Perception of Thermal Haptics in VR

The influence of additional temperature stimulation on perceived temperature change in VR

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VR is reaching wider audiences than ever before and is all about creating immersive experiences. Thermal haptic feedback systems are being used in combination with VR for even more immersion. One common technology used in these systems are Peltiers, but these are limited in temperature range. This research finds out if additional temperature influences perceived temperature change in VR. Therefore, a thermal haptic feedback setup using Peltiers was made that tested physical temperature stimuli in the palms of the hands and in the neck, in combination with a VR-scene that stimulated participants with temperature related object and environmental visuals. The results are significant in showing that additional stimulation in the neck in combination with environmental visuals leads to greater perceived changes in temperature than just stimulation in the hands and object visuals. This knowledge leads to more control over the fidelity of these haptic systems and thus can increase immersion.

Keywords: Virtual Reality, Thermal feedback, Haptics, Games, Peltier elements, Immersion

1 INTRODUCTION

A technology that is now becoming more common and affordable to wider audiences is Virtual Reality (VR). VR is all about creating more immersion and this is also the case for its use in the world of gaming. To make these experiences even more immersive, there has been a large influx in research and development around systems that try to simulate real-world stimuli such as touch or smell [2]. These systems that focus on touch can be called haptic systems. What this means is that it can let users sense or manipulate things through touch [26]. This paper looks at a thermal haptic feedback system and combines it with VR. Trough research, different implementations are tested to see if they can lead to an even greater level of immersion.

Slater [25] describes immersion as something that "*technology delivers from an objective point of view. The more that a system delivers displays (in all sensory modalities) and tracking that preserves fidelity in relation to their equivalent real-world sensory modalities, the more that it is 'immersive'.".* This form of immersion can also be defined as *system immersion* [17], since it describes immersion as a property of the technological aspects of a system. In this paper we will be focussing on trying to improve this type of immersion, since we will be investigating these technological aspects in the form of the VR-headset, a virtual scene and a haptic feedback system.

Several types of haptic feedback systems already exist for use with VR, but most of them focus on letting users sense the texture, stiffness and resistance of virtual objects [23, 24, 27–29, 35]. However, relatively less work has been done focussing on thermal haptics, despite this being a feedback dimension that can be implemented in many interesting ways for videogames. One way that temperature feedback differentiates itself from other forms of haptics is that it especially can work well for representing environments. Different environments can easily have temperatures associated with them (e.g. a chilly breeze, or the warmth of the sun). Several thermal haptic feedback devices do already exist, but some of them suffer from drawbacks such as large size, high cost, technological complexity or long feedback delays [3, 7, 9, 13, 30]. These factors do not help to encourage wider adoption of such technologies. Haptic systems using Peltier-elements also exist, which do not struggle with these problems [15, 19–22, 36]. Peltiers, also known as thermoelectric coolers, are small square plates that heat up on side and cool down on the other when are current is run through them. If the polarities are switched the other side cools down, and vice versa. However, due to low energy efficiencies, Peltier modules tend to overheat when they are set to too low or high temperatures and actuated over longer periods of time [5]. When these modules are incorporated into a wearable thermal haptic feedback system, it is difficult to add a lot of additional cooling. Therefore, the Peltier elements are limited in temperature range. However, a larger perceived temperature difference is desirable for VR experiences since it can increase the fidelity of the haptic system and thus would create more system immersion.

For this reason, it would be beneficial if there would be alternative methods for letting users perceive larger changes in temperature. The amount and location of the Peltier modules can for example be changed in combination different visual stimuli. This paper attempts to find out: *"How does additional temperature stimulation influence perceived temperature change in VR?"*. To investigate this question, a thermal haptic feedback system was made consisting out of three Peltier elements, two of which are meant to worn on both hand palms. The third should be worn in the back of the neck. Additionally, a VR-scene was made through which 11 participants were guided. When participants interacted with object based visuals, they only received thermal feedback in the palms of their hands. When participants found themselves surrounded by certain environmental visuals, they received feedback both in the palms of their hands and in the back of their neck. Results show that these environmental visuals accompanied with the representational additional neck stimuli significantly increases the perceived temperature change. There seems to be no significant difference in perceived intensity between cold and hot stimuli.

2 RELATED WORKS

While no thermal haptic feedback system for gaming has ever gone mainstream, that does not mean that no research and development has gone into creating them. There are quite some examples of thermal feedback systems that work in several different ways with all their benefits and drawbacks. One of these more common drawbacks is a large size. One example is the *CAVE* [9]. This system is a room filled with fans and infrared lights that managed to increase presence during use with games. However, if these systems are to be adopted by a wider audience, than it is hard to argue for the fact that a whole room needs to be dedicated to it and the costs being so high. Another proposed solution is the *ThermAirGlove* [3]. This system pumps hot and cold air to airbags on the fingers to provide its user with feedback. While it also has been proven that it increases presence, it also needs a large air chamber, making it less desirable for consumers. Two systems that have also shown to improve presence, but which are faced with problems, are called *Therminator* [7] and *Chemical Haptics* [13]. *Therminator* pumps water through a wearable harness which leads to very direct feedback, but needs to be hooked to a boiler and a household water connection. *Chemical Haptics* uses chemical stimulants to simulate temperature sensations while being quite compact. However, the feedback it provides is delayed and the sensations created cannot always be immediately stopped.

A substantial amount of thermal feedback systems therefore use Peltier elements to create both a cooling and warming effect [15, 19–22, 36]. Some of the advantages of these elements are their low cost and quick feedback. Furthermore, due to their small size they easily be integrated into wearables and make contact with the skin a variety of locations, such as around the wrist with *ThermalBracelet* [19], in the neck like *Ambiotherm* [22], in the palms of your hand such as

Ethermal [21] or on your face integrated into a VR-headset such as with *ThermoVR* [20]. *Ethermal* and *Ambiotherm* also seemed to lead to an increase of presence and perceived realism when paired with a VR-experience. One problem that Peltiers do struggle with is with heat dispersion due to their low cooling efficiency. Therefore, it would be desirable for the side of the element that is not touching the skin to be additionally cooled. However, it is difficult to incorporate larger heatsinks into wearables due to the increase in weight and bulkiness that would have as a consequence. Active cooling is also not desirable since fans would produce noise that might influence the immersion created by the system. Therefore, the temperature ranges and actuation durations are limited to prevent overheating.

Furthermore, it is important that the theory called the "*Uncanny valley of haptics"* [1] is taken into account when deploying haptic systems for creating greater immersion in VR. This theory states that the fidelity of the physical stimuli created by a haptic system should match the visual stimuli, otherwise the haptics could have an effect on decreasing the experienced immersion. Therefore, it is important that the location of the physical stimuli on the body match the visual stimuli accompanying them. Not coordinating this might lead to less immersion created by the system which would go against the greater goal of this project.

3 METHOD

3.1 Design

3.1.1 Thermal haptic Feedback System

The haptic system used for this research consists out of three Peltier modules. It is important that these elements make contact with the skin in locations that are not covered by clothing for two main reasons. First of all, the modules being covered by clothing during use would affect their ability to disperse heat, which would lead to overheating and a loss in ability to cool properly. Furthermore, having to remove clothing to wear the device is more intrusive for the participants. The location of the modules also had to make sense for the interactions participants had with the visual stimuli in the VR-scene.

One common occurring interaction scenario in VR is picking up objects, which makes placing the physical stimuli in the hands a good option. Moreover, there is a large variety of objects that people associate with certain temperatures.

Figure 1: *One of the Peltier elements worn on the right hand while holding the Meta Quest Touch Controller*

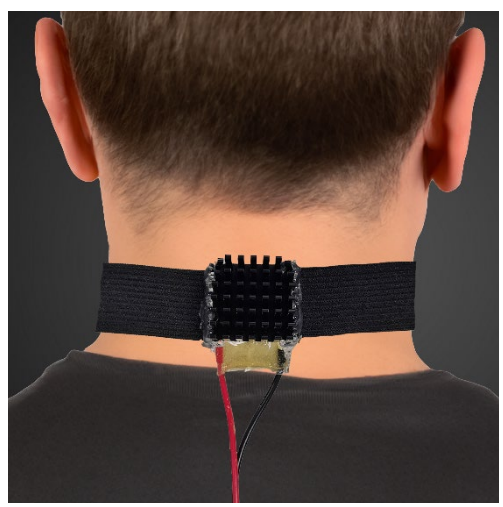

Figure 2: *One of the Peltier elements worn in the neck*

Therefore, the decision was made to place two of the Peltier elements in the palm of the hand (Figure 1). This exact location was further inspired by the placement of the similar thermal feedback system *Ethermal* and the positive reception it received in their research [21], and due to the high thermal sensitivity of this part of the skin [6]. The elements can be worn due to them being attached to two elastic straps and can quickly be removed by the participant in case of any discomfort.

For the third location, the back of the neck was chosen (Figure 2). Part of the reason for this choice is also the thermal sensitivity of the skin and the close proximity to the vertebral arteries [8, 14]. Furthermore, it is relatively far removed from the hands and therefore it was speculated that physical stimuli in this location, when paired with the hand stimuli, could work well for representing another form of common visuals found in games, namely environments. Temperature stimuli associated with environments are something one would feel spread out over the whole body, so it was deemed appropriate to also spread out the stimuli provided by the haptic system. This element can also be worn since it is attached to a wide elastic strap that can be closed and adjusted at the front of the neck using Velcro. It can also easily and quickly be removed by the wearers themselves.

The thermal feedback system used is an altered version of one made by Van de Waerdt for his Master's thesis at the department of Mechanical Engineering at Eindhoven University of Technology [34]. For this research some components had to be repaired or replaced. Furthermore, the wires were made longer to over three meters to offer participants freedom of movement and the Peltier elements were made wearable like mentioned above. The elements themselves have surface dimensions of 20mm x 20mm and are covered on one side by a heatsink of the same size to help with heat dispersion. On the other side they are covered with a aluminium plate of the same size with a thermistor in between. This thermistor is added to regulate and measure the actual temperature output of the elements. The polarities of the voltage supplied to the Peltiers are controlled by three H-bridges in the form of L298N-modules. By changing polarity the Peltier elements go from cooling to heating or vice versa. The H-bridges and Peltiers receive a maximum current draw of 1.5A at 5V per pair and are further controlled by an Arduino Uno. This microcontroller also reads the data from the thermistors to regulate the temperature.

The temperature always needs to stay within a range of 15˚C and 40˚C to cause no discomfort and for the skin to have the ability to somewhat adapt to the temperature [11]. The power to the modules cuts off outside of this range. The cooling temperature for the Peltiers also cannot be too low, since it this will lead to overheating. Therefore, through some informal testing it was decided that the temperature for the cooling stimuli would be 27˚C, for neutral 32˚C, and for hot 37˚C. These temperature changes were deemed as sufficiently noticeable while also being in a range that mitigates overheating. Furthermore, putting the baseline/neutral situation relatively high can help with making a higher temperature feel more cold, since the surrounding skin temperature will then be hotter for the neutral situation. Humans are especially good at sensing temperature differences and less so absolute values and the baseline temperature of the skin has an influence on this [10].

3.1.2 VR-Scene

The virtual scene made for this research was made in *Unity 3D* [32] using the *OpenXR plugin* [18] for VR implementation. Many of the assets used were retrieved from free packages (Appendix A) that can be found in the *Unity Asset Store* [31] and the visually most of them are in a low-poly style. This choice was made since the asset store offer a wide variety of these visuals and they run relatively smoothly. The *Meta Quest 2* [16] was used as VR-headset accompanied with the

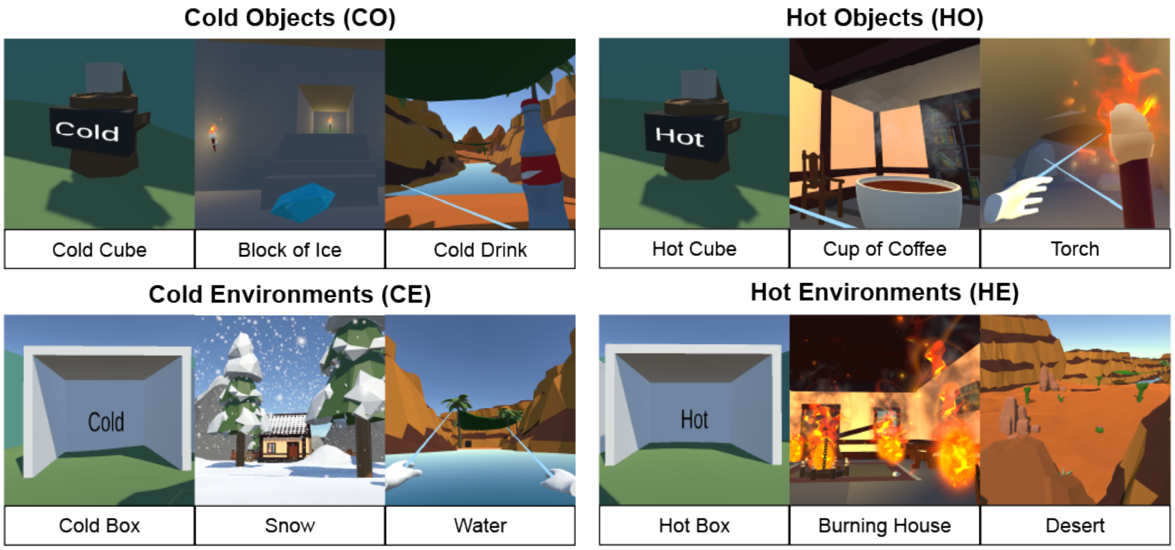

Table 1: *Overview of the different visuals that participants interacted with in the VR-scene*

Description	Type of interaction
Garden	N
Cold Box	CE
Garden	N
Hot Box	HE
Garden + Learning grabbing objects	N
Cold Cube	CO
Garden	N
Hot Cube	HO
Garden + Learning opening doors	N
Snow	CE
Cabin	N
Cup of coffee	HO
Break	
Cabin	N
Burning house	HE
Escape to cave	N
Torch	HO
Opening in cave	N
Ice block to get up stairs	CO
Cave opening	N
Desert	HE
Break	
Tent in oasis	N
Small body of water	CE
Tent is oasis	N

Table 2: *Description of all interactions in order of occurrence*

Meta Quest Touch controllers. Participants can move around using the thumbstick on the left controller. They can look around using the thumbstick on the right controller and by moving their head. The trigger buttons underneath their middle fingers are used for grabbing objects, activating items and opening doors.

In this scene, 6 object visuals are included that trigger the thermal feedback on both the hands when they are picked up by a participant. Both the hands got activated despite objects being picked up by only the left or right hand to keep the temperatures of both these elements as similar as possible. Half of these visuals, so 3, trigger cold thermal feedback and half of these hot feedback. Furthermore, 6 environmental visuals are presented in the scene that trigger haptic feedback on both the hands and neck when entered by a participant. Once again, half of these trigger cold thermal feedback and the other half hot feedback. For all cold instances the Peltier modules would drop to 27˚C and for the hot ones increase to 37˚C. 'Neutral' environments are also included where participants need to wait for the Peltier elements to get back to 32˚C after an interaction. The participants were not informed beforehand to which temperature the Peltier elements would change for any situation. The visual and physical stimuli can be divided up into 5 categories: *Cold Objects (CO), Hot Objects (HO), Cold Environments (CE), Hot Environments (EH), and Neutral (N).* Most of the visuals are based on things that could likely be encountered in VR-games and have different cold or hot

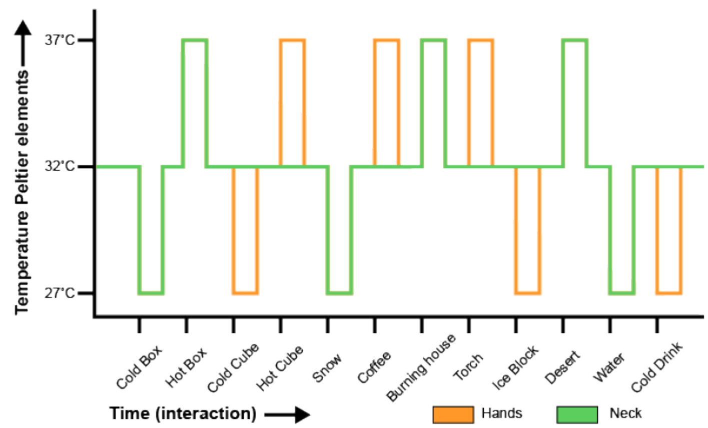

Figure 3: *Temperature of the different Peltier elements for each interaction*

temperature levels associated with them. However, for each instance also one simple visual stimulus was added that just stated hot or cold on it. The different visuals can be seen in Table 1.

The interactions in the VR-scene can be seen, in the order that they occurred, in Figure 3 and Table 2. A more detailed description can be found in Appendix B. The scene had to include different hot and cold objects and environments so the different amounts of physical stimuli could be tested with them. Before every interaction with hot or cold visual and physical stimuli, participants first would experience a neutral situation and visuals accompanying that. This was done so the Peltier elements have some time to get back to 32˚C and that therefore the change in actual temperature was always as similar as possible. Otherwise the perceived temperature change could not be compared equally. An additional goal when setting up the VR-scene was to connect the different interactions with each other in a logical order and that the different objects felt to belong in their respective environments. Examples of this are offering a hot cup of coffee to warm up after just coming from the chilly outside, or using the hot torch to see around a dark cave.

3.2 Procedure

The participants were recruited by advertising the research to students on the by the university offered platform Microsoft Teams [33] and through the social circle of the researcher. The only requirements for people to participate were that they had to be over the age of 18 and had normal or corrected to normal vision due to wearing glasses or contact lenses. In total 11 people took part in the research out of which only one had no prior experience with VR. All participants were asked whether or not they had done any form of exercise just before joining that might have influenced there body temperature. At most some participants came to the research location by bike at what they proclaimed 'normal' speeds. They also all got at the very least 5 minutes to calmly sit down and read through the informed consent form (Appendix C) and listen to the explanation about the research. Part of this explanation included how to quickly take of the thermal haptic feedback system and the VR-headset in case they experienced any discomfort. Furthermore, they were offered a glass of water in case they were feeling hot or just desired so. Before the participants started the experiment, the room temperature was measured and noted down. The thermometer used was not calibrated properly so no exact temperatures can be given, but between the lowest and highest measured temperature there should only be a 0.8˚C difference.

To measure the intensity of the perceived temperature changes participants were asked to report with a ratio scaling method called magnitude estimation [12]. This method can be used for measuring the intensity of sensory stimuli. After the participant had been helped to put on the VR-headset and the thermal haptic feedback system and they could freely move around the virtual scene, they were asked to assign a number to general temperature they experienced at that moment as a baseline. This number could be any number they wanted. The participants were then asked to express their current perceived temperature each time the researcher verbally asked them. The researcher asked them this question when the Peltier elements reached a temperature of either 27˚C for the cold stimuli and 37˚C for the hot stimuli. All numbers had to stay positive and thus if they perceived the temperature to be colder than baseline they assigned a lower number and for hotter a higher. Furthermore, all participants had to wait for the temperature to get back to 32˚C after each interaction and were then also asked to assign a number to temperature they were experiencing at that moment. This data was noted down by the researcher by hand (Appendix D).

All participants were guided through the virtual environment by verbal instructions from the researcher. They also interacted with all of the visual stimuli in the same order and thus also received the same physical stimuli in the same order. When participants picked up objects they were asked to hold them until the researcher told them to drop them so the modules had time to reach their target temperature. For the environments, the participants were also only allowed to leave them when the researcher noticed them for the same reason. They could only pick up new objects or enter new environments when the Peltier elements had first returned to a temperature of 32˚C. As can be seen in Table 2, two breaks were included in the procedure during which the participants took off the headset and the thermal feedback system. These were included in case they got motion sick or experienced any other form of discomfort, but to keep all tests equal, every participants had to take the breaks and also at the same moment.

Once all interactions were finished, the VR-headset and the thermal feedback system could be removed after which a semi-structured interview (Appendix E) followed to get some additional insights into their experience. These interviews were later transcribed (Appendix F).

3.3 Analysis

The participants were also asked the perceived temperature for each neutral scenario to check whether or not they felt hotter or colder than during other neutral scenarios, despite the temperature always being 32˚C. This distinction could have an influence on participants perceive the subsequent stimuli. To take this into account, the delta between the score a participant gave a certain stimuli and the score of the neutral situation before it is used for analysis. Therefore, the data shows the change in the perceived intensity of the temperatures and not the perceived intensity of the temperatures. To normalize these delta values, they were converted to z-scores for each participant separately. For example, a z-score of 2 for a certain set of visual and physical stimuli would mean that the change in perceived intensity of the temperatures for that specific set of stimuli is two standard deviations higher than the mean of all changes in perceived intensities for that specific participant. A negative z-score thus means that the delta value is lower than the mean of all the other delta values of that participant. Therefore, the z-scores of the cold stimuli should be negative. However, to better statistically compare the change in perceived intensities of both the cold and hot stimuli, all negative z-scores were converted to positive. With all these z-scores, a two-way repeated measures ANOVA was performed, with $\alpha=0.05$. The two independent variables were the direction of temperature change (hot, cold), and combined visual and physical representation (object visual and thermal hand stimulation, environment visual and hand & neck stimulation).

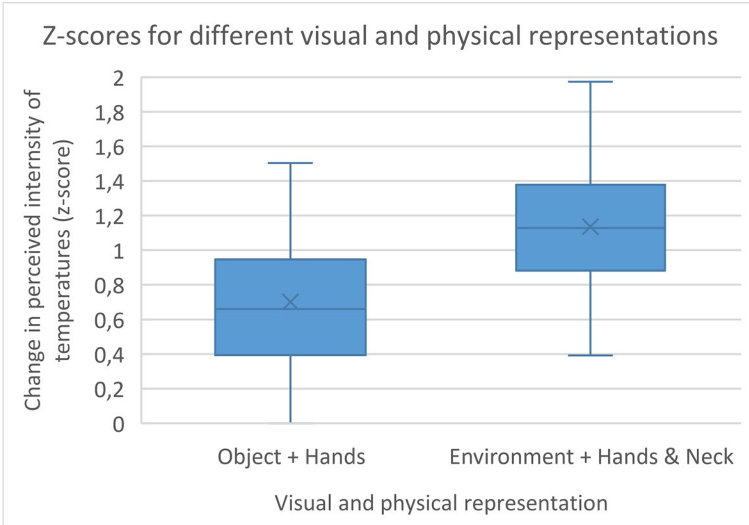

Figure 4: *Boxplot showing the effect of visual and physical representation on the change in perceived intensity of temperatures*

4 RESULTS

In a two-way repeated measures ANOVA , there was a statistically significant effect of visual and physical representation on the change in perceived intensity of the temperatures, $F(1,32) = 55.3$, $p < 0.001$. For Object + Hands M = 0.702 & SD = 0.334 and for Environment + Hands & Neck M = 1.137 & SD = 0.330. This influence of the representations on the z-scores is also visualized in Figure 4.

There seems to be no significant effect of the direction of temperature change on the change in perceived intensity of the temperatures, $F(1,32) = 0.01$, $p = 0.76$. Therefore, it does not seem the case that either the colder or hot temperatures were perceived as more a more intense change than the other. For cold M = 0.913 & SD = 0.331 and hot M = 0.925 & SD = 0.454. The only difference seems to be a greater standard deviation in z-scores for the hot temperatures as can also be seen in Figure 5.

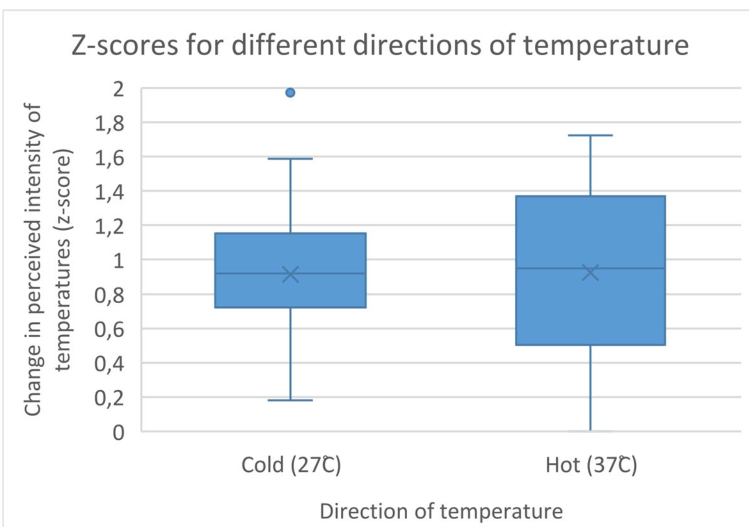

Figure 5: *Boxplot showing the effect of direction of temperature change on the change in perceived intensity of temperatures*

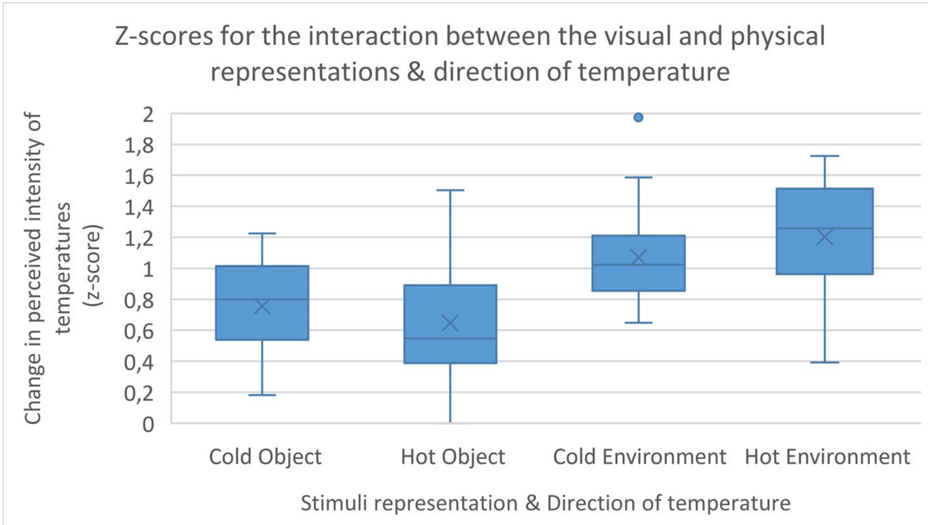

Figure 6: *Boxplot showing the interaction between visual and physical representation, and the direction of temperature change*

There is no statistically significant two-way interaction between visual and physical representation, and the direction of temperature change, F(1, 32) = 3.11, p = 0.09. For cold object M = 0.757 & SD = 0.309, for hot object M =0.646 & SD = 0.354, for cold environment M = 1.069 & SD = 0.278 and for hot environment M = 1.203 & SD = 0.366.

4.1 Interviews

Out of all the participants, 6 noted that they did not experience any discomfort related to the thermal feedback system. Three of them stated that the corners of the Peltiers pushed a bit into their hands, but only found this mildly uncomfortable. P10 stated to find the cold in the neck to be somewhat discomforting, but by this being the case, it enhanced the experience. This participant also found the strap in the neck to be uncomfortable at first, but got used to it quickly. P11 found the hot sensation to be leaning towards uncomfortable. Furthermore, 8 participants preferred the stimuli including the neck and the environmental visuals. Most of them stated that this preference was based on more intense perception of the physical stimuli in the neck. However, some mentioned that they did not want the neck element to be used to make the object interactions feel more intense. The others did not have a clear preference. All participants found the thermal haptic feedback to improve their experience for given reasons such as increased immersion. Furthermore, all participants that remarked to notice both hands got stimulated when picking up objects preferred this to not be the case.

5 DISCUSSION

The main thing that really stands out from the results is the statistically significant effect of the combination of both the visual and physical representation on the perceived intensity of the temperature change. What this means is that the combination of additional physical stimuli in the neck together with environmental visual stimuli were experienced as causing a greater change in perceived intensity of the temperatures. Moreover, it does not seem to matter whether or not the stimuli are hot or cold when looking at how great the change in intensity of the perceived temperature is.

Furthermore, while there is no statistically significant two-way interaction between visual and physical representation, and the direction of the temperature, the p-value of $p = 0.09$ is close to significant. Therefore, it might be possible that a larger study could find this effect which would mean that the variance for hot temperature perception is greater between the different stimuli representations than for cold temperature perception. This complies with research done by Luo et al. [14] that states the back of the neck is more sensitive for warm sensations compared the palms of the hands, while for cooling sensations, it is the other way around.

For designers these results could have some implications when using similar thermal feedback systems. Having this extra Peltier element in the neck can be used as an alternative to making the modules operate for a greater temperature range when you want to give thermal feedback to players immersed in a virtual environment. Not having to widen that range means that the stimulations can be given over longer periods of time without the system overheating. However, game designers should keep in mind that if they would like to give thermal feedback for object visuals, and want that to perceived as more intense than that for an environmental visual, while also linking it to the correct physical stimuli, than they should either make the temperature range for the environmental feedback smaller, or the range of the object feedback greater. Furthermore, it is important to note that one should be careful when increasing this range, since temperatures above 40˚C may be experienced as uncomfortable and over 48˚C as causing a burning sensation [4]. Therefore, it might also be worth it to look into whether or not increasing the amount of stimuli on one hand can increase the change in perceived intensity of the temperature. Moreover, the fact that the direction of the temperature does not seem to have an effect on temperature intensity perception means for a designer that the delta of the actual temperature should remain the same for both hot and cold stimuli if they want to be perceived as equally intense. The results from the interviews are also interesting to look at how similar systems can be improved. To make the wearing of it more comfortable sharp corners need to removed. Participants suggested to solve this problem by either incorporating the elements into either a glove or controllers for the hands. Furthermore, the interactions including neck stimuli seem to be preferred, but that does not mean that additional physical stimuli should be applied when trying to represent visuals that normally would not have an effect on the temperature of that part of the skin.

Most importantly, this research indicates that additional visual and thermal stimulation increases the change in perceived intensity of temperatures. Knowing this can give designers more control over the perceived intensity of temperatures which will help with increasing the fidelity of thermal haptic feedback systems. Improving the fidelity of technologically induced stimuli in relation to their real-world equivalents improves system immersion [25]. Therefore, taking into account the results of this research can help thermal haptic feedback systems with immersion creation when using them with VR.

6 CONCLUSION

In this paper an attempt to answer the question *"How does additional temperature stimulation influence perceived temperature change in VR?"* has been made, with the greater goal improving the ability of thermal haptic feedback systems using Peltier elements for stimulation to create immersion. The different physical stimuli that were located in the palms of participants' hands and in the back of their neck. Temperature stimulation in the hands was paired with visual stimuli in the form of virtual objects shown to participants in a VR-scene. Stimulation in both the neck and hands was paired with visual stimuli in the form of virtual environments.

There is a statistically significant effect of visual and physical representation on the change in perceived intensity of the temperatures. Receiving stimulation in both the hands and the neck in combination with the environmental visuals leads to more intensely perceived temperatures than the other interactions. Designers can use this knowledge to improve the fidelity of thermal haptic feedback systems when using them in combination with VR to create more immersive experiences.

7 ACKNOWLEDGMENTS

Most of the assets used to create the VR-scene were retrieved from the Unity Asset store, more details on this can be found in Appendix A. Credits need to be given to van de Waerdt [34] for his work on creating a thermal haptic feedback system that works with Arduino. An altered version of his setup was used for this research. Furthermore, the Arduino code used was also an altered version of his work. Also thanks to everyone at the Reshape lab at the Technical University of Eindhoven for letting me use their VR-headset and PC setup. More specific thanks for the support from Femke van Beek and Irene Kuling who work at the lab. Furthermore, I would like to thank my supervisor Max Birk for providing me with all the feedback on my work. Lastly, I would like to thank Jonas Kamps for his coaching, feedback and support with the data analysis.

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9 APPENDICES

9.1 Appendix A: List of used Unity assets

- https://assetstore.unity.com/publishers/24390
- https://assetstore.unity.com/packages/3d/vegetation/trees/free-trees-103208
- https://assetstore.unity.com/packages/3d/props/food/food-pack-free-demo-225294
- https://assetstore.unity.com/packages/3d/props/interior/cup-201601
- https://assetstore.unity.com/packages/3d/environments/fantasy/cartoon-fantasy-medieval-town-lite-low-poly-3d-by-justcreate-242322
- https://assetstore.unity.com/packages/3d/vegetation/trees/snowy-low-poly-trees-76796
- https://assetstore.unity.com/packages/3d/environments/dungeons/ultimate-low-poly-dungeon-143535
- https://assetstore.unity.com/packages/3d/environments/landscapes/polydesert-107196
- https://assetstore.unity.com/packages/3d/environments/landscapes/rpg-poly-pack-lite-148410
- https://assetstore.unity.com/packages/3d/environments/campfires-torches-models-and-fx-242552
- https://assetstore.unity.com/packages/3d/environments/landscapes/lowpoly-environment-pack-99479
- https://assetstore.unity.com/packages/3d/environments/landscapes/low-poly-simple-nature-pack-162153

9.2 Appendix B: text description VR-scene

The timeline of the VR-scene started in a small garden (N) in which the participants were asked to first step into the cold box (CE) once they figured out the controls. They were then asked to step back into the garden (N) followed by the hot box (HE). Once they stepped out they got a short explanation on how to pick up objects (N). Now that they understood this, they had to pick up the cold cube (CO). After dropping the cube they had to wait for a moment in the garden (N) and could then pick up the hot cube (HO). Next, the participants had to find a door and open it (N). Behind the door was a teleporter that sent them to snowy forest (CE) with a cabin in the corner (N) which they had to enter. In there a coffee (HO) was waiting for them on a table. To make sure the participants did not experience discomfort from motion sickness a very short break was held where they had to take the VR-headset and thermal feedback system off. Once they put everything on again they returned to the cabin (N). In the corner of the cabin a skull was placed which they had to activate. Doing this made the chandelier fall down and the house started going up in flames (HE). They were then told to trigger a book in the bookcase to enter a secret cave (N) to escape. In this cave they could teleport to a larger and darker cave in which they would find a burning torch (HO). While holding this object they were led to a larger opening (N) with a set of stairs. However, the first step was missing so the participants had to find a block of ice (CO) to use as a ramp. Once they got up the stairs they found another teleporter which brought them to a cave opening (N) leading out into a desert. They could then set foot in the burning desert (HE) sun where they had to find a tent in an oasis. Here they had a break once more for the same aforementioned reasons. The participants now returned to the shade of the tent (N) and could then swim around in a small body of water (CE) that led to another tent (N). The last interaction was waiting for them here in the form of a cold drink (CO) standing on a barrel.

9.3 Appendix C: informed consent form

<u>Information sheet for research project "The effects of virtual visuals on temperature perception using thermal haptics"</u>

1. Introduction

You have been invited to take part in research project "The effects of virtual visuals on temperature perception using thermal haptics", because you have been contacted by the researcher via e-mail, text message or verbally.

Participation in this research project is voluntary: the decision to take part is up to you. Before you decide to participate we would like to ask you to read the following information, so that you know what the research project is about, what we expect from you and how we deal with processing your personal data. Based on this information you can indicate via the consent declaration whether you consent to take part in this research project and the processing of your personal data.

You may of course always contact the researcher via j.a.m.v.gurp@student.tue.nl if you have any questions, or you can discuss this information with people you know.

2. Purpose of the research

This research project will be managed by Jules van Gurp.
The purpose of this research project is to see how visual elements in virtual environments can have an influence on temperature perception. This knowledge can help with the development of thermal haptic systems for use with virtual environments, which could be useful for training or entertainment purposes. The results of this project will be published in a project report.

3. Controller in the sense of the GDPR

TU/e is responsible for processing your personal data within the scope of the research. The contact details of TU/e are:

Technische Universiteit Eindhoven
De Groene Loper 3
5612 AE Eindhoven

4. What will taking part in the research project involve?

You will be taking part in a research project in which we will gather information by:

- Asking you the perceived temperature level you experience while wearing a thermal haptic feedback system and interacting with visual elements in a VR-environment. This will be noted down by the researcher in writing.
- Interviewing you about your experience in the VR-environment and your interaction with the thermal haptic feedback system, and record your answers via audio. Also, we will make a transcript of the interview.
- Presenting you a questionnaire about your presence levels while experiencing the VR-environment which you can fill in in writing.

For your participation in this research project you will not be compensated.

5. Potential risks and inconveniences

Your participation in this research project does not involve any legal or economic risks. It should also not involve any physical risks. The thermal feedback system is regulated to stay within a comfortable temperature range. However, if you do experience any discomfort or harm you can immediately remove the system and/or notice the researcher for help. The researcher will show you beforehand how to quickly remove the haptic system. You do not have to answer questions which you do not wish to answer. Your participation is voluntary. This means that you may end your participation at any moment you choose by letting the researcher know this. You do not have to explain why you decided to end your participation in the research project.

6. Withdrawing your consent and contact details

Participation in this research project is entirely voluntary. You may end your participation in the research project at any moment, or withdraw your consent to using your data for the research, without specifying any reason. Ending your participation will have no disadvantageous consequences for you.

If you decide to end your patricipation during the research, the data which you already provided up to the moment of withdrawal of your consent will be used in the research.
Do you wish to end the research, or do you have any questions and/or complaints? Then please contact the researcher via j.a.m.v.gurp@student.tue.nl or the project supervisor via m.v.birk@tue.nl

If you have specific questions about the handling of personal data you can direct these to the data protection officer of TU/e by sending a mail to functionarisgegevensbescherming@tue.nl. Furthermore, you have the right to file a complaint with the Dutch data protection authority: the Autoriteit Persoonsgegevens.

Finally, you have the right to request access, rectification, erasure or adaptation of your data. Submit your request via privacy@tue.nl.

7. Legal ground for processing your personal data

The legal basis upon which we process your data is consent.

8. What personal data from you do we gather and process?

Within the framework of the research project we process the folllowing personal data:

Category	Personal data
Audio data	*Voice recording of interview*

Within the framework of the research project your personal data will be shared with:

- *Storage solution: SURF ResearchDrive, Microsoft (Netherlands)*
- *Transcription tool: Microsoft (Netherlands)*
- *Data analysis tool: Miro (EU)*

9. Confidentiality of data

We will do everything we can to protect your privacy as best as possible. The research results that will be published will not in any way contain confidential information or personal data from or about you through which anyone can recognize you, unless in our consent form you have explicitly given your consent for mentioning your name, for example in a quote.

The personal data that were gathered via audio recordings and other documents within the framework of this research project, will be stored on storage facilities that are supported by the ICT service of TU/e.

The raw and processed research data will be retained for a period of year. Ultimately after expiration of this time period the data will be either deleted or anonymized so that it can no longer be connected to an individual person. The research data will, if necessary (e.g. for a check on scientific integrity) and only in anonymous form be made available to persons outside the research group.

This research project was assessed and approved on 21/04/23 by the ethical review committee of Eindhoven University of Technology.

***** Scroll down for the consent form *****

Consent form for participation by an adult

By signing this consent form I acknowledge the following:

1. I am sufficiently informed about the research project through a separate information sheet. I have read the information sheet and have had the opportunity to ask questions. These questions have been answered satisfactorily.

2. I take part in this research project voluntarily. There is no explicit or implicit pressure for me to take part in this research project. It is clear to me that I can end participation in this research project at any moment, without giving any reason. I do not have to answer a question if I do not wish to do so.

3. I am sufficiently informed by the researcher on how to quickly remove the haptic thermal feedback system and have had the opportunity to ask questions about this.

Furthermore, I consent to the following parts of the research project:

3. I consent to processing my personal data gathered during the research in the way described in the information sheet.

1. YES ☐ NO ☐

4. I consent to making (sound) recordings during the interview and to processing my answers into a transcript.

   YES ☐ NO ☐

5. I consent to using my answers for quotes in the research publications – without my name being published in these.

2. YES ☐ NO ☐

6. I consent to retaining research data gathered from me and using this for future research in the field of Human Computer Interaction in which recognized ethical standards for scientific research are respected, and for education purposes.

3. YES ☐ NO ☐

Name of Participant:

Signature:

Date:

Name of researcher:

Signature:

Date:

9.4 Appendix D: measurements table

Participant number		
Ambient Temperature		
Had drink?		
Experience VR?		
Exercised before?		
Start		
Cold box		
Neutral		
Hot box		
Neutral		
	Test stone	
Cold cube		
Neutral		
Hot cube		
Neutral		
Snow		
	Close door	
Neutral		
Coffee		
	Pause	
New start		
Fire		
Neutral		
Torch		
Neutral		
Ice		
Neutral		
Dessert		
	Pause	
New Start		
Water		
Neutral		
Cola		

9.5 Appendix E: interview questions

Did you experience any discomfort during the research? In what way? (e.g. the straps)

(To which degree did you feel like this impacted your experience?)

How did the thermal haptic feedback system influence your experience? To which degree? In what ways?

Did you experience any noticeable temperature differences between the different hot interactions? To which degree?

To which degree did you feel like the different hot interactions matched the visuals? Why?

Did you experience any noticeable temperature differences between the different cold interactions? To which degree?

To which degree did you feel like the different cold interactions matched the visuals? Why?

How would greater temperature differences have influenced your experience? Why?

Do you have a preference when comparing the environmental thermal feedback and object based one? Why (not)?

At the very start you some interacted with some objects that were not visually linked to certain temperatures. Do you feel like that impacted your temperature perception in any way compared to the other interactions? In what way?

What are additional things you liked/disliked about the thermal haptic feedback system? Why?

What would be things you would like to change about the thermal feedback system? Why?

What problems did you encounter in the virtual environment that impacted your experience?

What did you enjoy or dislike about the virtual demo?

Do you still have any remarks?

9.7 Appendix G: z-scores temperature delta

Participant number	P1	P2	P3	P4	P5	P6	P7	P8	P9	P10	P11
Start											
Cold box	-1,08917	-1,22343	-0,93264	-1,22581	-0,85536	-1,58642	-1,33334	-1,19623	-0,69336	-0,972077446	-0,830257182
Hot box	0,653502	1,655233	1,065877	1,081593	0,955994	1,36298	1,546672	1,419007	1,190484	1,586021096	1,405050616
Cold cube	-1,08917	-0,82042	-0,66617	-1,22581	-0,85536	-0,51391	-0,37333	-1,07999	-0,69336	-1,21083331	-1,021854993
Hot cube	0,653502	0,38862	0,799408	0,504744	0,654101	0,290471	0,266668	0,954076	0,562536	1,17672533	0,574793434
Snow	-0,79872	-1,33858	-1,46558	-0,64896	-1,15726	-1,31829	-1,97334	-1,19623	-1,00733	-0,972077446	-1,149586868
Coffee	0,363057	0,503767	1,199112	0,504744	0,955994	0,290471	1,226671	0,547262	-0,37938	0,835645524	0,44706156
Pause											
Fire	1,524838	1,367367	1,465581	1,370018	1,257887	1,631107	0,522669	1,419007	1,504457	1,244941291	1,724380301
Torch	0,943948	0,38862	0,799408	1,370018	0,352208	0,558598	0,394668	0,547262	1,504457	0,392241777	0
Ice	-0,79872	-0,6477	-0,93264	-1,22581	-1,15726	-0,78204	-0,18133	-0,90565	-1,00733	-0,801537543	-0,830257182
Desert	1,524838	1,0795	0,399704	0,793168	1,559779	1,094852	0,97067	0,837844	0,87651	0,392241777	1,213452805
Pause											
Water	-0,79872	-1,10829	-0,93264	-0,93738	-0,85536	-0,78204	-0,88534	-0,7313	-1,16432	-1,108509368	-1,021854993
Cola	-1,08917	-0,24469	-0,79941	-0,36053	-0,85536	-0,24578	-0,18133	-0,61506	-0,69336	-0,562781679	-0,510927497