Touch It Like It's Hot: A Thermal Feedback Enabled Encountered-type Haptic Display for Virtual Reality

Steeven Villa* LMU Munich.
Kenji Ishihara† LMU Munich.
Moritz Ziarko‡ LMU Munich.
Sebastian Günther§ Urban Software Institute GmbH.
Florian Müller¶ LMU Munich.

Figure 1: We introduce an Encountered-type Haptic Display that incorporates thermal feedback to enrich VR experiences, our study shows significant improvements in user immersion and haptic realism.

Abstract

In recent years, the community has presented various novel solutions to address the lack of haptic feedback in virtual reality experiences. Yet, it remains a major challenge for Virtual Reality applications. Encountered-type Haptic Displays (ETHDs) have emerged as a promising alternative to enable haptic feedback in VR without requiring the user to wear any device while allowing for sensorily rich experiences such as texture, kinaesthetic feedback, and even ultrasonic tactile feedback. Nevertheless, as important as thermal feedback is for daily life interactions, such as assessing the temperature of a mug or knowing if the microwave is on, thermal feedback in ETHD has remained largely unexplored. In this paper, we present a novel ETHD that provides thermal feedback and explore its potential in VR. We describe the design of our ETHD, and we report the results of a user study that compares different thermal feedback settings in VR. Our results show that thermal feedback can significantly enhance the user immersion and haptic experience in VR, and we discuss the implications of our findings for the design of ETHD and VR experiences.

Index Terms: Haptics, Robotics, Thermal Feedback, Encountered-type Haptics, Virtual Reality

1 Introduction

From enjoying the chill of holding a cold drink on a hot summer's day to checking if our child has a fever, our experiences of temperature when touching an object add strongly to how we experience the physical world. While this haptic experience is a natural part of how we experience the physical world, today's Virtual Reality (VR) environments are largely built around visual and auditory stimuli and, thus, lack an essential haptic dimension of interaction.

To overcome these limitations and to create a VR experience that is closer to the experience in the physical world, previous work has proposed various solutions to enable tactile feedback in VR environments [39]. One class of these solutions are encountered-type haptic displays (ETHDs) [35], which are anchored in the physical world, often through robotic arms [33, 54, 53], and are able to provide actual counterforce in contrast to body-worn systems. Besides tactile feedback, previous work investigated approaches to provide temperature sensations, e.g., by attaching thermal elements directly to a user's headset [42, 41], arms [12], or full body [21]. However, tackling temperature perception is a complex challenge [23] including the dependency and sensitivity of the actuated body part [28].

However, the combination of tactile and temperature feedback remains underexplored since most only focus on the true-to-life representation of one haptic dimension individually. Consequently, the interplay of multiple haptic experiences, as we know it from the physical world, is lost.

In this work, we go beyond the state-of-the-art haptic feedback for VR systems by integrating ETHDs with temperature feedback delivered through a dynamic surface attached to a robotic arm. Our approach tracks the users' movements and relocates the robotic arm according to props and objects in the virtual environment, providing a solid contact and an appropriate thermal sensation while touching. Further, depending on the expected temperature of a virtual element, the surface can get slightly shifted to warmer or colder areas to provide even more realistic temperatures.

The contribution of this paper is three-fold: 1) We contribute to the design and implementation of a thermally-enabled ETHD that provides tactile and temperature feedback at an arbitrary position and orientation in the tracking area. 2) We provide a comprehensive technical assessment to investigate the relocation speed and temperature performance. 3) We conducted a systematic user study (N=26) that explored the effects on immersion, realism, and haptic experience compared to a non-thermal baseline (see Figure 2).

Our results indicate that our thermally-enabled ETHD signifi-

*e-mail: villa@posthci.com
†e-mail: kenji@ishihara.dev
‡e-mail: moritz@ziarko.de
§e-mail: research@sebastian-guenther.com
¶e-mail: florian.mueller@ifi.lmu.de

2473-0726/24/$31.00 ©2024 IEEE
DOI 10.1109/ISMAR62088.2024.00085

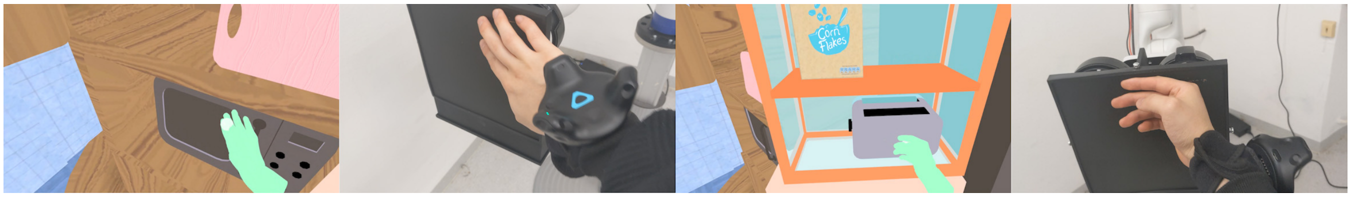

Figure 2: In the VR experience, the participant interacts with a microwave and toaster, experiencing thermal feedback. Subsequent images show real-world views of the scenarios.

cantly improved both immersion and haptic experience while featuring a novel approach using multiple thermal elements on a surface attached to a highly-dynamic robotic arm.

2 Background

Haptic rendering remains a challenge for VR applications, given the intricacies of haptic perception [52]. Unlike vision or auditory senses [50], haptic perception is distributed through the body [22] and comprises multiple sub-senses such as touch, kinaesthesia, temperature, and pain [15, 48]. Although many apparatuses have been proposed to deliver haptic feedback in VR [52], they are mostly sub-sense constrained and can be used only in very specialized scenarios [56] or require the user to wear something in order to feel haptics [39]. Recently, researchers have directed their attention to bare-hand interaction techniques such as mid-air haptics [19], encountered-type devices [35, 11], and even combinations of those [54]. In this manuscript, we align with this vision and propose a thermal encountered-type haptic display that can provide thermal feedback to enhance immersion in VR and Spatial Interaction. This section provides background information on ETHD and thermal feedback.

2.1 Encountered-Type Haptic Displays (ETHD)

ETHDs as defined by Mercado et al. [35] are devices capable of placing part of themselves or in their entirety in an encountered location that allows the user to have haptic feedback at the proper time and location. The physical properties of ETHDs vary significantly, ranging from movable tables [60] and bags [31] to robot arms [33, 54, 53] swarm robots [11], or even drones [1] and others [20]. The case of robot arms in the context of VR is especially interesting since those are grounded devices and can provide kinaesthetic feedback while being fast enough to locate their end-effector in the desired positions promptly.

In this line, robot arms also provide the possibility to attach different end-effectors, which can be used for further extending the range of sensations rendered by the ETHD. For example, ENTROPiA and FrictionHaptics [33, 30] enable ETHDs to render infinite textures by integrating a circular/spherical attachment that, synchronized with the robot movement can generate the sensation of touching a continuous surface. Furthermore, attaching objects of interest such as buttons [59], or even switching objects at runtime [34] enable high fidelity object-specific rendering. Indeed, higher complexity end-effectors such as ultrasonic mid-air haptic arrays have been successfully shown to extend the range of sensations of ETHD [54], highlighting the potential of this method for rendering haptics in VR.

Yet, the use of ETHDs for temperature rendering has been underexplored; one of the few examples of thermal rendering using an ETHD is Snake Charmer [3], a prototype that proposes the use of laser-cut end-effector prototypes to render texture, shape, object size, and, temperature, however without exploring the thermal aspect of the system. Focusing on the immersion aspects of thermal ETHDs remains thus under-explored [35] and can potentially reduce failures during interaction [5]. In this manuscript, we propose a thermal encountered-type haptic display that can provide thermal feedback to enhance immersion in VR and Spatial Interaction.

2.2 Thermal Feedback in VR and HCI

Temperature is a fundamental object property [38, 55] that shapes user experience but also the way people interact with the environment [48], and has been explored in various forms, such as phones [58], rings [37, 45], hand-held devices [29, 25], and other tangibles [62]. Even though temperature perception can be triggered just by visuals [24, 51], an actual thermal rendering of temperature is still rarely included in VR applications in favor of more straightforward forms of haptic rendering such as vibrotactile [56], or haptic illusions [27, 40], and due to its own challenges [23]. However, it has been shown that thermal feedback has strong associations with subjective experiences such as emotions and memory [18], but also environment-related properties such as traces of use [26, 36] or material properties [16], which may have an impact on involvement and presence. As such, thermal displays has been incorporated in various work in order to give a tangible sense of temperature, e.g., by applying it directly to HMDs [41, 32], the environment in form of non-contact based approaches [21, 14], or different body parts, such as arms and hands [12, 13], upper- and lower-body [9, 44], and feet [10].

Notable prototypes have been reported for rendering thermal feedback in VR are Therminator [12], a wearable sleeve that uses a flowing liquid to render temperature, which was also implemented in PneuMod [61] but with air as the working fluid. Chernyshov et al. [8] and Cai et al. [6] also used water and air to convey haptics, however, they packed it in gloves. Other authors such as Hoffmann et al. [17] integrated thermal feedback in a handheld device, while Ragozin [43] and Peiri [42] integrated it directly in the Head Mounted Displays (HMD), and Eska et al. [10] explored thermal feedback on the feet.

Nevertheless, the vast majority of devices that provide high-definition thermal feedback still require to be worn or are bulky. In this manuscript, we follow instead, an approach that can be used without the need to wear anything, that can provide a wide range of thermal sensations, and is incremental to the existing literature of encountered-type haptic end-effectors.

3 Implementation: A Thermal ETHD

In this paper, we designed an ETHD end-effector that enables VR thermal rendering. Unlike previous approaches, we do not use pneumatics or hydraulics to vary the temperature of the tactile surface; instead, we strategically placed an array of Peltier elements in the end-effector surface to generate the desired thermal stimuli while keeping the hands of participant unoccluded for interaction. This section describes our thermal encountered-type haptic display system and design strategies. In detail, we (1) describe the hardware required to build the interface, (2) report the user intent prediction strategy to locate the end effector in the virtual environment timely, and (3) propose two different thermal rendering strategies. All the materials used in this paper are available

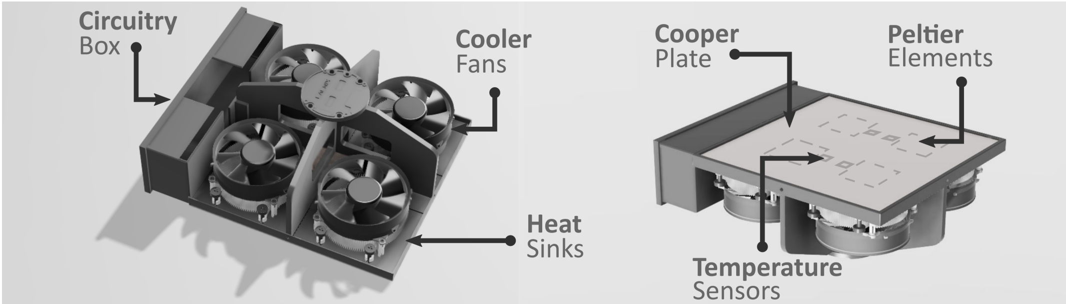

Figure 3: System architecture overview: Summary of the major physical components of the proposed end-effector

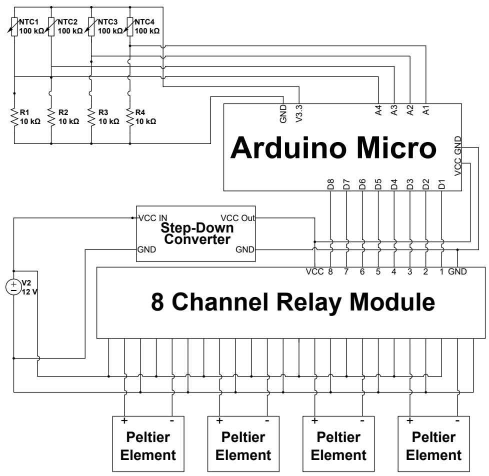

Figure 4: System electronic schematic: The system is powered by an Arduino micro microcontroller and an 8 channel relay module for power control of the Peltier modules

at https://github.com/mimuc/RoboThermalHaptics for replicability.

3.1 Hardware

We used a Kinova Gen3 Cobot as our base platform. The cobot was controlled directly from the graphic engine Unity3D using a control package provided by Villa and Mayer [53]. We used an Acer Predator Laptop with a Nvidia 2070 graphic card and an HTC Vive Pro Headset to run the VR application. We also used a LeapMotion for hand tracking and a Vive Tracker for detecting the hand position outside the LeapMotion tracking as done previously by [54].

3.1.1 End-effector Design

Our end-effector design is based on a 3D-printed model containing all the system components. The model is designed to be attached to the robot arm using a default Kinova connection. It comprises four parts: the main body, 225mmX225mm cooper plate, securing frame, and a circuitry box. The main body contains the core components of the system, the copper plate serves as a thermal transfer medium and provides a flat surface for the thermal stimuli, the securing frame is used to keep the copper plate in place and pressured to the peltier elements, and, finally, the circuitry box host the electronics of the end-effector.

The cover is attached to the main body using four M3 screws. The main body is attached to the robot arm using the Kinova default connector. The end-effector is designed to be printed on a consumer 3D printer (Bambu Lab p1s). The end-effector weighs 2.3 kg, which is well within the payload capacity of the robot arm (4kg).

The main body of the end effector has four spaces of 40mmx40mm to fit the Peltier modules and four smaller 10mm radius holes for the temperature sensors in the frontal side. On the back side, it has four screw spaces around the Peltier holes to fit heat sinks and cooling fans. The interface between the Peltier modules and the copper plates was filled with small copper inserts and thermal pads for optimal heat transfer, while the interface between the Peltier modules and the heat sinks was filled with thermal paste for dissipation. The holes of the temperature sensors were filled with thermal paste to ensure heat transfer between the copper plate and the body of the sensors. We used 4 Peltier elements rated 57 Watt; for the heat sink and cooling fans, we used the AMD Wraith Stealth Socket AM4. For the temperature sensors, we used NTC thermistors (see Figure 3). We selected copper as the conducting material given its high thermal transfer compared to materials such as aluminum or iron, and the plate had a thickness of 1mm to optimize thermal transfer speed.

3.1.2 Circuit Design

The electronics driving the end-effector functionality is composed of an Arduino micro microcontroller which controls an 8-channel relay module that drives the power from the power supply to the Peltier modules. The power supply is set to deliver 12V and a maximum of 10A to the system. We used a step-down circuit to reduce the voltage from 12V to 5V supported by the Arduino board. For temperature measurements, we use four NTC thermistors 100$k\Omega$. We used an HCS 3602 USB power supply which can deliver a maximum of 32V at 30A in the current prototype. For details on the circuit configuration, see Figure 4

3.1.3 Firmware Design

The microcontroller featured a simple binary delayed setpoint strategy for temperature control; As thermodynamic phenomena are typically slow in nature, we implemented a binary temperature control strategy with a dead zone and a switch delay. Temperature control is implemented for each peltier element individually. When the temperature measured by the closer temperature sensor is below the setpoint plus the temperature tolerance, the Peltier element will be set to heat; when the measured temperature by the closer temperature sensor is above the setpoint minus the temperature tolerance, the Peltier element will be set to cool-down. The system communicates with the virtual environment using serial communication via USB and allowing individual control of the Peltier elements and set of target temperatures for each element.

3.2 Intent Prediction Strategy

The intent prediction algorithm incorporates gaze tracking and hand velocity assessment, with the interaction phase dictated by the latter's speed. The system persistently monitors the hand's position

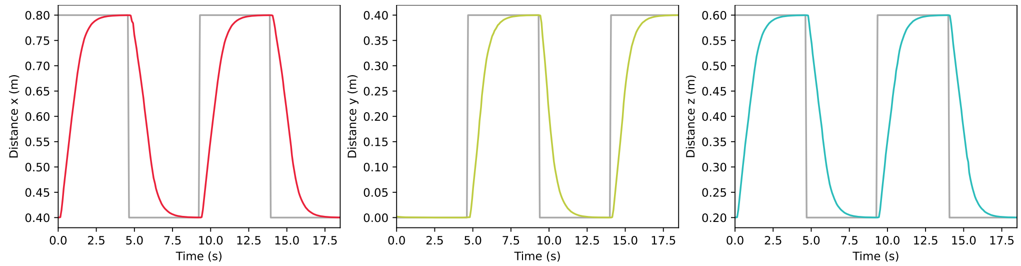

Figure 5: Robot end-effector relocation speed assessment, in grey: the target position. Plots per axis.

and velocity, triggering a gaze-based target prediction via raycasting from the head's position until the hand speed crosses a 3 cm/s threshold.

Upon reaching or surpassing this velocity threshold, the algorithm assumes a straight-line reaching trajectory and employs a direction vector from the index finger's tip for raycasting to identify potential interaction points within the environment. If the projected interaction target lies beyond the system's reachable workspace—defined as a radius of 90 cm from the robot base—a reach redirection strategy is implemented. Here, the redirection origin is marked at the point where the hand velocity first exceeds the threshold.

This approach integrates the REACH+ [11, 57] algorithm for refining the hand position offset and applies a smoothstep interpolation for a natural interaction flow. User disengagement is recognized when the hand's average speed toward an intended target falls below 0.5 cm/s for a duration exceeding 100 ms. For experimental purposes, the system architecture was augmented to incorporate a reactive relocation feature, enabling the robot to adjust its position towards a pre-established location of the interactable object as dictated by the experimental task parameters. This enhancement retains the foundational intent prediction mechanisms of hand speed thresholding and gaze tracking yet introduces a dynamic spatial adjustment to facilitate user interaction.

3.3 Thermal Rendering Strategies

Thermal phenomena are slow in nature, making it challenging to achieve drastic changes in temperature in a short time, especially when the area to heat up or cool down is big. To address these challenges, we propose two thermal rendering strategies that can be leveraged depending on the rendering requirements:

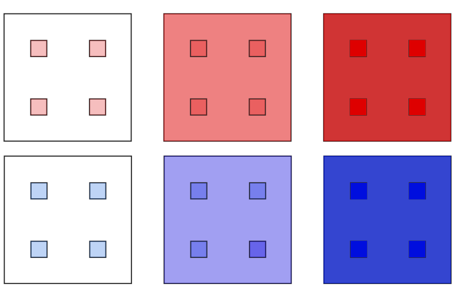
Figure 6: Render Strategy 1: All the Peltier modules act together to achieve a whole-plate temperature level

3.3.1 Whole plate rendering method

With this method, it is possible to render a target temperature across the whole plate, enabling a bigger area of touch. In this method, the target temperature is set to the desired value, and the plate will reach the desired temperature within a given time. Then, using the end-effector intent prediction, the end effector is located in the encountered locations during the interaction. As a disadvantage, the time to reach the target temperature can be high, especially in temperatures far from room temperature, given extreme temperatures require a higher energy consumption (see Figure 6).

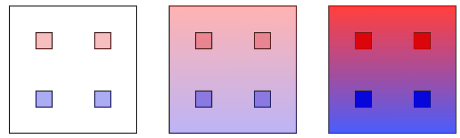
Figure 7: Render Strategy 2: A thermal gradient is rendered by setting two elements to heat up and two to cool down, temperature selection is done by setting the encountered location at the desired temperature

3.3.2 Gradient rendering method

With this method, it is possible to render a spectrum of temperatures across the whole plate, quickly enabling access to a wide range of temperatures. In this method, half of the Peltier elements are set to a high temperature. In contrast, the other half is set to a low temperature and held in this configuration during interaction. Then, using the end-effector intent prediction, the end effector is located in the encountered locations during the interaction, and the target temperature is modulated using the REACH+ algorithm to redirect the users to touch the desired temperature point in the gradient (see Figure 7). As a disadvantage, the temperature interaction area can significantly be reduced, which can be especially noticeable when the user uses the whole hand to interact or slides their finger through the surface.

4 Technical Assessment

To characterize the proposed system's technical capabilities, we conducted two relevant technical tests for Thermal ETHDs: First, the movement capabilities of the system to relocate itself, and second, a thermal dynamics assessment of the end-effector. In this section, we report the results of these tests.

4.1 Robot Relocation Speed Assessment

To characterize the system's translational dynamics, we implemented an automated evaluation procedure, assessing the robot's velocity across each translational axis with the actual hardware in operation. Specifically, the robot was instructed to traverse a linear path between two points, designated as A and B, separated by a distance of 40 cm. The duration required for the robot to arrive at its destination was recorded and reported in Figure 5. The robot consistently took around 2.5 seconds to reach the target position under the specified conditions. As visible in the figure, the robot approaches rapidly when far from the target and slows down when close to it. All the speeds used in the test are set so as not to go over the maximum allowed cobot speeds in HCI [4].

Additionally, the system's rotational capabilities were analyzed, centering primarily on the pitch and yaw axes due to the marginal impact of roll movements on the effectiveness of static ETHD interactions. For this purpose, the end-effector was rotated through a predetermined arc, transitioning from angle α_a to α_b, where the angular displacement amounted to 90 degrees (Figure 8). The robot also consistently took around 2.5 seconds to reach the target angle. In the figure, it is visible that there is a small overshoot once the target angle is achieved.

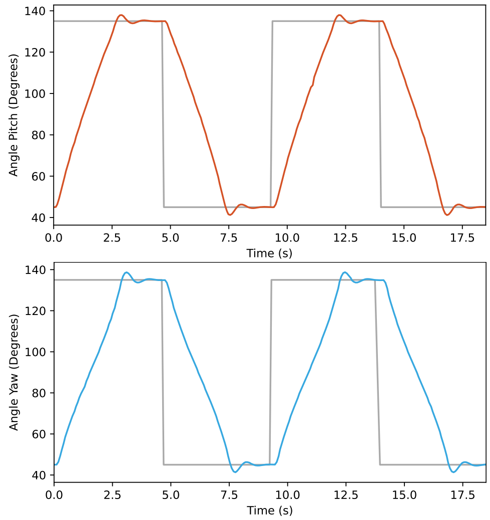

Figure 8: Robot end-effector rotation speed assessment, in grey: the target position. Plots per rotation

4.2 Static Thermal Test

In order to characterize the end-effector's thermal capabilities, we conducted a thermal test following three scenarios: (1) Starting from room temperature and heating up the plate until 85 degrees celsius. (2) Starting from room temperature and cooling down until 10 degrees celsius. Finally, (3) starting from room temperature and generating a heat gradient in the plate. All temperatures were measured using an Optris 28-0023 thermal camera. Figure 9 and Figure 10 depict the transient temperature progression in each scenario, while Figure 11 shows the measured temperature plots in each element. The test for scenario (1) yielded that the end effector achieved a temperature of 70 degrees Celsius in the first minute and a temperature of 85 degrees Celsius for almost four minutes, an absolute difference of 56 degrees Celsius. In contrast, in scenario (2), After four minutes, the system reached an average of 14 degrees Celsius, an absolute temperature change of 14 degrees Celsius. Achieving a stable gradient took a total of four minutes; the measured temperature between the sides of the gradient was 20 degrees Celsius.

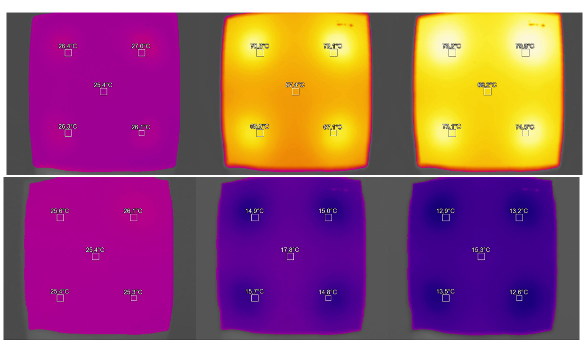

Figure 9: Thermal test for whole-plate temperature control. Top: Heating up, Bottom: Cooling down, both starting from room temperature

5 User Experience Assessment

ETHDs have been shown to improve immersion [33], realism [34], and overall experience in VR [3]; therefore, the baseline condition of this study was chosen accordingly: we evaluate the encountered type of haptic feedback with and without additional thermal feedback on top. This reduces confounding variables, such as the kinaesthetic feedback being the main contributor to the haptic experience or immersion. Therefore, the results of this study have to be considered in addition to the benefits of ETHDs that have already been reported in the literature [35]. To assess the capabilities of the proposed system to enhance the VR experience, we conducted a within-subject, in-lab study with 26 participants using the gradient rendering method of the system with and without thermal feedback. In this section, we describe and report on such a study.

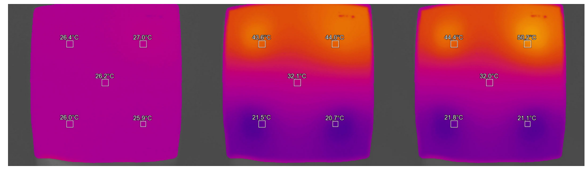

Figure 10: Thermal test for gradient temperature control

5.1 Task

Participants were required to engage in a VR exploration game involving interaction with various objects within the virtual environment: a cutting board, cereal box, microwave, toaster, sandwiches in Fridge, and a cake container. They were instructed to navigate around these objects to explore them, receiving directional cues for subsequent interactions. Each object was designed to convey thermal properties reflective of its type and condition. The task was finished once the participant interacted with all the objects.

5.2 Participants

26 participants took part in the experiment, from which 2 were removed from the analysis given due to irregular setup behavior, leading to a total of 24 participants; participants were primarily University Students with an average age of 23 years old (M=23.04, SD= 2.20); 6 participants self-reported to be female, 16 to be male and 1 preferred not to disclose. One participant reported high familiarity with VR, 11 reported using VR often, and 12 reported low familiarity with VR. Participants were recruited using the university communication channels. Each participant was compensated with 10 Euros/Hour. The study had an average duration of 50 minutes (M=50.60, SD=11.8). The recruitment and study procedures were conducted in accordance with the LMU Munich IRB guidelines to ensure the ethical treatment of all participants.

Table 1: HX Questionnaire Items: Please notice that we used the original item labeling proposed by the authors of the questionnaire

Item	Question	Factor
R1	The haptic feedback was realistic	**Realism**
R2	The haptic feedback was believable	**Realism**
R3	The haptic feedback was convincing	**Realism**
H3	The haptic feedback felt disconnected from the rest of the experience	**Harmony**
H5	The haptic feedback felt out of place	**Harmony**
I1	The haptic feedback distracted me from the task	**Harmony**
H2	I like having the haptic feedback as part of the experience	**Involvement**
I2	I felt engaged with the system due to the haptic feedback	**Involvement**
E4	The haptic feedback changes depending on how things change in the system	**Expressivity**
E5	The haptic feedback reflects varying inputs and events	**Expressivity**
E1	The haptic feedback all felt the same	**Expressivity**

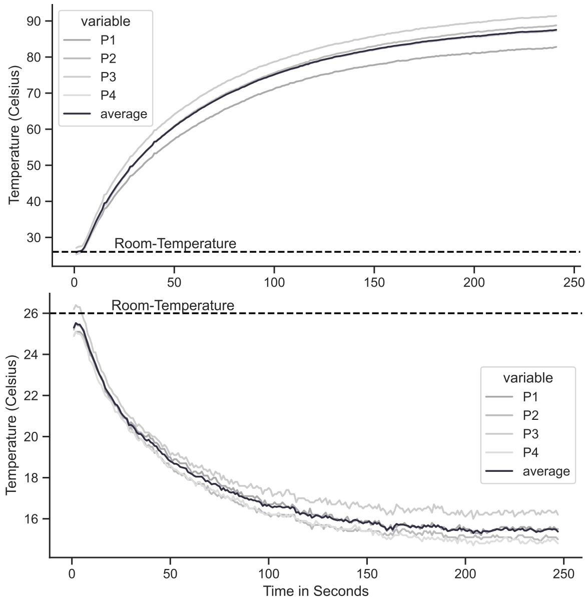

Figure 11: Thermal response. Top: Heating up, Bottom: Cooling down, starting from room temperature. PN refers to Peltier elements

5.3 Measures

We collected VR experience data with two questionnaires; the Igroup Presence Questionnaire questionnaire measured presence in three subscales: Spatial Presence, Involvement, and Realism [47]. And the HX model questions proposed by Anwar et al. [2] and originally derived from Sathiyamurthy et al. [46] to measure haptic experience across multiple haptic modalities. This set of items includes four factors: Realism, Harmony, Involvement, and Expressivity. While the realism factor measured by the IPQ focuses on the contrast between virtual and real feedback, assessing how closely virtual experiences mimic real life, the HX realism evaluates the plausibility of the haptic feedback itself. Finally, we included 3 custom questions: *How easy was it to identify objects through physical interaction, like touching an object or bumping into an object? (Q1).* , *How easily did you adjust to the control devices used to interact with the virtual environment? (Q2).* , and, *Was the information provided through different senses in the virtual environment (e.g., vision, hear- ing, touch) consistent? (Q3).*

5.4 Procedure

On arrival, the experimenter introduced the participant to the study goals and procedure and requested informed consent for participation. Afterward, the participant was asked to fill out a pre-study questionnaire, asking about their previous experience with VR, handedness, and demographic information. The experimenter then explained the study's procedure and the experimental tasks.

The participant was then asked to put on the VR headset, and the experimenter proceeded to calibrate the VR setup for the participant. Afterward, the participants were asked to interact with the objects to familiarize themselves with the VR setup and the interaction mechanics. The task included interaction with the whole system, where the participant had to touch several points in the virtual objects with a virtual representation of the robot so that the participants knew that the physical robot was moving.

After the training tasks, the participant was asked to perform the experimental tasks without feedback from the real robot location so as not to break immersion. The participant was asked to perform the tasks in a counterbalanced order and complete the questionnaires after each condition. After completing all tasks, the participants participated in a semi-structured interview, were debriefed about the experiment, and were finally compensated.

5.5 Results

In the following section, we report the results of our user study in which we compared the utility of temperature feedback (`with temperature`) against a system without temperature feedback (`without temperature`). For aggregated (grouped and averaged) values like the IPQ questionnaire, we report the mean (M) and standard deviation (SD). For individual questions, we report the median and the Median Absolute Deviation (MAD) as a measure of variability. Figure 12 depicts all dependent variables grouped by our two conditions. The table presented in **??** lists all significance tests.

5.6 IGroup Presence questionnaire

We analyzed the impact of our independent variable on the participants' perceived presence using the IGroup Presence questionnaire (IPQ). Similarly to the approach of the IPQ's authors[1], we calculated the group means and used parametric tests to analyze the data. For this, we first checked the data for normality using Shapiro–Wilk's test, where we found no violation of the assumption of normality (sp: $W = 0.93, p = 0.11$, inv: $W = 0.94, p = 0.18$, real: $W = 0.92, p = 0.07$). Therefore, we proceeded with paired-samples t-tests. The analysis indicated a significant ($p < .05$) effect on *realism (real)* (`without temperature`: $M = 2.44$, $SD = 0.6$, `with temperature`: $M = 2.65$, $SD = 0.65$). Besides that, the analysis did not reveal significant effects for the other two subscales *spatial presence (sp)* (`without temperature`: $M = 3.64$, $SD = 0.55$, `with temperature`: $M = 3.69$, $SD = 0.47$) and *involvement (inv)* (`without temperature`: $M = 3.08$, $SD = 0.83$, `with temperature`: $M = 3.39$, $SD = 0.59$).

Table 2: Significance test for the dependent variables.

	DV	Test	Statistic	*p*	*sig*
IPQ	sp	*t*-test	t(23) = -0.45	.659	
	inv	*t*-test	t(23) = -1.8	.086	
	real	*t*-test	t(23) = -2.29	.032	*
HX - Realism	R1	wilcox	W = 23	.239	
	R2	wilcox	W = 16.5	.092	
	R3	wilcox	W = 56	.651	
HX - Harmony	H3	wilcox	W = 62	.916	
	H5	wilcox	W = 68	.668	
	I1	wilcox	W = 30	1.000	
HX - Involvement	H2	wilcox	W = 12	.562	
	I2	wilcox	W = 9	.009	**
HX - Expressivity	E4	wilcox	W = 26	.007	**
	E5	wilcox	W = 10.5	.013	*
	E1	wilcox	W = 167.5	.002	**
Own Questions	Q1	wilcox	W = 3.5	.027	*
	Q2	wilcox	W = 8	.453	
	Q3	wilcox	W = 24	.505	

5.7 Haptic Experience

Further, we assessed the haptic experience of our participants using the Haptic Experience questionnaire as proposed by Anwar et al. [2] Similar to [49], we decided to test the items individually. Because of the non-parametric nature of the data, we used Wilcoxon signed-rank test to test for significant differences between the paired samples. In the following, we only report the significant results. The remaining questions as well as all significance tests can be found in Table 2.

[1]https://www.igroup.org/pq/ipq/data.php, Retrieved July 22, 2024

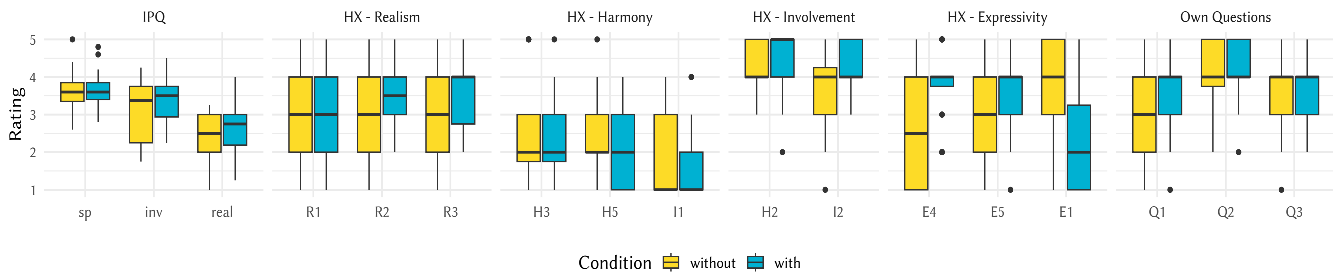

Figure 12: Boxplots of the dependent variables meassured in the study.

The analysis indicated a significant ($p < .01$) effect on the item *I felt engaged with the system due to the haptic feedback (I2)* with a higher agreement for `with temperature` ($M = 4$, $MAD = 0$) compared to `without temperature` ($M = 4$, $MAD = 1.48$).

Also, we found a significant ($p < .01$) effect on the item *The haptic feedback changes depending on how things change in the system (E4)* with, again, higher agreement for `with temperature` ($M = 4$, $MAD = 0$) compared to `without temperature` ($M = 2.5$, $MAD = 2.22$). Additionally, the analysis showed a significant ($p < .05$) effect on the item *The haptic feedback reflects varying inputs and events (E5)*. As before, `with temperature` ($M = 4$, $MAD = 1.48$) resulted in higher agreement compared to `without temperature` ($M = 3$, $MAD = 1.48$). Finally, we found a significant ($p < .01$) effect on item *The haptic feedback all felt the same (E1)* with higher agreement for `without temperature` ($M = 4$, $MAD = 1.48$) compared to `with temperature` ($M = 2$, $MAD = 1.48$).

5.8 Custom Questions

Besides the standardized questionnaires, we employed three custom questions to gain further insights into the appropriateness of temperature feedback for encountered-type haptic feedback. First, we asked participants *How easy was it to identify objects through physical interaction, like touching an object or bumping into an object? (Q1)*. The analysis indicated a significant ($p < .01$) effect with higher ratings for `with temperature` ($M = 4$, $MAD = 1.48$) compared to `without temperature` ($M = 3$, $MAD = 1.48$). Second, we asked our participants *How easily did you adjust to the control devices used to interact with the virtual environment? (Q2)*. The analysis did not indicate a significant difference between `with temperature` ($M = 4$, $MAD = 1.48$) and `without temperature` ($M = 4$, $MAD = 1.48$). Finally, we asked our participants *Was the information provided through different senses in the virtual environment (e.g., vision, hearing, touch) consistent? (Q3)*. Again, the analysis did not show a significant difference between `with temperature` ($M = 4$, $MAD = 0.74$) and `without temperature` ($M = 4$, $MAD = 1.48$).

6 Discussion

Through our two evaluations, we have shown the technical feasibility and the suitability of the approach to deliver more realistic VR experiences. In the following, we discuss the implications of our findings.

6.1 The Implementation of a temperature-enabled ETHD

We found from our technical tests that the system takes around 2.5 seconds to achieve a target point 40cm away from the initial point at the maximum recommended speeds for cobot interaction. Aligned with literature [35, 11], this highlights the relevance of implementing intent prediction strategies. In this work, we used a combination of gaze-based prediction and hand trajectory tracking to relocate the cobot end-effector preemptively.

With regard to thermal rendering, we propose two rendering strategies. First, setting all the Peltier elements simultaneously to the target temperature allows for a bigger rendering area, which is especially useful for multi-finger or full-hand surface palpation and also allows a more consistent temperature rendering across the surface. Yet, it requires more time to be ready for temperature rendering as it has to change the temperature of the whole thermal plate for each target temperature. This is especially critical at higher temperature differences and is further impaired when trying to reach low temperatures, which are generally more energy-intensive when using Peltier elements. The second rendering strategy exploits the multiple Peltier elements in the end effector to create a thermal gradient containing the lowest and highest temperatures. This rendering method provides the advantage of rapidly switching temperatures, given that the temperature is location-based within the end-effector plate, and the contact point can be altered using hand redirection. However, temperatures are not uniform through the plate, which means that sliding through the plate in the direction of the gradient will let the user know that the temperature is not uniform. We show how such a rendering strategy would work in subsection 3.3.

On the other hand, the non-uniform temperature rendered using gradient rendering can be beneficial for generating thermal affordances such as temperature-based sliders, where, on one side, the slider's value is cold, and, on the other, it is warm.

6.2 The integration of temperature feedback enhances the realism of haptic VR Experiences

From the user study, we found that the added thermal feedback influenced the participant's presence as defined by the IPQ questionnaire Realism factor but not in the Spatial Presence or Involvement factors. The ratings for these two factors were already positive compared to those for traditional ETHD. At the same time, realism had a more mixed rating from participants, suggesting that adding thermal feedback can support these ratings where ETHD does not perform well. On a perceptual level, this can be explained by sensory immersion; object properties include stiffness, temperature, and texture. While typical ETHD provides kinaesthetic and tactile sensory information, the proposed system adds additional stimulation that increases haptic immersion.

This contrasts the realism factor of the Haptic Experience questionnaire, which addresses the plausibility of the haptic feedback (**HX - Realism**) rather than the contrast of the virtual and real feedback (**IPQ - Real**). In this sense, thermal ETHD and typical ETHD had similar ratings in the **HX - Realism** with only indistinguishable higher ratings (higher is better) favoring thermal ETHD.

Regarding the Haptic Experience questionnaire, we found that the thermal ETHD significantly enhanced the haptic experience's Expressivity component (**HX - Expressivity**) in all the subscale items (notice that E1 is a reversed polarity item). This suggests the thermal ETHD was perceived as more dynamic by the experiment participants and better integrated with the events occurring in the virtual environment.

Regarding the Involvement factor (**HX - Involvement**), we found a significant impact of the thermal ETHD over the typical ETHD, with higher ratings in the item *I felt engaged with the sys-*

tem due to the haptic feedback (I2) (higher is better), but not for the other item (H2) which may be due to the already positive ratings for both versions of the system. This might be partially a limitation of the questionnaire item, given that this item apparently saturates at some level of haptic immersion (we can call this a ceiling effect).

The final factor from the Haptic Experience questionnaire is the Harmony factor (**HX - Harmony**), which presented no significant differences nor ceiling effects, suggesting no improvement of thermal ETHDs over the overall haptic experience.

Regarding the custom questions, we found significant effects only in Q1: *How easy was it to identify objects through physical interaction, like touching an object or bumping into an object?* suggesting that thermal ETHDs do improve the identification of material properties given the higher haptic immersion, coherently with **IPQ-Real**.

Although typical ETHD has been shown to improve the overall VR and haptic experience, we found that adding thermal feedback can substantially improve ETHD, making it reasonable to consider it as a component to be integrated into future haptic interfaces.

7 Limitations and Future Work

Although the proposed system offers substantial benefits, the system itself and the configuration space explored in this paper have several limitations outlined in this section.

First, regarding the overall setup, similar to other non-vibrotactile-only haptic interfaces, the current setup can be rather complex for the current consumer market and average VR user. On the technical side, it is worth highlighting that even if the current setup is more compact and less cumbersome than several setups presented in the literature that use fluid dynamics to transfer temperature [12, 7]. Using peltier elements demands a high energy consumption, making it unsuitable to be integrated directly into the cobot interface for power supply. Instead, it is necessary to use a high-power power supply. For the current evaluations, we set the maximum power consumption to 12V and 10A, which were used constantly almost all the time when rendering temperatures far from room temperature. Regarding the tested configurations, we acknowledge that the interaction space might be bigger than the one explored in this paper, including interactions such as transient temperature interactions. For example, a teapot gets hot while the participant touches it, or elements freeze after being exposed to hydrogen.

8 Conclusion

Thermal feedback in Encountered-type Haptic Displays (ETHDs) significantly impacts the VR experience in multiple ways, especially in the perceived expressivity of the system (as measured by the Haptic Experience questionnaire). Some aspects of the haptic experience are already positively rated by participants for typical ETHDs (such as Spatial Presence, IPQ Involvement, and HX Involvement), yet in the factors where typical ETHDs do not perform as well; thermal ETHDs are especially impactful for rounding up an overall enhances VR experience. In this paper, we propose thermal-enabled ETHDs for VR; we present the system's design and report two technical tests and a user study evaluating the user experience in VR.

References

[1] M. Abdullah, M. Kim, W. Hassan, Y. Kuroda, and S. Jeon. HapticDrone: An encountered-type kinesthetic haptic interface with controllable force feedback: Example of stiffness and weight rendering. In *2018 IEEE Haptics Symposium (HAPTICS)*, pp. 334–339, Mar. 2018. ISSN: 2324-7355. doi: 10.1109/HAPTICS.2018.8357197 2

[2] A. Anwar, T. Shi, and O. Schneider. Factors of Haptic Experience across Multiple Haptic Modalities. In *Proc. of the 2023 CHI Conf.*, pp. 1–12. ACM, Hamburg Germany, Apr. 2023. doi: 10.1145/3544548.3581514 6

[3] B. Araujo, R. Jota, V. Perumal, J. X. Yao, K. Singh, and D. Wigdor. Snake Charmer: Physically Enabling Virtual Objects. In *Proc. of the TEI '16: Tenth Intl. Conf. on Tangible, Embedded, and Embodied Interaction*, pp. 218–226. ACM, Eindhoven Netherlands, Feb. 2016. doi: 10.1145/2839462.2839484 2, 5

[4] R. Bogue. Robots that interact with humans: a review of safety technologies and standards. *Industrial Robot: An Intl. Journal*, 44(4):395–400, Jan. 2017. Publisher: Emerald Publishing Limited. doi: 10.1108/IR-04-2017-0070 4

[5] E. Bouzbib and G. Bailly. "Let's Meet and Work it Out": Understanding and Mitigating Encountered-Type of Haptic Devices Failure Modes in VR. In *VR 2022 - IEEE Conf. on Virtual Reality*. IEEE, Christchurch, New Zealand, Mar. 2022. 2

[6] S. Cai, P. Ke, T. Narumi, and K. Zhu. ThermAirGlove: A Pneumatic Glove for Thermal Perception and Material Identification in Virtual Reality. In *2020 IEEE Conf. on Virtual Reality and 3D User Interfaces (VR)*, pp. 248–257. IEEE, Atlanta, GA, USA, Mar. 2020. doi: 10.1109/VR46266.2020.00044 2

[7] S. Cai, P. Ke, T. Narumi, and K. Zhu. ThermAirGlove: A Pneumatic Glove for Thermal Perception and Material Identification in Virtual Reality. In *2020 IEEE Conf. on Virtual Reality and 3D User Interfaces (VR)*, pp. 248–257, Mar. 2020. ISSN: 2642-5254. doi: 10.1109/VR46266.2020.00044 8

[8] G. Chernyshov, K. Ragozin, C. Caremel, and K. Kunze. Hand motion prediction for just-in-time thermo-haptic feedback. In *Proc. of the 24th ACM Symposium on Virtual Reality Software and Technology*, pp. 1–2. ACM, Tokyo Japan, Nov. 2018. doi: 10.1145/3281505.3281573 2

[9] A. El Ali, X. Yang, S. Ananthanarayan, T. Röggla, J. Jansen, J. Hartcher-O'Brien, K. Jansen, and P. Cesar. Thermalwear: Exploring wearable on-chest thermal displays to augment voice messages with affect. In *Proc. of the 2020 CHI Conf.*, pp. 1–14. ACM, New York, NY, USA, apr 2020. doi: 10.1145/3313831.3376682 2

[10] B. Eska, J.-O. Iyalekhue, S. Günther, J. Niess, and F. Müller. Thermfeet: Assessing on-foot thermal stimuli for directional cues. In *Proc. of the 22nd Intl. Conf. on Mobile and Ubiquitous Multimedia*, MUM '23, p. 166–171. ACM, New York, NY, USA, 2023. doi: 10.1145/3626705.3627974 2

[11] E. J. Gonzalez, P. Abtahi, and S. Follmer. REACH+: Extending the Reachability of Encountered-type Haptics Devices through Dynamic Redirection in VR. In *Proc. of the 33rd Annual ACM Symposium on User Interface Software and Technology*, UIST '20, pp. 236–248. ACM, New York, NY, USA, Oct. 2020. doi: 10.1145/3379337.3415870 2, 4, 7

[12] S. Günther, F. Müller, D. Schön, O. Elmoghazy, M. Mühlhäuser, and M. Schmitz. Therminator: Understanding the Interdependency of Visual and On-Body Thermal Feedback in Virtual Reality. In *CHI20*, CHI '20, pp. 1–14. ACM, New York, NY, USA, Apr. 2020. doi: 10.1145/3313831.3376195 1, 2, 8

[13] S. Günther, A. Skogseide, R. Buhlmann, and M. Mühlhäuser. Assessing the influence of visual cues in vr on the spatial perception of physical thermal stimuli. In *(to appear) Proc. of the CHI Conf. (CHI '24)*. ACM, New York, NY, USA, May 2024. doi: 10.1145/3613904.3642154 2

[14] P.-H. Han, Y.-S. Chen, K.-C. Lee, H.-C. Wang, C.-E. Hsieh, J.-C. Hsiao, C.-H. Chou, and Y.-P. Hung. Haptic around: Multiple tactile sensations for immersive environment and interaction in vr. In *Proc. of the 24th ACM Symposium on VR Software and Technology*, pp. 1–10. ACM, New York, NY, USA, nov 2018. doi: 10.1145/3281505.3281507 2

[15] B. Hannaford and A. M. Okamura. Haptics. In B. Siciliano and O. Khatib, eds., *Springer Handbook of Robotics*, pp. 1063–1084. Springer Intl. Publishing, Cham, 2016. doi: 10.1007/978-3-319-32552-1_42 2

[16] H.-N. Ho, H. M. Chow, S. Tsunokake, and W. Roseboom. Thermal-Tactile Integration in Object Temperature Perception. *IEEE Transactions on Haptics*, 12(4):594–603, Oct. 2019. Conf. Name: IEEE Transactions on Haptics. doi: 10.1109/TOH.2019.2894153 2

[17] P. P. Hoffmann, H. Elsayed, M. Mühlhäuser, R. R. Wehbe, and M. D. Barrera Machuca. ThermalPen: Adding Thermal Haptic Feedback to

3D Sketching. In *Extended Abstracts of the 2023 CHI Conf.*, CHI EA '23, pp. 1–4. ACM, New York, NY, USA, Apr. 2023. doi: 10.1145/3544549.3583901 2

[18] M. Hojatmadani, S. Shepard, K. Salomon, and K. Reed. A Controlled Study on Evaluation of Thermal Stimulation Influence on Affective Measures of Uninformed Individuals, Nov. 2023. arXiv:2311.12989 [cs]. 2

[19] T. Howard, G. Gallagher, A. Lécuyer, C. Pacchierotti, and M. Marchal. Investigating the Recognition of Local Shapes Using Mid-air Ultrasound Haptics. In *2019 IEEE World Haptics Conf. (WHC)*, pp. 503–508, July 2019. doi: 10.1109/WHC.2019.8816127 2

[20] H.-Y. Huang, C.-W. Ning, P.-Y. Wang, J.-H. Cheng, and L.-P. Cheng. Haptic-go-round: A Surrounding Platform for Encounter-type Haptics in Virtual Reality Experiences. In *CHI20*, pp. 1–10. ACM, Honolulu HI USA, Apr. 2020. doi: 10.1145/3313831.3376476 2

[21] D. Iwai, M. Aoki, and K. Sato. Non-contact thermo-visual augmentation by ir-rgb projection. *IEEE Transactions on Visualization and Computer Graphics*, 25(4):1707–1716, apr 2019. doi: 10.1109/TVCG.2018.2820121 1, 2

[22] L. Jones. *Haptics*. MIT Press, Sept. 2018. Google-Books-ID: SrT4DwAAQBAJ. 2

[23] L. Jones and H.-N. Ho. Warm or cool, large or small? the challenge of thermal displays. *IEEE Transactions on Haptics*, 1(1):53–70, jan 2008. doi: 10.1109/TOH.2008.2 1, 2

[24] M. Kocur, L. Jackermeier, V. Schwind, and N. Henze. The effects of avatar and environment on thermal perception and skin temperature in vr. In *CHI23*, vol. 1, pp. 1–15. ACM, New York, NY, USA, apr 2023. doi: 10.1145/3544548.3580668 2

[25] V. Kotsev, A. Nikolev, K. Pawlak, and M. Löchtefeld. Investigating the usage of thermal feedback as an active game element. In *Proc. of the 16th Intl. Conf. on Mobile and Ubiquitous Multimedia*, pp. 91–95. ACM, New York, NY, USA, nov 2017. doi: 10.1145/3152832.3152853 2

[26] J. Li and L. Hirsch. Multi-modal transition and traces in everyday mobile vr. In H.-C. Jetter, J.-H. Schröder, J. Gugenheimer, M. Billinghurst, C. Anthes, M. Khamis, and T. Feuchtner, eds., *ISS'21 Workshop Proceedings: "Transitional Interfaces in Mixed and Cross-Reality: A new frontier?"*, 2021. doi: 10.18148/kops/352-2-1dhqpjucpo75v9 2

[27] Y. Liu, S. Nishikawa, Y. a. Seong, R. Niiyama, and Y. Kuniyoshi. ThermoCaress: A Wearable Haptic Device with Illusory Moving Thermal Stimulation. In *Proc. of the 2021 CHI Conf.*, CHI '21, pp. 1–12. ACM, New York, NY, USA, May 2021. doi: 10.1145/3411764.3445777 2

[28] M. Luo, Z. Wang, H. Zhang, E. Arens, D. Filingeri, L. Jin, A. Ghahramani, W. Chen, Y. He, and B. Si. High-density thermal sensitivity maps of the human body. *Building and Environment*, 167:106435, jan 2020. doi: 10.1016/j.buildenv.2019.106435 1

[29] M. Löchtefeld, T. Lappalainen, J. Väyrynen, A. Colley, and J. Häkkilä. Comparing thermal and haptic feedback mechanisms for game controllers. In *Proc. of the 2017 CHI Conf. Extended Abstracts on Human Factors in Computing Systems*, pp. 1829–1836. ACM, New York, NY, USA, may 2017. doi: 10.1145/3027063.3053172 2

[30] R. Meguro, P. Ratsamee, T. Mashita, Y. Uranishi, and H. Takemura. FrictionHaptics : Encountered-Type Haptic Device forTangential Friction Emulation. In *2019 IEEE Intl. Symposium on Mixed and Augmented Reality Adjunct (ISMAR-Adjunct)*, pp. 382–383, Oct. 2019. doi: 10.1109/ISMAR-Adjunct.2019.000-6 2

[31] L. A. Mendez S., H. Y. Ng, Z. Y. Lim, Y.-J. Lu, and P.-H. Han. MovableBag: Substitutional Robot for Enhancing Immersive Boxing Training with Encountered-Type Haptic. In *SIGGRAPH Asia 2022 XR*, SA '22, pp. 1–2. ACM, New York, NY, USA, Nov. 2022. doi: 10.1145/3550472.3558406 2

[32] X. Meng, J. Han, G. Chernyshov, K. Ragozin, and K. Kunze. Thermaldrive - towards situation awareness over thermal feedback in automated driving scenarios. In *27th Intl. Conf. on Intelligent User Interfaces*, pp. 101–104. ACM, New York, NY, USA, mar 2022. doi: 10.1145/3490100.3516453 2

[33] V. Mercado, M. Marchal, and A. Lecuyer. ENTROPiA: Towards Infinite Surface Haptic Displays in Virtual Reality Using Encountered-Type Rotating Props. *IEEE Transactions on Visualization and Computer Graphics*, 27(3):2237–2243, Mar. 2021. doi: 10.1109/TVCG.2019.2963190 1, 2, 5

[34] V. R. Mercado, T. Howard, H. Si-Mohammed, F. Argelaguet, and A. Lécuyer. Alfred: the Haptic Butler On-Demand Tangibles for Object Manipulation in Virtual Reality using an ETHD. In *2021 IEEE World Haptics Conf. (WHC)*, pp. 373–378, July 2021. doi: 10.1109/WHC49131.2021.9517250 2, 5

[35] V. R. Mercado, M. Marchal, and A. Lécuyer. "Haptics On-Demand": A Survey on Encountered-Type Haptic Displays. *IEEE Transactions on Haptics*, 14(3):449–464, July 2021. Conf. Name: IEEE Transactions on Haptics. doi: 10.1109/TOH.2021.3061150 1, 2, 5, 7

[36] T. Narumi, A. Tomohiro, Y. A. Seong, and M. Hirose. Characterizing the space by thermal feedback through a wearable device. In *Lecture Notes in Computer Science (including subseries Lecture Notes in Artificial Intelligence and Lecture Notes in Bioinformatics)*, vol. 5622 LNCS, pp. 355–364. 2009. doi: 10.1007/978-3-642-02771-0_40 2

[37] A. Niijima, T. Takeda, T. Mukouchi, and T. Satou. Thermalbitdisplay: Haptic display providing thermal feedback perceived differently depending on body parts. In *Extended Abstracts of the 2020 CHI Conf.*, pp. 1–8. ACM, New York, NY, USA, apr 2020. doi: 10.1145/3334480.3382849 2

[38] S. Okamoto, H. Nagano, and Y. Yamada. Psychophysical dimensions of tactile perception of textures. *IEEE Transactions on Haptics*, 6(1):81–93, 2013. doi: 10.1109/TOH.2012.32 2

[39] C. Pacchierotti, S. Sinclair, M. Solazzi, A. Frisoli, V. Hayward, and D. Prattichizzo. Wearable haptic systems for the fingertip and the hand: Taxonomy, review, and perspectives. *IEEE Transactions on Haptics*, 10(4):580–600, 2017. doi: 10.1109/TOH.2017.2689006 1, 2

[40] S. Patwardhan, A. Kawazoe, D. Kerr, M. Nakatani, and Y. Visell. Too hot, too fast! Using the thermal grill illusion to explore dynamic thermal perception. In *2018 IEEE Haptics Symposium (HAPTICS)*, pp. 145–150, Mar. 2018. ISSN: 2324-7355. doi: 10.1109/HAPTICS.2018.8357167 2

[41] R. L. Peiris, L. Chan, and K. Minamizawa. Liquidreality: Wetness sensations on the face for vr. In D. Prattichizzo, H. Shinoda, H. Z. Tan, E. Ruffaldi, and A. Frisoli, eds., *EuroHaptics 2018: Haptics: Science, Technology, and Applications*, pp. 366–378. Springer Intl. Publishing, Cham, 2018. doi: 10.1007/978-3-319-93399-3_32 1, 2

[42] R. L. Peiris, W. Peng, Z. Chen, L. Chan, and K. Minamizawa. ThermoVR: Exploring Integrated Thermal Haptic Feedback with Head Mounted Displays. In *Proc. of the 2017 CHI Conf.*, CHI '17, pp. 5452–5456. ACM, New York, NY, USA, May 2017. doi: 10.1145/3025453.3025824 1, 2

[43] K. Ragozin, X. Meng, R. Lalintha Peiris, K. Wolf, G. Chernyshov, and K. Kunze. ThermoQuest - A Wearable Head Mounted Display to Augment Realities with Thermal Feedback. In *20th Intl. Conf. on Mobile and Ubiquitous Multimedia*, pp. 62–66. ACM, Leuven Belgium, May 2021. doi: 10.1145/3490632.3490649 2

[44] K. Ragozin, D. Zheng, G. Chernyshov, and D. Hynds. Sophroneo: Fear not. a vr horror game with thermal feedback and physiological signal loop. In *Extended Abstracts of the 2020 CHI Conf.*, pp. 1–6. ACM, New York, NY, USA, apr 2020. doi: 10.1145/3334480.3381659 2

[45] T. Roumen, S. T. Perrault, and S. Zhao. Notiring. In *Proc. of the 33rd Annual ACM Conf. on Human Factors in Computing Systems*, pp. 2497–2500. ACM, New York, NY, USA, apr 2015. doi: 10.1145/2702123.2702350 2

[46] S. Sathiyamurthy, M. Lui, E. Kim, and O. Schneider. Measuring Haptic Experience: Elaborating the HX model with scale development. In *2021 IEEE World Haptics Conf. (WHC)*, pp. 979–984. IEEE, Montreal, QC, Canada, July 2021. doi: 10.1109/WHC49131.2021.9517220 6

[47] T. Schubert, F. Friedmann, and H. Regenbrecht. The Experience of Presence: Factor Analytic Insights. *Presence: Teleoperators and Virtual Environments*, 10(3):266–281, June 2001. doi: 10.1162/105474601300343603 6

[48] A. R. See, J. A. G. Choco, and K. Chandramohan. Touch, Texture and Haptic Feedback: A Review on How We Feel the World around Us.

Applied Sciences, 12(9):4686, Jan. 2022. Number: 9 Publisher: Multidisciplinary Digital Publishing Institute. doi: 10.3390/app12094686 2

[49] V. Shen, C. Shultz, and C. Harrison. Mouth Haptics in VR using a Headset Ultrasound Phased Array. In *Proc. of the 2022 CHI Conf.*, CHI '22, pp. 1–14. ACM, New York, NY, USA, Apr. 2022. doi: 10.1145/3491102.3501960 6

[50] G. A. d. Souza, L. A. Torres, V. S. Dani, D. S. Villa, A. T. Larico, A. Maciel, and L. Nedel. Evaluation of visual, auditory and vibrotactile alerts in supervised interfaces. In *2018 20th Symposium on Virtual and Augmented Reality (SVR)*, pp. 163–169, 2018. doi: 10.1109/SVR.2018.00033 2

[51] J. Takakura, T. Nishimura, D. Choi, Y. Egashira, and S. Watanuki. Nonthermal sensory input and altered human thermoregulation: effects of visual information depicting hot or cold environments. *Intl. Journal of Biometeorology*, 59(10):1453–1460, oct 2015. doi: 10.1007/s00484-015-0956-3 2

[52] Q. Tong, W. Wei, Y. Zhang, J. Xiao, and D. Wang. Survey on Hand-Based Haptic Interaction for Virtual Reality. *IEEE Transactions on Haptics*, 16(2):154–170, Apr. 2023. Conf. Name: IEEE Transactions on Haptics. doi: 10.1109/TOH.2023.3266199 2

[53] S. Villa and S. Mayer. Cobity: A Plug-And-Play Toolbox to Deliver Haptics in Virtual Reality. In *Proceedings of Mensch und Computer 2022*, MuC '22, pp. 78–84. ACM, New York, NY, USA, Sept. 2022. doi: 10.1145/3543758.3543775 1, 2, 3

[54] S. Villa, S. Mayer, J. Hartcher-O'Brien, A. Schmidt, and T.-K. Machulla. Extended Mid-air Ultrasound Haptics for Virtual Reality. *Proc. of the ACM on Human-Computer Interaction*, 6(ISS):578:500–578:524, Nov. 2022. doi: 10.1145/3567731 1, 2, 3

[55] S. Villa Salazar, J. A. Ticona, R. Torchelsen, L. Nedel, and A. Maciel. Heat-based bidirectional phase shifting simulation using position-based dynamics. *Computers and Graphics*, 76:107–116, 2018. doi: 10.1016/j.cag.2018.09.004 2

[56] C. Wee, K. M. Yap, and W. N. Lim. Haptic Interfaces for Virtual Reality: Challenges and Research Directions. *IEEE Access*, 9:112145–112162, 2021. doi: 10.1109/ACCESS.2021.3103598 2

[57] Y. Weiss, S. Villa, A. Schmidt, S. Mayer, and F. Müller. Using pseudo-stiffness to enrich the haptic experience in vr. In *CHI23*, CHI '23. ACM, New York, NY, USA, 2023. doi: 10.1145/3544548.3581223 4

[58] G. Wilson, E. Freeman, and S. A. Brewster. Multimodal affective feedback: Combining thermal, vibrotactile, audio and visual signals. *ICMI 2016 - Proc. of the 18th ACM Intl. Conf. on Multimodal Interaction*, 9781450345(January):400–401, 2016. doi: 10.1145/2993148.2998522 2

[59] M. Yafune and Y. Yokokohji. Haptically rendering different switches arranged on a virtual control panel by using an encountered-type haptic device. In *2011 IEEE World Haptics Conf.*, pp. 551–556, June 2011. doi: 10.1109/WHC.2011.5945545 2

[60] A. Yamaguchi, S. Yokoi, K. Matsumoto, and T. Narumi. TableMorph: Haptic Experience with Movable Tables and Redirection. In *SIGGRAPH Asia 2023 Emerging Technologies*, SA '23, pp. 1–2. ACM, New York, NY, USA, Nov. 2023. doi: 10.1145/3610541.3614574 2

[61] B. Zhang and M. Sra. PneuMod: A Modular Haptic Device with Localized Pressure and Thermal Feedback. In *Proc. of the 27th ACM Symposium on Virtual Reality Software and Technology*, VRST '21, pp. 1–7. ACM, New York, NY, USA, Dec. 2021. doi: 10.1145/3489849.3489857 2

[62] M. Ziat, C. A. Balcer, A. Shirtz, and T. Rolison. *A Century Later , The Hue-Heat Hypothesis : Does Color Truly Affect Temperature Perception ? A Century Later , the Hue-Heat Hypothesis : Does Color Truly Affect Temperature Perception ?*, vol. 9774 of *Lecture Notes in Computer Science*. Springer Intl. Publishing, Cham, 2016. doi: 10.1007/978-3-319-42321-0 2