# Therminator: Understanding the Interdependency of Visual and On-Body Thermal Feedback in Virtual Reality

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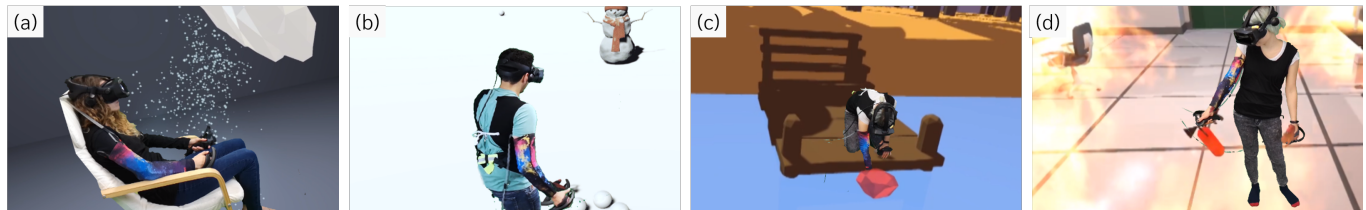schoen@tk.tu-darmstadt.de

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**Figure 1. Therminator concepts and example VR applications showing (a) a user during our experiment with a snow visual stimulus, (b) a cold game environment with a user throwing snowballs, (c) a warm tropical islands, and (d) a firefighting simulation with a user extinguishing flames.**

## ABSTRACT

Recent advances have made Virtual Reality (VR) more realistic than ever before. This improved realism is attributed to today's ability to increasingly appeal to human sensations, such as visual, auditory or tactile. While research also examines temperature sensation as an important aspect, the interdependency of visual and thermal perception in VR is still underexplored. In this paper, we propose Therminator, a thermal display concept that provides warm and cold on-body feedback in VR through heat conduction of flowing liquids with different temperatures. Further, we systematically evaluate the interdependency of different visual and thermal stimuli on the temperature perception of arm and abdomen with 25 participants. As part of the results, we found varying temperature perception depending on the stimuli, as well as increasing involvement of users during conditions with matching stimuli.

## Author Keywords

Haptics, Temperature, Thermal Feedback, Virtual Reality

## CCS Concepts

•**Human-centered computing** → **Human computer interaction (HCI);** *Haptic devices;* User studies;

## INTRODUCTION

VR is on the rise and depicts real-life more realistically than it ever had before. Further, VR even allows creating obscure and surreal situations that are perceived as realistic, such as flying or being on fire. With this, the immersion [5] and presence [63] of users is constantly increasing as human sensations are stimulated by lifelike visuals, sound effects, and haptic feedback. While the latter is mostly attributed to vibrotactile [24, 25, 30], pressure [9], tangible [15] or kinesthetic actuation [14, 36], there are many other haptic channels needed to reach Sutherland's vision of an ultimate display [51], such as the sensation of temperature.

In recent years, research has emerged that applies thermal displays to various body parts, such as hands [4] or the lower back [13], and range from Head-Mounted Display (HMD) [6] to small thermoelectric wearables [37]. While this already facilitates a wide range of thermal applications that reflect the properties of objects and ambient temperature, thermal displays can be used for even more scenarios. For example, to simulate training environments close to reality, such as fire fighting [48] or disaster simulations, or even as a supportive method for rehabilitation [22]. Moreover, it can be used for notifications [62] and even social aspects [32], such as well-being and comfort. However, when using contact-based thermoelectric components like actuators, movements in VR can get hindered through the rigidity of the thermal elements. In contrast, existing non-contact thermal displays (e.g., [18]) do not affect motion but are usually limited to room-scale actuations with low precision for moving users.

Further, while the aforementioned contributions provide a broad range of application scenarios, the mutual interaction

in VR of *"what we see"* and *"what we feel"* with regards to temperature is still underexplored. To the best of our knowledge, there is no systematic evaluation yet to investigate the interdependency between visual and thermal stimuli in VR.

In this paper, we close this gap by first introducing Therminator, a thermal display concept, and a system that allows localized thermal haptic feedback on the body with a high degree of freedom in VR. We combine hot and cold liquids to create different temperature gradations that are circulated through a network of tubes. The temperature is then transmitted to the user by thermal conduction between the body and our liquid-based actuators. Second, we performed a systematic evaluation with 25 participants in VR, where we investigated the interdependency of visual stimuli with different temperature expectations and varying thermal stimuli on the abdomen and arm. In addition, we present three example applications based on our concepts and findings.

In summary, this paper contributes 1) a localized on-body thermal display concept based on liquids flowing through a network of tubes, 2) an interactive system demonstrating the viability of our concept for the arm and abdomen, and 3) a systematic evaluation of the interdependency of visual and thermal stimuli in VR.

## RELATED WORK
Thermal feedback and displays have been investigated in numerous studies and related work. The spectrum ranges from the physiological and physical properties of the human body, its psychological effects, up to the use in HCI related topics. In the following, we will highlight relevant research activities and categorize them with regard to their use.

### Thermal Displays in HCI
Thermal feedback and displays have been used by a variety of related work in the field of HCI. Due to the positive properties and the good temperature perception of humans, not only haptic systems, such as tangible user interfaces [35], but also multimedia applications can be improved by thermal displays. The use of temperature to support emotional events, both for novel devices [41, 34] and for digital contents such as pictures in social media [1], covers a large area of application. For example, Wilson et al. use thermal displays in mobile devices to support different emotional states on the palm of the hand [57, 59, 60]. Further, the authors investigated how thermal stimuli are perceived differently for wrist, palm, and arm in a mobile context, such as mobile phones [61]. Akiyama et al. [2] transfer moods of music through temperature augmentation, while Halvey et al. [17] uses temperature to support general media experiences. Further, thermal displays are investigated for the use in gaming scenarios, such as game controller [33] or directly as active game element [31].

Another use case of thermal displays are notifications and navigation applications, which use temperature changes instead of vibration to inform about specific events. While Tewell et al. [53] and Zhu et al. [67] investigate the ability of people to locate and discriminate temperature differences for spatial awareness, do Narumi et al. [38] employ warm spots in public places to bring people together at certain locations.

### Thermal Feedback in VR
Thermal feedback in VR is on the rise. As one of the missing links, it provides a haptic component that has not yet been investigated much and can be categorized into two areas: Contact and contact-less thermal feedback. With contact-based feedback, thermal displays are usually placed directly onto the body. For example, Peiris et al. [42] and Chen et al. [6] use Peltier elements and fans directly at the VR HMD to display different temperatures at the head. In a more recent version, the authors have also investigated how wetness can be generated with their system on the face purely by temperature changes [40]. In a similar work by Ranasinghe et al. [44], small fans were attached to the HMD to simulate cooling wind effects, and in a follow-up olfactory effects [45]. Recently, Maeda et al. [37] presented a system with modular Peltier elements that can be worn on the body to provide localized thermal feedback, and also commercial VR suits, such as Teslasuit[1], propose the usage of Peltier elements. Further, Peng et al. [43] used the elements to investigate how passing through objects or virtual avatars can be enhanced.

However, while easy to deploy and inexpensive, Peltier elements are usually spatially very localized with small surfaces of 1-5 $cm^2$. It is possible to use thermally conductive carrier materials to extend the effect range, but this can lead to temperature losses and increased actuation times. Further, using multiple Peltier elements can result in inflexible and rigid arrays with high power consumption needing heatsinks [2]. As a result, it can hamper the user movements in VR. As a possible alternative, the Haptx glove[3] uses microfluids (small amounts of liquid) to generate thermal stimuli. While this allows for less restricted movements, their concepts are focusing on an actuation of the hand. A similar concept is used by NASA to cool down spacesuits for astronauts [27] where small amounts of liquids in a mesh-like network lower the temperature inside the suit. While those concepts are similar to our approach, they did not focus on actively raising and lowering the temperature dynamically nor VR applicability.

In contrast, there also exist non-contact thermal feedback, such as done by Iwai et al. with a heating infrared-lamp combined with projector-based visuals [26]. A very sophisticated approach by Han et al. [18] uses a fixed system at the ceiling that can provide heat by a warming lamp and cold by ventilation and vaporized spray. Similar, Hulsmann et al. [23] created an ambient large-scale thermal system for a CAVE environment. In a project by Shaw et al. [48], the authors use directed high-energy heating units behind mechanical shutter to regulate the thermal intensity and hotness of a simulated fire evacuation scenario in a Virtual Reality Environment (VRE). While most focus on the stimulation of heat, Xu et al. [65] designed a small cold non-contact stimulus on the neck through air vortexes in a non-VR environment.

(a) Concept                                                (b) Adjustable four parameters
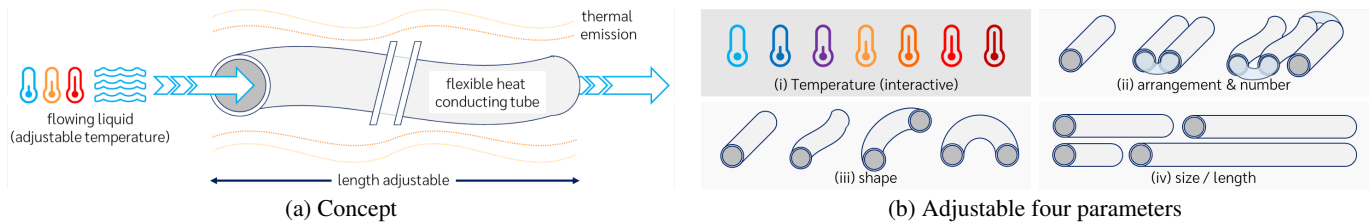
**Figure 2. Concept of our Therminator system. a) We use heat conducting tubes which can be flexibly formed to fit various shapes of different body parts. We let liquids with adjustable temperatures flow through the tubes which are then emitting their temperature. b) We have four parameters to adjust the temperature, arrangement and number, shape, and size of each tube.**

**Interaction between Thermal and Visual Stimuli**

Understanding the interaction effects between haptic and visual stimuli is critical for immersion and presence in VR. While mutual influences of Electrical Muscle Stimulation (EMS) and vibrotactile-based haptics are with visual stimuli are already explored [11], there is still no systematic evaluation of visual and thermal stimuli in VR yet. The thermal perception of visuals is tight to learned and experienced mental models and vice-versa. For example, psychological studies with a modified rubber hand experiment showed existing interaction effects between visual and thermal stimuli affecting thermal judgments [29, 54]. Further, the temperature can affect how users perceive the physical properties of objects, such as the perceived wetness of clothes by changing the coldness [49]. Further, Wilson et al. [58] investigated how thermal stimuli are subjectively interpreted to different meanings, such as digital contents and social media.

Takakura et al. [52] investigated the adaptation of the body temperature to changes of the general room temperature. Here, the authors found that once the participants were shown a hot looking video (pictures of a desert), the body temperature subtly reduced compared to a neutral control image. In contrast, when showing a cold video (pictures of snow), the body temperature altered to a slightly higher temperature than during the neutral stimulus. In a different work, Wang et al. investigated how the thermal effect of color from walls inside buildings affects temperature sensation and comfort [55]. Balcer [4] and Ziat et al. [68] investigated how the visual appearance in the form of color temperature does not match the perceived temperature. For this, the authors changed the color hue from blue to red in a VR environment and used Peltier elements to change the proxy object's temperature to warm or cold. As one finding, incongruent stimuli resulted in longer reaction times than congruent stimuli. While those are already a good depiction of identifying interdependencies, the study focused on color temperature and did not consider visual stimuli in the form of 3D visualizations. Also, the influence on the involvement was not investigated.

Weir et al. designed an Augmented Reality (AR) application that ignites a user's hand with a virtual flame and smoke. While they did not provide any thermal stimuli, about a fifth of the participants reported an increased heat stimulation on their hands just by seeing the fire [56]. A similar effect was observed by Hoffmann et al. to distract burn patients with a VR game with no thermal feedback which resulted in subjectively less pain perception [22]. Yoshikawa et al. [66] and

Iwai et al. [26] use projector-based visualizations, but also provide non-contact warmth feedback through localized infrared projection to enhance social interaction and temperature perception. While it already provides useful insights into psychophysical effects of warmth, projector-based visualizations are limited to 2-dimensional representations and in contrast to VR are not omnipresent around the user.

**THERMINATOR CONCEPTS AND SYSTEM**

Localized thermal feedback offers a versatile spectrum of application scenarios, such as immersive interaction or media enrichment. However, for the use at varying body parts in VR applications, specific requirements have to be considered. Besides the physical challenges of temperature for thermal displays [28], the complexity of the human body requires a localized thermal display concept that features actuators flexible enough to adapt to any physical and anatomical shapes (e.g., ranging from the narrow cylindrical shape of an arm to the convex and larger shape of a belly). With Therminator, we address these challenges as detailed in this section. First, we describe the design space of localized thermal displays in VR and, second, detail on our system implementation.
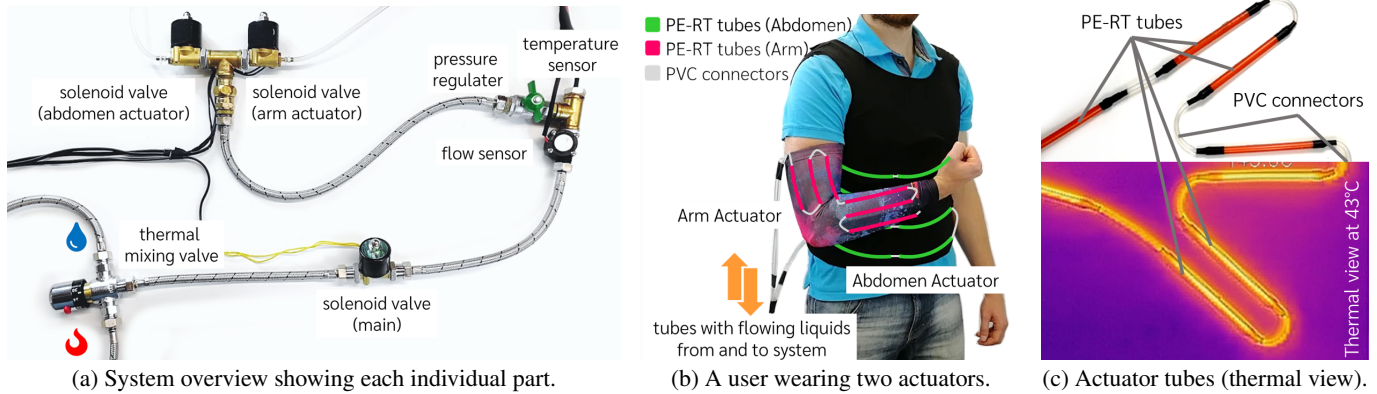
**Concepts**

As an alternative to electrothermic elements, we use the advantage of liquids with different temperatures which can flow through a network of deformable and thermally conductive tubes (depicted in Figure 2a). This approach can adapt to a variety of shapes and transfer temperatures directly to individual body parts. Also, using tubes instead of larger liquid chambers guarantees a homogeneous temperature distribution to evenly distribute liquids through the whole system at a constant rate. As our design space, we define four adjustable parameters: 1) temperature, 2) shape, 3) size, and 4) the arrangement and number of elements (depicted in Figure 2b).

*Temperature*

A large network of thermoreceptors under the skin communicates the current thermal properties of the environment, in order to warn of overheating and overcooling as well as to give a sense of well-being in ideal conditions. While the human capabilities to perceive temperature is very pronounced, for example, in differentiating surfaces through thermal properties [21], the spatial resolution is limited [47]. Also, because the temporal demand for temperature often does not match the users' expectations [31], a thermal display should have the possibility to adapt fast to changing situations.

(a) System overview showing each individual part.

(b) A user wearing two actuators.

(c) Actuator tubes (thermal view).

**Figure 3. A technical overview of our Therminator system showing the technical components, a user wearing two actuators on the arm and abdomen, as well as a detailed perspective of the network of actuator tubes including a thermal camera view at** $43\,°C$**.**

Therefore, we leverage liquids as a medium for a thermal display since it has excellent thermal properties that can transfer temperature fast (water 0.59 W $\cdot m^{-1} \cdot K^{-1}$ compared to air 0.03 W $\cdot m^{-1} \cdot K^{-1}$). Further, there are a number of possibilities to vary the temperature of liquids. For example, by having a cold and warm liquid source, we can blend them with a thermal mixing valve, or it is possible to use individual heating elements directly. In theory, this allows any desired temperature to flow through the actuators. However, people perceive temperatures individually, and the perception threshold changes over lifetime [50]. Therefore, as research investigated [19, 20], a lower limit of about $15\,°C$-$17\,°C$ and a maximum of $45\,°C$-$52\,°C$ should be considered to avoid causing pain irritation associated with the thermoreceptors.

*Shape*
As already mentioned, actuators have to be adaptable to fit the shapes of each part of the body. The anatomy of individual body parts can differ largely and may be rather straight as the shin, convex as the abdomen, or bent as the spine. By using deformable pipes and tubes, each actuator can be designed to match varying curvatures. This can result in straight, curved, or even bent form factors that match any possible body part.

*Size*
In addition to a suitable shape, the length of the actuators must be individually dimensioned. If, for example, an actuator is mounted on the thigh, the tubes can be larger than tubes mounted on a forearm actuator. Further, to provide the best actuation, also different body sizes of the users should be considered, which leads to different measured actuators.

*Arrangement and Numbers*
Body parts have different dimensions, shapes, and different sized surfaces which result in varying degrees of freedom that should not be restricted by actuators. For example, arms or legs have joints allowing them to bend and stretch. Consequently, individual actuators should not be designed as a single large tube, but as an interconnected network of tubes with appropriate form factors for desired body locations. As a result, the tubes need to be connected by even more elastic tubes that are bendable to allow fluids to flow from one actuator tube to another. In this way, actuators can use a series of tubes that can be arranged in a variety of configurations, such as horizontal, vertical, and diagonal.

**System**
Based on the requirements for VR, we opted for a highly flexible and contact-based solution. We built a system based on liquids in a network of tubes. Regular water already offers excellent thermal conductivity, and flexible tubes allow nearly unlimited possibilities to adjust to different shapes.

*Actuators*
For our actuators, we use thermoplastic PE-RT tubes (*polyethylene of raised temperature resistance*) with a diameter of 12 mm as thermally conductive elements. Those have a very good thermal conductivity which is close to the thermal conductivity of water (water 0.59 W $\cdot m^{-1} \cdot K^{-1}$, PE-RT 0.43 W $\cdot m^{-1} \cdot K^{-1}$). They are commonly used for professional thermal appliances (e.g., underfloor heating) and the outside temperature of PE-RT tubes is adapting very quickly to the internal temperature (between 2-5 seconds). Hereby, they provide high durability with a pressure resistance of up to 1300 kPa at flow temperatures of up to $70\,°C$[4].

Although PE-RT pipes are not very flexible per se, they can be permanently deformed by high heat to adapt to uneven surfaces. However, since they still have a bending radius of about 10 cm, we connect the individual PE-RT elements by ultra-flexible PVC tubes that have a very small bending radius and negligible thermal properties. This allows for a "grill" like arrangement with a 5 cm spacing between each actuator tube. Such an arrangement is sufficient enough since the thermal resolution of the body is low [47, 50] and also more energy-saving than having large chambers for the liquids. Figure 3c depicts a closeup perspective of the actuator tubes, as well as an example thermal camera view at $43\,°C$. Figure 3b shows a user wearing two actuators on the right arm and the abdomen.

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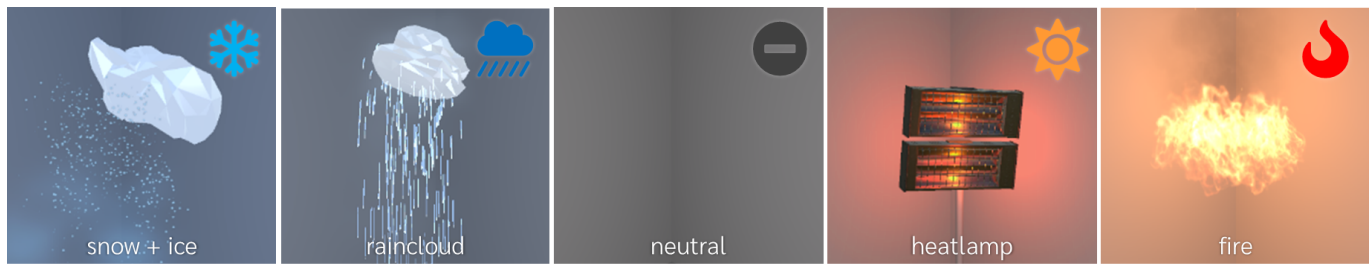[4]https://plasticpipe.org/building-construction/bcd-pe-rt.html, last accessed 2020-01-08

**Figure 4. Visual stimuli based on their expected temperature from cold to hot: snow, rain cloud, neutral / no visualization, heating lamp, fire.**

*Liquid sources*
We opted for two separate water supplies. For the cold water, we use a conventional household connection providing water at 17 °C. For hot water, we use a 30-liter boiler heated up to 55 °C. Further, we collect the warm reflux from the system in our boiler. Both sources are connected to a mechanical, thermal mixing valve, which can be regulated between 18 °C and 48 °C. However, as the hot water boiler does not provide its own pressure, we attached a separate pump (*Daypower WP-165*) with a throughput of up to 6 l/min.

Following the mixing valve, we have connected a mechanical pressure regulating valve to limit the flow in the further system to 40 ml/s. This keeps the pressure in the system low but still provides enough to flow through the actuators quickly. The temperature-controlled and pressure-reduced water flow is now controlled by a switchable solenoid valve to switch the system on and off. Since the temperature must be kept stable for each condition, we have integrated a temperature and a flow sensor that continuously monitor the internal flow. Furthermore, every actuator should be able to be operated individually depending on the body part, so that we have placed two further solenoid valves after a Y-connector. An overview of our system is depicted in Figure 3a.

*Performance*
Our system changes the temperature at a rate of 1.75 °C/s on average, rendering a full temperature change from cold (22.5 °C) to hot (42.5 °C) in 12 s. While this process can be accelerated through an overdriving, e.g. increasing the flow rate of the hot or cold source, we intentionally opted for a more constant variant during the study to avoid possible temperature overshooting which may affect the results. Further, the human skin adapts to the actuators' temperature in about 2 s to 5 s depending on the temperature difference. To avoid any temperature loss and cooling down effect after some time besides the intended thermal conductivity, we use a constant flow of liquids through the actuator tubes at 40 ml/s.

**Safety measurements**
The users' safety was in focus at all times. Each component complies with maximum safety standards, and power switching devices are operated at low voltages (12 V) with physical and software sided emergency switches. Both water supplies have separate mechanical valves to interrupt any flow and all solenoid valves (normally-closed) can be turned off immediately. The mechanical bimetallic valve further never allows too high or cold temperatures reaching the user.

**METHODOLOGY**
In order to evaluate the thermal feedback in VR, we investigate the following research questions:

RQ1. How does the interdependency of thermal and visual stimuli affect the perceived temperature?

RQ2. How do the thermal and visual stimuli affect the involvement of users?

RQ3. How do the thermal and visual stimuli affect the comfort of users?

**Design and Task**
We used a within-subjects design and varied the physical temperature, the visualization, and the actuated body part as three independent variable (IV) in a repeated measures design.

*Thermal Stimuli*
We defined five levels for the temperature, centered around the mean neutral skin temperature between 30 °C-36 °C [39, 28]. To provide a neutral thermal stimulus used as a thermal baseline, we measured the epidermis (*skin*) temperature of 5 persons at a constant room temperature of 23 °C. As the skin temperatures of the test subjects always ranged between 31 °C and 33.5 °C, we defined the neutral thermal stimulus at 32.5 °C. Starting from this neutral point, we varied the temperature in 5 °C steps, resulting in 22.5 °C, 27.5 °C, 32.5 °C, 37.5 °C, and 42.5 °C. We chose the minimum and maximum temperature to cover a broad but safe temperature range, avoiding pain sensations [28, 12].

*Visual Stimuli*
We varied the visualization to incorporate different thermal mental models and expected temperatures. As outlined by Fenko et al., different materials and objects convey different expectations of their temperature based on two factors: a literal meaning that aligns with the physical warmness, and figurative meaning of an object related to "social activity, intimacy, and friendly atmosphere" [10]. For example, if a visual stimulus should have a cold expected temperature, we need something that users will identify as *looking* cold.

Therefore, before the actual controlled experiment, we interviewed 7 individuals and asked them about objects, entities, and situations in which they have different expectations about thermal appearances. In parallel, we collected visualizations commonly used in related work.

In each interview, the participants provided us with up to 20 items that propagate different temperatures. We further asked

to describe the expected temperature of each on a continuous scale from *very cold* to *very hot*. Next, we collected all mentioned items, recorded their frequency, and compared them with their occurrence in related work. Further, we mapped matching items (e.g., fire and flame, ice and snow) and sorted them according to the participants' expected temperature.

In a final step, we selected the four most applicable visualizations according to their frequency and thermal properties in relation to four temperature gradations (*very cold, cool, warm, very hot*) plus *no visualization* as the neutral baseline. Subsequently, this process led to the following visualizations: snowfall, rain cloud, no visualization, heat lamp, and burning fire. All five visualizations are depicted in Figure 4.

For our controlled experiment, we use those five different types of visualization and, in addition, slightly change the visual color temperature of the virtual room to 4500 K for warmer visual stimuli, while the colder visuals are set to 9500 K. During the neutral visualization and between conditions, the color temperature of the room was reset to neutral 6800 K. No audio feedback was given for any of the visualizations to prevent aural side-effects.

*Actuators*

We varied the body part in two levels: the *abdomen* and *right arm*. The abdomen is a central part of the human body which has a major impact on the thermal comfort [3]. The right arm, in contrast, has a completely different anatomy and consists of an upper and lower part, and temperature is perceived differently [12]. Both locations cover a large part of the surface of the human body and, thus, have a large impact on the human thermal sensation[12]. To ensure comparability between arm and abdomen, each actuator consists of exactly 8 PE-RT tubes with a length of 15 cm each. Therefore, both actuators in the experiment had the same contact surface with the body, and thus transferred the same amount of thermal energy.

In total, this resulted in $5 \times 5 \times 2 = 50$ conditions. We use a balanced Latin square design to counterbalance the levels of temperature and visualization. However, the location of the actuation was either always starting with the arm followed by the abdomen, or vice-versa.

*Task and Dependent Variables (DV)*

The participants' task was to assess their sense of warmth while being simultaneously exposed to visual and thermal stimuli at a body part. For this, we asked the participants to sit down in a provided chair. In the following, each condition presented a combination of a visual and a thermal stimulus. Once the system reached the target temperature, the visual stimuli appeared and were displayed to the participant for 25 s. During this time, participants were allowed to move their arms and legs freely and could look around without restriction except not to stand up.

As dependent variables (DV), we asked the participants to rate their temperature perception, their comfort, and their involvement with regards to the thermal and visual stimuli after each condition. The first two items are based on Arens et al. [3], whereas the latter two are based on the Witmer-Singer presence questionnaire [63] as derived by Peiris et al. [42].

*Q1 How do you rate the thermal sensation?*
A 9-Point Likert scale ranging from *very cold* to *very hot*.

*Q2 How do you rate the thermal comfort?*
A 6-Point Likert scale ranging from *very comfortable* to *very uncomfortable*. As defined in the related work, there was no *neutral* level and the participants had to answer at least *just comfortable* or *just uncomfortable*.

*Q3 How much did the visual aspects involve you?*
A 7-Point Likert scale ranging from *not involved at all* to *completely involved*.

*Q4 How much did the thermal aspects involve you?*
A 7-Point Likert scale ranging from *not involved at all* to *completely involved*.

In a final questionnaire, we asked the participant to rate the overall experience of thermal feedback in VR on a 7-Point Likert scale with 7 as the best.
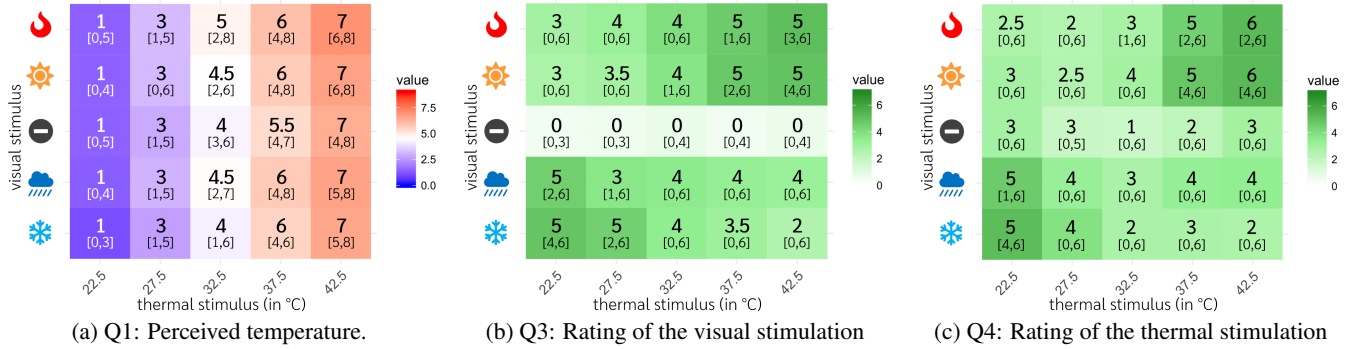
*Study Setup and Apparatus*

We use a state-of-the-art VR setup (*Valve Index*) for tracking the participant and providing a virtual environment. The user is sitting in a regular comfortable chair wearing the HMD, two hand-held controllers, an additional tracker on each foot, as well as our system. Each participant also had to wear a provided long-sleeve (100% cotton, 140 g/$m^2$) without any other clothing below to mitigate any effects of different clothing and fabrics between our system and the participant's skin. We also ensured the shirts fit tightly but not constrain the participants in any way. A separate private dressing area was set up in another room. To provide a high level of detail, we modeled a person representing the user in the physical look-a-like chair from the ego-perspective. We use inverse-kinematic and the tracking devices to simulate realistic limb movements. Further, this allows the visualizations to follow the corresponding actuated body part interactively.

To reduce distracting influences, the participant was situated in a neutral virtual room with no specific details and dimmed lighting to prevent interferences with the visual and thermal stimuli. Besides a break between switching the body part, the participant stayed in VR during the whole experiment. Thus, after each trial, we showed our questionnaire on a virtual screen in front of the user which could be answered with the hand-held controllers. Further, to also reduce aural distractions from the real world, the participants were listening to neutral ambient music which is suited for concentration tasks [16] at ~60 bpm. The real-world temperature of the setup room was always kept at constant 23 °C. Figure 1a) shows a participant while exposed to the snow visualization.

**Procedure**

*Before the Study.* After we welcomed the participants, we introduced them to the aim of our study and described all the necessary details of the system to them. We explained that all data, including personal information, are anonymized. We then asked to fill out a demographic questionnaire, consent, and privacy protection form.

(a) Q1: Perceived temperature.  (b) Q3: Rating of the visual stimulation  (c) Q4: Rating of the thermal stimulation

**Figure 5. Results of the questionnaires showing a) the perceived temperature of participants on a 9-Point Likert scale (lower perceived temperatures in blue, higher in red). b) The participants' rating of how visual stimuli were perceived, and c) how thermal stimuli were perceived (both on 7-Point Likert scales). The more participants felt affected by the visual or thermal stimuli, the higher the rating. All thermal stimuli are given in °Celsius.**

Afterward, we provided matching long sleeves and showed participants the changing room. We then introduced the actuators and assisted by putting them on. Participants were asked to sit on the chair and we mounted the additional trackers on their feet. Then, participants put on the HMD and took the hand-held controllers. Once the participants were comfortable, we started the study with the first condition.

*During the Study.* We started the study either with actuating the abdomen or the right arm. Here, each of the five visual stimuli was combined with each thermal stimuli. Once ready, we started the first condition and adjusted the thermal mixing valve to the needed temperature. When the target temperature was reached, an additional 5 s countdown started until the visual stimulus was presented. This allowed the outside temperature of the actuator tubes to adjust to the target temperature. Then, the visual and the thermal stimuli were presented for precisely 25 s. Once that time passed, the visuals disappeared and the temperature was adjusted to 32.5 °C again. The VR room illumination turned up and our questionnaire was presented to the participants on a virtual screen. Each question could be answered by using the hand-held controller. After answering all questions, the next condition started. After finishing one body part, we enforced a 5-minute break where participants put of the HMD, and followed by the next conditions on the other body part afterward.

*After the Study.* After completing all conditions, we helped participants to take off the actuators and they could change their clothes again. In a semi-structured interview and a post-questionnaire, we asked for additional qualitative feedback.

**Participants**
We recruited 25 participants (12 female, 13 male) between 20 and 55 years (M=30.28, SD=8.6). 9 of them had little or no experience with VR while 13 used it a few times before. Three users stated to be a regular or experienced VR user. Besides snacks and drinks, no compensation was provided.

**RESULTS**
In the following, we report the results of our controlled experiment. We start by the qualitative analysis, followed by quantitative feedback of the participants.

**Analysis**
We performed a non-parametric analysis using a 3-way repeated-measures ANOVA to evaluate our collected data. Since we have non-continuous data of the Likert questionnaires, we use an Aligned Rank Transform (ART) to investigate interaction effects as proposed by Wobbrock et al. [64]. If our analysis revealed significant effects, we used a Tukey corrected pairwise t-test for post-hoc analysis. We report the effect size as partial eta-squared $\eta_p^2$ using Cohen's classification categorizing the effect as small, medium, or large [7, 46]. Because of the ordinal nature of the Likert data, we further report the medians $\tilde{x}$ of the results.

*Q1 Perceived Temperature*
The analysis with regards to the perceived temperature of the participants revealed significant effects for the visual with a large effect size ($F_{4,92} = 13.36, p < .001$, $\eta_p^2 = .37$ ). Post-hoc tests confirmed significant differences between almost all visual stimuli (ice-rain, $p < .001$; ice-heatlamp, $p < .001$; ice-fire, $p < .001$; rain-none, $p < .05$; heatlamp-none, $p < .05$; fire-none, $p < .001$). The analysis also identified significant effects for the thermal stimuli with a large effect size ($F_{4,92} = 347.79, p < .001$ , $\eta_p^2 = .94$ ). Here, the post-hoc tests confirmed significant differences between every thermal stimulus (all $p < .001$).

Further, the analysis indicated significant effects for the body part ($F_{1,23} = 5.1, p < .05$ , $\eta_p^2 = .18$ ) which are confirmed by the post-hoc tests (*arm-abdomen*, $p < .05$). Significant interaction effects were also revealed between thermal stimuli and body part ($F_{4,92} = 7.06, p < .001$ , $\eta_p^2 = .23$ ) with a large effect size. We depict the medians including the minimum and maximum ratings for each condition in Figure 5a. While the medians for each temperature level are mostly identical, the visual stimuli affect the distribution of the ratings.

*Q2 Perceived Comfort*
Our analysis revealed significant effects of the thermal stimuli on the perceived comfort with a large effect size ($F_{4,92} = 25.57, p < .001$ , $\eta_p^2 = .53$ ). Post-hoc tests confirmed significant differences between all temperature levels besides *27.5-42.5, 32.5-37.5,* and *32.5-42.5* (all $p < .001$). Further, the the answers indicate that extreme temperatures closer to the cold

and hot pain thresholds have a negative impact on the participants' level of comfort (22.5 °C: both body parts $\tilde{x}$ = 2-uncomfortable, 27.5 °C: both body parts $\tilde{x}$ = 3-slighty uncomfortable, 32.5 °C: both body parts $\tilde{x}$ = 4-slighty comfortable, 37.5 °C: arm $\tilde{x}$ = 4.5-(very) comfortable and abdomen $\tilde{x}$ = 4-comfortable, 42.5 °C: arm $\tilde{x}$ = 3-slightly uncomfortable and abdomen $\tilde{x}$ = 4-comfortable). While there were no significant effects for the body part or the visualization, the analysis revealed significant interaction effects between the thermal stimuli and body part with a large effect size ($F_{4,92}$ = 4.94, $p$ <.01 , $\eta_p^2$=.17 ), as depicted in Figure 6.

*Q3 Involvement of Visual Stimuli*
The analysis of the visual stimuli involvement on the perceived temperature showed significant differences for the visualization with a large effect size ($F_{4,92}$ = 85.31, $p$ <.001 , $\eta_p^2$=.79 ). Post-hoc tests confirmed significant differences between all levels and the neutral visualization for the visual stimuli (all $p$ <.001).

There were also significant effects with a medium effect size for the thermal stimuli ($F_{4,92}$ = 3.22, $p$ <.05 , $\eta_p^2$=.12 ). Post-hoc tests also confirmed significant differences between (27.5 °C-37.5 °C, $p$ .<05 and 27.5 °C-42.5 °C, $p$ .<05).

Further, the analysis revealed significant interaction effects between visual and thermal stimuli with a large effect size ($F_{16,268}$ = 23.18, $p$ <.001 , $\eta_p^2$=.50 ), which we depict in Figure 5b. In addition, we included minimum and maximum ratings for each condition. We could not find any significant effects with regards to the body part ($F_{1,23}$ = 11.81, $p$ >.05 ).

*Q4 Involvement of Thermal Stimuli*
With regards to the involvement of the thermal stimuli on the perceived temperature, our analysis revealed significant effects with a large effect size ($F_{4,92}$ = 19.24, $p$ <.001 , $\eta_p^2$=.46 ). Further, the post-hoc tests confirmed significant differences between the majority of the temperature levels (22.5 °C-27.5 °C, 22.5 °C-32.5 °C, 27.5 °C-37.5 °C, 27.5 °C-42.5 °C, 32.5 °C-37.5 °C, and 32.5 °C-42.5 °C; all $p$ <.001).

Interestingly, the analysis has revealed significant differences for the visualization ($F_{4,92}$ = 13.38, $p$ <.001 , $\eta_p^2$=.37 ) and could confirm interaction effects between visual and thermal

stimuli with a large effect size ($F_{16,368}$ = 14.41, $p$ <.001 , $\eta_p^2$=.39 ). As depicted in Figure 5c, the median rating as well as the minimum and maximum ratings show differences with regards to the visuals. Also, the analysis revealed significant differences for the body part with a large effect size ($F_{1,23}$ = 14.78, $p$ <.001 , $\eta_p^2$=.39 ). Post-hoc tests confirmed significant differences between *arm* and *abdomen* ($p$ <.001).

**Overall Experience of Thermal Feedback**
In our final questionnaire, we asked for the overall experience on a 7-Point Likert scale. Overall, the participants rated the thermal feedback as very positive (M=5.8, SD=1.1).

**Qualitative Feedback**
The general consensus of the participants was very positive, which is also confirmed by our qualitative results. They described our concepts as "interesting idea" (P1, P22), "funny simulation" (P24), and "cool idea with great potential" (P21). One participant said it was a great experience to dive into a virtual world with thermal feedback (P19). Further, P20 highlighted the "different and rapidly changing temperature possibilities", while P10 remarked that the appearance of the visual stimuli was very well synchronized.

The thermal stimuli felt "realistic" (P14), "especially at very high or low temperatures" (P9). The displayed temperatures were "very well recognizable" (P14). While P10 said that all temperatures were "very pleasant and did not feel disturbing at all", most participants described the warming stimuli as preferable (P7, P9, P11, P17, P18), and even more distinguishable than the colder ones (P10). As our quantitative analysis confirms, participants perceived cold temperatures generally more unpleasant (P2, P17, P19, P20). However, two participants said it could be even colder (P4, P10), and one asked for "more heat while burning" (P24).

The visual stimuli were kept basic, and their appearance was based on their thermal expectations. In general, the participants identified the visuals as "appropriate and fitting for the experience" (P4). In particular, a majority of the participants emphasized the effects and the "immersive experience when the perceived temperature corresponds to the expectations from the visual and personal experiences" (P3, P5, P12). For example, "it felt more realistic if the thermal feedback matched" (P24). One participant even said that they "have goosebumps during the snow effect while perceiving a cold temperature" (P25). In contrast, during conditions where the visual stimuli did not match the expected thermal stimuli, the participants felt "more uncomfortable or uncanny" (P24, P1, P8), thus, the "discrepancy between perceived and visually expected temperature was too high" (P23).

As for the visual stimuli themselves, the participants were able to depict them very well to different levels of anticipated temperatures (P4). Although we carefully selected the visualizations in relation to different temperature assumptions, participants had different mental models of the raincloud visualization. A possible reason for this was given by P11, who explained that it "reminded of a warm shower". In addition, two participants stated that the overall visualizations could have shown more specific and "*wow* effects" (P14, P16).
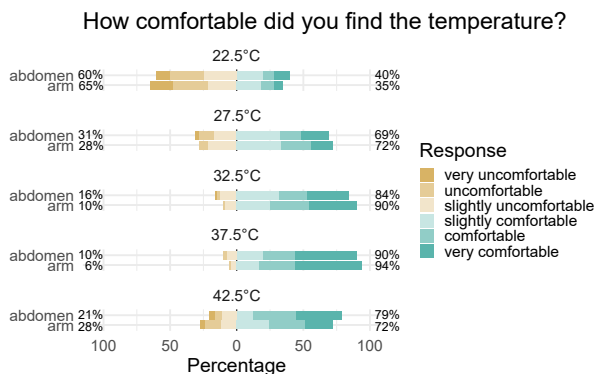


**Figure 6. Comfort rating of the participants with regards to the thermal stimuli (from *very uncomfortable* to *very comfortable*). Each temperature level is split into both body parts.**

As a further suggestion, "the experience may be enhanced by appropriate sound effects" (P15, P20), which we intentionally omitted in order to avoid cross-effects with aural stimuli. While we did not ask for the wearing comfort of our system directly, no participant reported negative impacts that go further than already needing the HMD cable. Though, this was also not reported as an issue since the study was conducted while sitting. In summary, the qualitative feedback given by the participants was generally positive and yielded valuable insights to support our findings even further.

## DISCUSSION

Our analysis and the qualitative feedback from participants indicate interdependencies and mutual interaction effects between visual and thermal stimuli. In the following section, we discuss the results of the evaluation and give answers to the aforementioned research questions.

### Thermal Stimuli Overwrites Visual Stimuli

The analysis revealed significant differences in the perceived temperature. Looking at the median results of *Q1* (cf. Figure 5a), the thermal stimuli have the highest impact on the perceived temperature. As a consequence, for example, a visualization showing a hot fire feels cold with a cold thermal stimulus applied. Hence, visual stimuli are overwritten. In the same way, cold visualizations, such as snow, are perceived as hot if a high thermal stimulation is presented.

While the thermal stimuli showed the most influence on the perceived temperature, the visual stimuli are not completely neglected, and our analysis revealed significant effects for them as well. For this, we need to take a look into two things: the perceived temperature 1) at incongruent stimuli, and 2) at a neutral thermal stimulus.

Considering incongruent stimuli, such as *fire* at 22.5 °C or *snow* at 42.5 °C, we mostly observed only marginal effects on the median compared to congruent conditions. However, if we take the distribution of the perceived temperature ratings into account, we observed a clear trend to broadened minima and maxima for incongruent stimuli compared to matching stimuli which only have a very narrow distribution.

Further, if we consider the neutral thermal stimulus of 32.5 °C, we can observe the impact of the visual stimuli on the perceived temperatures the most. For example, a *fire* visualization has a significantly higher temperature rating than *snow*, indicating that a purely visual stimulus without thermal stimulus can alter the perceived temperature of participants. However, as already mentioned in the qualitative results section, the temperature expectations of visualizations also need to be considered. While we carefully selected five visualizations which meet five different temperature expectations, the *raincloud* was at times interpreted as warm *shower* instead of cold *rain* which explains the higher median.

Concluding, VR applications can highly benefit from additional thermal stimuli since pure visual stimuli can not provide the same adequate temperature perception as without.

### Congruent Stimuli Increase Involvement

The analysis showed significant results for both the involvement of the visual and the thermal stimuli. Thereby, the results of our study show that the more similar the temperature expectations of a visual stimulus and the applied thermal stimulus matches, the higher the involvement of each participant is. Interestingly, we expected the involvement ratings of the visual and thermal stimuli to be opposing. For example, if we consider a *snow* visualization with a warm thermal stimulus of 42.5 °C, we expected the visual stimuli to be more involving than the thermal. However, both are on a similarly low level ($\tilde{x} = 2$). Interestingly, our results reveal the opposite effect: For more congruent stimuli that match the expectations of the participants (see the lower left and upper right quadrants of Figure 5b and Figure 5c), the involvement resulted in higher medians for both stimuli. This was also supported by the qualitative feedback of our participants who stated that matching stimuli felt very involving, while incongruent stimuli were often perceived as uncanny or surreal.

During a neutral visualization (*no visualization*), our results confirmed no involvement for the visual stimulus as expected. However, considering the involvement of the thermal stimuli, we observed similar low median ratings for all levels as for visual stimuli that do not match the expectations. As a result, even though thermal stimuli have a major impact on the perceived temperature (cf. Figure 5a), they only slightly affect the involvement if there is no visual stimulus displayed.

With regards to the body part, our analysis only revealed a significant difference in involvement for the thermal stimuli, but not for visual stimuli. This can be an indication that temperature expectations of visualizations always apply to the whole body instead of single body parts.

### Comfort depends on Thermal Stimuli

With regards to the comfort, our analysis could reveal significant effects showing that temperatures closer to the neutral skin temperature (32.5 °C) and slightly warmer temperatures (37.5 °C) are perceived comfortable. In contrast, temperatures close to the minimum and maximum are perceived as more uncomfortable (cf. Figure 6). However, as we limited the thermal stimuli to a range between 22.5 °C to 42.5 °C to avoid pain sensations, most participants reported that the warmest stimulus 42.5 °C still felt comfortable, thus, could be even hotter. In contrast, the coldest stimulus (22.5 °C), which ranges about 10 °C lower than the neutral skin temperature [28, 39] and approximates the pain threshold at 17 °C [19, 20], was often described as very chill and always rated as more uncomfortable. While increasing and decreasing the temperature with regards to the neutral always had the same interval step size of ± 5 °C and ± 10 °C, our experiment could confirm that cold stimuli were always perceived as more intense than warm, aligning with existing research [50].

In addition, the analysis revealed significant differences of the level of comfort between the body parts. Aligning with related research, limbs are very good in perceiving temperature while the abdomen feels less and loses sensitivity over the age even further [50].

## EXAMPLE APPLICATIONS

We created three interactive example VR applications that implement our concepts. In each of the applications, both, the arm and the abdomen, are automatically and dynamically actuated depending on the situation for an immersive and engaging experience.

### Firefighting Simulation

Crisis simulation is an emerging scenario for VR. Emergency forces, such as firefighters, can train their individual abilities and perform rescue operations with realistic yet harmless and safe environments. In our example, we simulate such a rescue mission where a firefighter has to save a burning building from the flames as depicted in Figure 1d). Our Therminator concepts support a high involvement and increase realism towards real-world training. In our application, the controller acts as a fire hose with which the fires, that spread throughout the building, can be extinguished. To recreate the hot environment, Therminator emits constant heat to the firefighter's abdomen. In addition, the closer the firefighter gets next to a fire, the greater the temperature rises. Contrary, the further the distance is, or the more flames are extinguished, the closer the temperature will adjust to a neutral level.

### Pirates in the Sun

In this example application, the user plays a pirate at the beach of an isolated island (depicted in Figure 1c), discovered on a treasure map. Everywhere on the beach, precious gems are treasured. To obtain them, the player must find sparkling spots and dig using handheld controls. The island harbors a hot tropical climate at high temperatures. Thus, when the player walks out in the sun, the abdomen actuator turns very warm affecting the comfort. To regain a neutral temperature and cool down, the player must search for shaded spots, such as palm trees. While there are gems buried in the sand, some are hidden in the near shallows of the sea. In this case, the player must reach for each gem and insert their arm into the water, causing cold localized thermal stimulation.

### Angry Snowman

During this interactive game, the player is in a snow-covered cold landscape with an enchanted snowman as depicted in Figure 1b). The snowman throws snowballs at the player, which the player needs to evade. However, each time the player is hit, our system causes a very cold stimulation of the abdomen. The sudden coldness recovers within a short time to a calmer temperature, unless the player is not hit again. In the same way, the player can take action and throw snowballs to target the snowman. As the player holds a snowball in his hand, the arm experiences a cooling sensation from our system that recedes when the snowball is thrown.

## LIMITATIONS AND FUTURE WORK

As we investigated the interdependency of visual and thermal stimuli in VR, we also identified some limitations. In our experiment, we focused on two body parts, namely the arm and abdomen. For further insights, it should be considered to also investigate the effects of other body parts, such as the legs, back, or head. For example, thermal stimuli at the head may be perceived as more intense than everywhere else. Furthermore, we have focused on only one body part at a time to exclude possible cross effects. However, it can also be interesting to investigate how users perceive temperature if multiple body parts are actuated together. Also, by actuating individual bodyparts together with different thermal stimuli for each actuator, other interaction effects could be observed, such as the thermal grill illusion [8].

In our study, we focused on five visual stimuli carefully selected with regards to users' temperature expectations, however, not all of them yielded the same expectations for all participants. In particular, the *raincloud* had a mixed reception and some identified it as a warm shower instead of cold drops. Also, in a future experiment, more visual stimuli and the combinations of those could be presented to investigate their effects on temperature perception as well. Similar, having different thermal stimuli at the same time can be interesting to investigate. Additionally, exploring individual scenarios, such as training environments, weather simulations, or rehabilitative therapies [22], could benefit from a purposeful use of thermal displays and, thus, further improve current existing positive but visually based effects.

While the wearability of our system during our study and demo applications was limited due to external liquid sources and our focus on the interdependency between visual and thermal stimuli, our concepts and actuators are designed with wearability in mind. From a technical perspective, our system currently uses a constant cold water supply, and while we re-use the re-flux during conditions having a higher temperature than $32.5\,°C$, the cold water could only partly recycled to water plants in our institute. Also, smaller containers with faster heating and cooling of the liquids could increase wearability. While the tubes leading to the users were not reported to restrict movements further than having the cable of the HMD, mobility could be increased by using a pressure-based system with smaller amounts of liquids in a wearable backpack. However, reducing the overall size also means a need for faster thermal elements to avoid any temperature loss within the system.

## CONCLUSION

In this paper, we presented Therminator: a concept for thermal haptic feedback in VR through the usage of flowing liquids in a network of temperature conducting tubes. Further, we contributed a system demonstrating our concepts at the example of an arm and abdomen actuator. In a following systematic evaluation, we investigated the interdependency of visual and thermal stimuli in VR. Our results confirm that thermal stimuli overwrite visual stimuli with regards to the perceived temperature, and impact heavily the comfort of users. While both stimuli significantly affect the involvement in VR, the involvement increases further for congruent and matching thermal and visual stimuli.

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