0 cable to a HP Zbook Studio G3 mobile workstation, containing a Nvidia Quadro M1000M GPU, Intel Core i7-6700HQ CPU, and 16GB of RAM. The virtual environment (see Section IV-A) was run at 72 frames per second (the highest supported framerate for the HMD) on the HP Zbook.

As the study was undertaken during the Covid-19 pandemic, several measures to protect the health of our participants were implemented. The researcher and participant preserved a distance of at least 1.5 meters between them and both wore a face mask. In addition, the rooms were well ventilated and the prototype, VR equipment, and surfaces were disinfected between participants. To keep travel time for the participants short the sessions were conducted in a dedicated room at the first author's home or at a room at the university.

First, the purpose and procedure of the study was explained, after which they were asked to carefully read and sign an informed consent form. The participant then filled in the first part of a questionnaire that covered demographic information and assessed how often they play 3D video games and how often they use VR technology. The latter two were captured on a 5-point scale ranging from 1 (never) to 5 (regularly). Afterwards, they were briefed on how to wear the thermal feedback devices and asked to put both the right and left one on. For comparability we requested participants to keep them on in both conditions as the wires may influence the presence score as they limit movement to some extent. The order of the conditions was kept fixed: first the non-thermal condition followed by the thermal condition.

The participant was then instructed to put on the HMD and pick up the *Oculus Touch* controllers. The researcher verified that the participant was wearing the HMD correctly and that they could see clearly. After explaining the controls, the participant was asked to look around using the thumbstick of the right *Oculus Touch* controller and then walk forward through the river using the other thumbstick. Once the other side was reached, the participant was told to warm up at the campfire and then continue along the path until spotting a table with six snowballs that could be picked up. These snowballs could be thrown at three targets at different ranges. After throwing all of them, the participant was instructed to pick up the *Trophy Finder* from the table to play the *Hold & Cold* game and the researcher explained how it can be used to find three trophies hidden in the map. Once the last trophy was found, the participant was asked to remove the HMD and fill in the second part of the questionnaire with the IPQ.

Subsequently, the participant was requested to put the HMD back on and perform the same interactions in the same order with thermal feedback enabled (and color feedback disabled). The interaction for the *Hot & Cold* game remained the same as well except that hot thermal feedback was given when being closer to the trophy than the last time the button was pressed and cold feedback when being further away. Once finished they were required to fill in the IPQ for a second time and evaluate the usability of the system using the SUS. Furthermore, they were asked if they experienced cybersickness on a 5-point scale (1 = never felt ill to 5 = felt ill all the time).

Lastly, a semi-structured interview took place. During the interview we inquired about which interactions had the best and worst implementation of thermal feedback and why. Afterwards, we collected their feedback on the other remaining interactions. In addition, we asked whether they preferred thermal feedback or visual cues for the *Hot & Cold* game and why, how they liked the location of the thermal feedback, if they felt something was missing, how they would use it if they would be game designers, and what kind of games they would want to use it for. After the interview concluded, we thanked the participant for their time and the devices were disinfected for the next participant.

D. Participants

Participants were invited through the social circle of the researchers and by advertising the study among student groups at the university of the first author. Participants were screened and selected based on if they fulfilled the following four criteria: (1) have adequate vision with or without the help of glasses or contact lenses, (2) be at least 18 years old, (3) be proficient in the English language, and (4) have experience with 3D video games (flatscreen or VR). Previous experience with VR was preferred but not required.

In total, 10 participants took part in the study of which nine were male and one female. Age ranged from 23 to 31 years with an average of 24 years. Out of the 10 participants one wore glasses and three wore contact lenses. With respect to frequency of play, answers ranged from 2 to 5 ($M = 4.00$, $SD = 1.25$). Participants rarely used virtual reality technology before, with responses between 1 and 3 ($M = 1.80$, $SD = 0.63$). Six of the participants indicated to never felt cybersick during the study (= 1), three responded with a 2. Only one participant, responding with a 4, was affected by cybersickness.

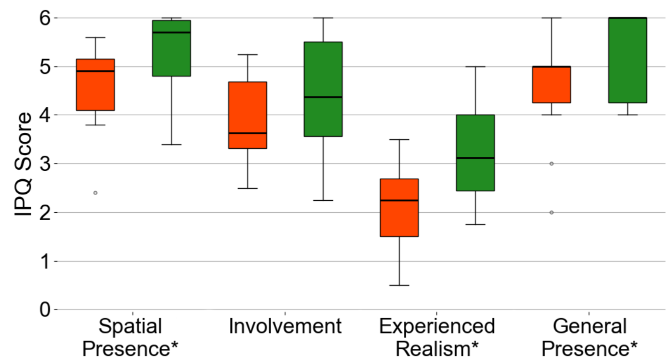


Fig. 3: Mean comparison of the IPQ ratings with (■) and without (■) thermal feedback. Error bars show standard error of mean. Thermal feedback scored significantly higher for SPATIAL PRESENCE, EXPERIENCED REALISM, and GENERAL PRESENCE with $^*p < .05$.

V. RESULTS

In the following we first present the quantitative results followed by the qualitative analysis of the interviews.

A. Presence and Usability

Results of the post-immersion IPQ are shown in Figure 3. Wilcoxon signed-rank tests were conducted to assess if the IPQ subscales were significantly different between the two conditions. Effect sizes to quantify the magnitude of group differences were calculated, following [39], as $r = z/\sqrt(N)$ where N is the number of observations (= 20). The test indicated that SPATIAL PRESENCE was significantly higher for the thermal condition ($Mdn = 5.70$, $IQR = 4.60-6.00$) than for the non-thermal condition ($Mdn = 4.90$, $IQR = 3.95-5.20$) with $Z = -2.816$, $p = .005$, $r = -0.630$. There was, however, no significant difference in INVOLVEMENT between the thermal ($Mdn = 4.38$, $IQR = 3.44 - 5.81$) and the non-thermal condition ($Mdn = 3.63$, $IQR = 3.25 - 4.81$)

with $Z = -1.602$, $p = .109$, $r = -0.358$. In case of EXPERIENCED REALISM, the thermal condition ($Mdn = 3.13$, $IQR = 2.25 - 4.25$) again scored significantly higher than the non-thermal condition ($Mdn = 2.25$, $IQR = 1.50 - 2.88$) with $Z = -2.530$, $p = .011$, $r = -0.566$. Likewise, a significant difference for GENERAL PRESENCE between the thermal ($Mdn = 6.00$, $IQR = 4.00 - 6.00$) and non-thermal condition ($Mdn = 5.00$, $IQR = 3.75 - 5.25$) was observed ($Z = -2.111$, $p = .035$, $r = -0.472$). Effect sizes showed moderate to large effects, following [39], in all four instances.

Usability was rated on average as "good" ($M = 80.25$, $SD = 9.96$) but also varied widely from 60 to 90, indicating "OK" to "excellent" usability following the adjective interpretation proposed by Bangor et al. [40].

B. Interviews

The audio recordings of the interviews were transcribed, after which a qualitative content analysis with inductive coding was used to analyse the replies to the open-ended interview questions on a per-question basis. Code generation started after an initial read through of the whole corpus. The analysis was performed by a single researcher. In the following the results are discussed, structured according to the research questions two to five outlined in Section IV.

Thermal vs. Visual (RQ 2): When asked whether the participants preferred the thermal or color feedback for the *Hot & Cold* game, five out of the 10 participants preferred the thermal feedback, three the color feedback, and two did not express a clear preference.

Among those who preferred the thermal feedback, two participants stated that the main reason for their preference was that they did not have to constantly look at the *Trophy Finder* remote. For instance:

> *It's a lot more convenient, it makes a lot more sense cause your task is to find trophies and having temperature to tell you whether you are closer or farther away. You don't snap out of your task, you don't have to look at the thing. Also it's quite novel.* [P5]

Two participants mentioned that it enhanced their feeling of going into the right direction. P8 preferred thermal feedback because it better matched his expectations.

Those who preferred the color feedback over the thermal feedback considered it to be clearer (2 mentions) and faster (2 mentions). For instance, one participant reflected:

> *I stand still for a moment anyway when I think about what way I should go but now I had to wait until I felt the right temperature, the color feedback was instant.* [P4]

The remaining two participants did not pronounce a strong preference for either feedback type, or at least their preference was situational. Both mentioned that it was easier to find the trophies with the color feedback but that the temperature feedback was more fun.

Preferred Interaction (RQ 3): With respect to the question of what interaction(s) had the best implementation of thermal feedback, seven out of 10 participants responded that the interaction with the water was the best. For five participants, the main reason for their choice was that it felt realistic. For instance, one participant expressed that:

> *It felt exactly like water, like swimming outside. I think that even with my eyes closed I would have thought that it was water.* [P2]

The other two participants preferred it because it was surprising to them, as illustrated by the following quote:

> *Unexpected, it felt like a sort of logical surprise. I just entered cold water, that must feel cold.* [P3]

Applications (RQ 4): Participants were also asked how they would use thermal feedback if were to design their own VR game. The majority (i.e. nine participants) answered that they would primarily focus on making the virtual environment itself more immersive as exemplified by the following quote:

> *It would react to the weather, items you pick up. But mostly for the weather, that would have the most impact for me, for the environment. And when you get attacked, if you get hit with a fireball or something like that.* [P4]

Two participants would use it for carried items. P8 also suggested that it could be used to signify danger besides enhancing the environment.

With regard to the question for which kinds of VR games thermal feedback is most suited for, most (i.e. seven) participants agreed that it would be best suited for games that heavily focus on adventure and exploration of the virtual world, as for these games presence is a key aspect of the game experience:

> *Games that focus on adventure, it's for the experience. I wouldn't do it for a competitive shooter, where less feedback is better. But for games where you want to be completely absorbed by the game, for RPGs would be best. Or maybe also car games. But focusing mostly on the environment, that's what I liked most.* [P3]

P10 stated that they would like to use it to make a horror game more realistic:

> *Horror games, to make it more realistic, those kinds of games where your feelings play an important role.* [P10]

Two participants mentioned that they would not use it for (competitive) shooters.

Location (RQ 5): All 10 participants responded positively when asked what they thought about the location of the thermal feedback. For instance, one participant thought it was:

> *Very good, I don't know why but it worked very good, it feels like the right feedback even though it is only in the palm of your hands.* [P4]

However, participants also mused about ways to enhance the feedback further. P4 suggested to also have feedback in the neck to make, for instance, the water sensation even more intense. P7, on the other hand, proposed to add additional thermal feedback on the back of the hand to have the feedback on a larger area.

VI. Discussion

With *Ethermal* we aimed at creating a cheap, easy-to-build, system for thermal feedback which can be assembled using off-the-shelf technology without the need of developing custom parts and electronics. The costs for building a pair of gloves amounted to approximately 90€ for an Arduino Uno, two Peltier elements, two speed controllers, charger, PLA filament, cables, and elastic bands. At the same time, we aimed for a system that is able to generate convincing thermal feedback for VR games. Overall, the results of our evaluation align with this goal, showing statistically higher General and Spatial Presence as well as Experienced Realism. While previous studies (e.g., [18], [41]) have already demonstrated the positive influence of thermal feedback on presence, our results indicate that this benefit can already be leveraged through simple means. In terms of absolute scores, both General and Spatial Presence scored at the very top of the scale. We suspect that the latter benefited from our choice of linking the thermal feedback with environmental assets (e.g., river). Experienced Realism, however, scored lower with ratings around the midpoint of the scale. As the IPQ asks about how real the virtual world is perceived, the graphical representation of the game – a low-poly cartoon style – may have impacted the scores. Another influential aspect here could be that thermal feedback was only provided on a small area of the hand. While the majority of our participants appreciated this, others suggested to extend the thermal feedback to other parts of the body to further enhance the sensation caused by it. However, the study showed that thermal feedback was able to significantly improve on the Experienced Realism. The non-significant difference in case of Involvement, i.e. attention devoted to the virtual environment, can be partially attributed to the researcher providing instructions to the participants during the VR experience. This likely lowered overall involvement as one IPQ question [38] specifically inquires about sounds and other people in the room.

Our results also point to a trade-off between the experience created by thermal feedback and its efficiency when used as part of a gameplay mechanic. Participants preferred the immediate color feedback compared to the slightly delayed thermal feedback. This preference is also reflected in the responses for which use cases participants would apply thermal feedback and which mainly revolved around environmental applications rather than their direct integration into game mechanics. This is in line with results published by Löchtefeld et al. [42] where participants also expressed the need for faster feedback when used as part of game mechanics. Kotsev et al. [43] also explored the use of thermal feedback for gameplay mechanics, finding that it can be useful for some mechanics while for others it can be problematic. In certain cases, temperatures were found to be difficult to interpret which to some extent is also evident in our results with some participants considering the visual feedback to be clearer. In summary, our findings indicate that the gloves were able to improve experience without detrimental effects in two (❶, ❷) out of the three ways we stipulated in Section III. When used for a game mechanic itself (❸) the delay caused until the onset of the thermal feedback needs to be carefully considered.

There are different possibilities to enhance the current prototype. First, the system is currently not wireless. While we used long wires of three meters it still limits movement which, in turn, might reduce presence. Using a wireless connection instead will avoid players getting entangled in wires while playing. For safety reasons, we also limited the intensity of the warm and cold feedback. These sensations could be enhanced by including a temperature sensor which precisely regulates the thermal feedback. Lastly, while all participants liked the location of the thermal feedback with no one complaining about interfering with the controller, integrating the thermal feedback directly within an existing controller itself would very likely improve user experience further.

The results also need to be interpreted within the limitations of the study which was conducted in a non-counterbalanced order. In addition, we only tested with a limited number of participants who only had some prior VR experience which could have increased the novelty aspect. It remains to be seen how the impact on presence upholds across a wider, more diverse, range of participants. We also only studied a limited number of interaction possibilities within the VR environment. Considering additional use cases will yield further design insights on how to utilize thermal feedback within playful VR environments. Future studies could also benefit from providing instructions in a diegetic manner to avoid negative effects from external voice instructions.

VII. Conclusions

In this paper, we presented a lightweight thermal feedback solution for use with VR games. The design was guided by the goal to achieve convincing thermal feedback through low-key technological means. An evaluation of the device showed that it is capable of improving different types of presence. Thermal feedback with such a low-cost device can help design for new types of game experiences. However, the modality is undervalued and underrepresented in current game design approaches due to the missing off-the-shelf technologies, but could be a valuable component for novel game experiences when it comes, for example, to interactive experiences in museums.

In terms of use cases, in conformity with findings of previous research, results point to a preference of players for using it for environmental cues while the delay until the onset of the temperature sensation may make it less suitable for game mechanics which benefit from fast feedback. We can also envision a range of games with completely different design elements, where warm or cold as perception could be the main element of the game and not an add-on for an existing one.

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