

Face/On: Multi-Modal Haptic Feedback for Head-Mounted Displays in Virtual Reality

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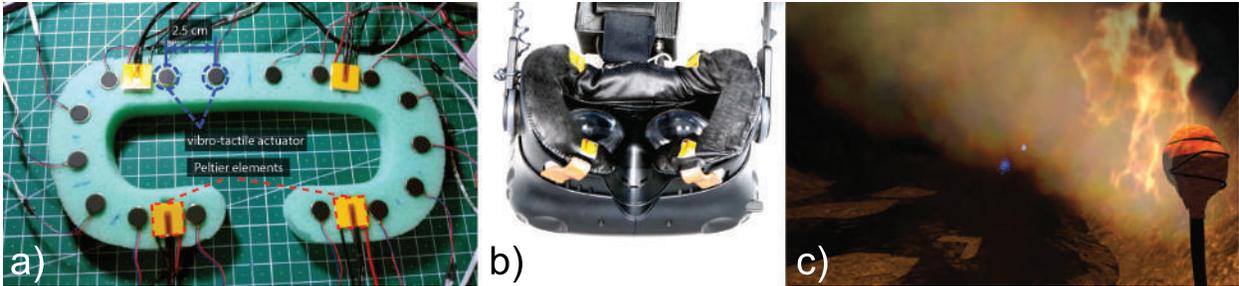


Fig. 1. Face/On combines a high density of vibrotactile actuators with additional thermal sources in a compact form factor (a). The surface area of the cushion offers space for additional actuators to further increase multi-modality (b). With its high resolution and multi-modality, Face/On can create feedback for a complex effect such as the wind force of a moving torch in front of the user's face and the heat of its flame on the user's skin.

Abstract—While the real world provides humans with a huge variety of sensory stimuli, virtual worlds most of all communicate their properties by visual and auditory feedback due to the design of current head mounted displays (HMDs). Since HMDs offer sufficient contact area to integrate additional actuators, prior works utilised a limited amount of haptic actuators to integrate respective information about the virtual world.

With the Face/On prototype complex feedback patterns are introduced that combine a high number of vibration motors with additional thermal sources to transport multi-modal and spatial information. A pre-study determining the boundaries of the feedbacks' intensities as well as a user study showing a significant increase of presence and enjoyment validate Face/On's approach.

Index Terms—VR, haptic feedback, multi-modal, thermal feedback.

1 INTRODUCTION

In 1965, Ivan Sutherland proposed his visionary idea of an ultimate display that would offer users total immersion [43]. Since then, there have been many suggestions on how to increase immersion in virtual environments (VEs) [40]. Usually, these solutions include wearable devices like haptic gloves [14], grounded force-feedback devices [16] or ambient feedback generators [34].

Most of these solutions have two common limitations: (1) users require additional instrumentation (e.g. a separate neck attachment [37]) and (2) their low actuator resolution provides only limited feedback (e.g. actuating the whole HMD with vibration [33]). Therefore, on our common endeavour to bring sensations of the physical world to virtual environments [35] we should focus on overcoming these limitations by exploring alternative approaches.

Most VR experiences that incorporate haptic feedback do so via the hand held controllers of the VR device being used. Some experiences and/or VR systems also make use of gloves and haptic vests embedded with small motors. Such devices expand the usage of tactile feedback by providing focused haptic feedback to enhance interaction and therefore immersiveness of the experience [31]. However, many state-of-the-art VR experiences include the users' head as a collision object without providing appropriate haptic feedback. Adding haptic sensations to the facial area offers great potential to increase user presence in virtual environments and provide an additional artistic tool to

VR experience designers. In this paper, we explore the potential of high-resolution vibrotactile feedback with additional thermal sources in the facial region.

The main contributions of this paper are:

- the design and implementation of a modular and interchangeable feedback system in form of a VR face cushion
- the design and evaluation of complex feedback patterns that leverage Face/On's high vibrotactile resolution
- design guidelines for multi-modal haptic feedback for the facial area

2 A MODULAR MULTI-MODAL HAPTIC FEEDBACK APPROACH

With *Face/On*, we present an approach to tackle the low resolution feedback of haptic devices and investigate effects of multi-modality in the facial region. Similar to how users get accustomed to perpetual skin contact with wrist-watches, clothes, and glasses, they can be expected to shift their attention from the facial contact area with the HMD towards the virtual environment [32,46]. This allows *Face/On* to provide haptic feedback that blends with the virtual experience rather than distract from it by the use of additional instrumentation. To this end, all actuators were embedded inside an HMD face cushion as can be seen in Fig. 1 a. Our vision is the use of a modular hardware design to allow for interchangeable VR cushions to fit different requirements. A cushion for a diving simulation for example could incorporate additional pressure actuators to create a sense for the current under-water depth while a cushion for a flight simulator could explore vibrotactile feedback with fewer but more-powerful actuators to better simulate wind turbulence and high speed. In this work, we explore a combination of vibrotactile and thermal feedback. To achieve a compact form factor with mobility in mind, all hardware controllers are contained in

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Fig. 2. For the final *Face/On* prototype small openings were cut into the synthetic cushion cover to increase skin contact with the thermal elements. Custom designed copper heat-sinks were attached to the HMD via Velcro to remove excessive heat. This way, no actuators require a separate set-up and are ‘attached’ to the face along with the HMD itself.

a single 3D-printed case on top of the HMD (see Fig. 2). Currently, *Face/On* requires a separate electrical cord as the USB connection of an HTC Vive HMD does not provide enough energy. In future, less power-consuming versions of *Face/On* could be powered by a medium-sized battery and, thus, be completely mobile.

3 RELATED WORK

The role of multi-sensory feedback has been identified as an important factor significantly influencing the feeling of presence in VR applications [7, 10]. Haptic feedback is one of them and is sub-divided into several modalities, like for example recognising touch or temperature [28]. This work draws from findings in the field of vibrotactile and thermal feedback. Due to the vast amount of work on body-worn haptic feedback in VR, we limit our focus to related work targeting the facial area and do not consider non-vibrotactile haptic feedback such as suction [21], pressure [3], EMS [27] or wind [39].

3.1 Vibrotactile Feedback

Vibrotactile stimuli as a channel for directional information has been explored for different body parts [22]. Kaul and Rohs investigated the performance of vibrotactile directional cues on the head against visual and auditory cues [23]. Their results indicate that vibrotactile feedback outperforms spatial audio (using a generic head-related transfer function) and is only marginally outperformed by visual cues (96.4% vs. 99.7% success rate respectively). This dominance of visual over auditory cues has been demonstrated for non-VR applications as well [44]. Funk et al. explored haptic, visual, and auditory feedback to signal errors in a manual assembly workplace suggesting that a combination of visual and haptic feedback might increase perception speed of error messages [11]. Wolf and Kuber explored coding schemes for vibrotactile feedback to increase situational awareness with a headband [45]. Their results suggest that a careful mapping of the signals to the different areas of the head must be performed to achieve optimal performance. This sort of mapping is vital since their study demonstrated that some participants struggled to interpret multi-parameter coding. Dobrzynski et al. investigated vibrotactile feedback on the head as an additional information channel for visually impaired users [8]. Their findings suggest that users perform better at localising single motors than multiple vibrotactile stimuli. This is consistent with previous work by Jones and

Safer [20] and could be explained by the way vibrations are propagated through our skull [29]. A further explanation of this behaviour is the ‘funneling illusion’ where two vibrotactile stimuli are perceived as one [25]. Kerdegari et al. report this effect as being strongest for an inter-actor distance of at least 2.5 cm. While it can be misleading for directional cues, this motivated us to leverage this effect for directed feedback via a high-density of vibrotactile actuators.

3.2 Thermal Feedback

Three of the main factors of thermoception are the site of the actuated skin, the amplitude and the rate of temperature change [19]. Due to its high density of thermoreceptors in the skin, the facial area is highly suitable for thermal feedback [13]. This potential was recognised by Peiris et al. in 2017 and motivated them to embed Peltier actuators in a VR HMD to provide directional cues [34]. A preliminary evaluation of their ThermoVR prototype suggested that users felt an increased sense of presence in virtual environments with thermal feedback. However, participants also reported discomfort resulting from the pressure the actuators put on their faces. This motivated us to focus on a small, comfortable form factor for our design.

Follow-up studies explored further use cases for ThermoVR such as checking the weather [5] and providing dynamic thermal feedback [4]. A combination of ThermoVR feedback with low frequency vibration resulted in a sensation of wetness [33] which motivated us to combine vibrotactile and thermal actuators to further explore the potential synergy effects between both actuator types.

Ranasinghe et al. presented Ambiotherm, a wearable accessory that provided thermal and wind feedback on the head [36]. Instead of the facial area, the back of the neck was chosen for thermal feedback due to its proximity to the thermoregulatory centre of the central nervous system [17]. Their results indicate that adding thermal and wind feedback contributed to an enhanced sense of presence compared to traditional VR experiences. In a follow-up project, Ranasinghe et al. added a third, olfactory actuator to the Ambiotherm prototype [37]. Participants’ sense of presence was increased with respect to traditional VR experiences by adding any of the two modalities and improved even further by providing a combination of both modalities. This finding further supports our bi-modal design.

As a conclusion, we think that although vibrotactile and thermal feedback has been investigated for the head area, the potential of high-resolution multi-modal feedback in the facial area for VR applications is still under-explored. In contrast to prior works having a focus on precise localisation of individual stimuli (as explored by e.g. [12, 34]) *Face/On* builds on respective findings but is designed to investigate the complex effects and synergies that can be created with multi-modal and high-resolution haptic feedback.

4 IMPLEMENTATION

4.1 Hardware Prototype

During the design of *Face/On*, we drew from findings of related work regarding the optimal distribution of vibro-tactile actuators to create ‘funneling illusions’ - sensations that would allow to simulate continuous movements along the users face [25]. Therefore, 16 3V vibration motors with 12 mm diameter (coin type, 75mA, 12500 rpm) were embedded inside an 18 mm face cushion for the HTC Vive HMD with a distance of 2.5 cm to each other (see Fig. 1 a). Four 15 × 15 mm Peltier cooler modules (ET limited, 8.6 W, 3.6 V, 3.9 A) were distributed below the eyes and on the forehead as proposed by Peiris et al. [34]. The temperature actuation was measured via NTC-type thermistors calibrated according to the Steinhart-Hart equation [42] (see Fig. 3). Due to the modules inherent inefficiency the excess heat had to be conducted away via copper heat pipes that were attached to each module (see Fig. 2). Each actuator type was connected to a separate Adafruit 16-channel 12-bit PWM/servo driver as a module controller (see Fig. 3 and Fig. 4). Additionally, we installed H-bridges between Peltier modules and their respective module controller. All module controllers were interfaced via I²C by an ESP32 micro-controller that was plugged into the Vive HMD via USB. All modules and micro-controllers were placed inside a 3D-printed case and attached to the top strap of the HMD (see Fig. 2).

This way, the additional weight could be distributed evenly on the users' head to increase comfort. Due to the high power consumption of the Peltier elements, *Face/On* is powered by a separate 3.3 V, 6 A power supply. The HMD was connected to a PC with an Intel Core i7-4790K CPU (4.0 GHz), an AMD Radeon R9 390 GPU (8 Gb, GDDR5) and 32 Gb RAM.

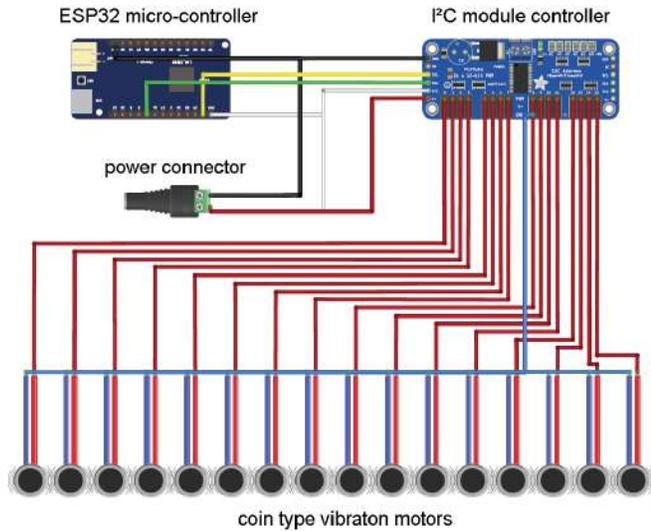


Fig. 3. A schematic view of the vibrotactile module.

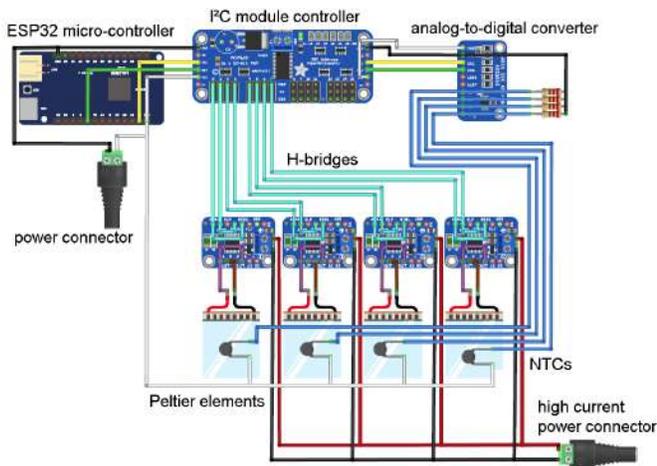


Fig. 4. A schematic view of the thermal module.

5 APPLICATION EXAMPLES

With its high-resolution and multi-modal design, *Face/On* is able to generate a broad range of effects via haptic feedback. We identified four major categories of effects that can be supported by the prototype: environmental effects, game events, forces, and the player state.

5.1 Environmental Effects

Haptic feedback plays an integral role of perceiving the climate of an environment and has been shown to increase user presence significantly when added to a virtual environment [34]. Environmental effects such

as rain are usually continuous and particle-based rather than discrete and punctual. Therefore a high spatial resolution of vibrotactile actuators to simulate the impact of many individual water drops is necessary (see Fig. 5). As shown in previous work, combining cold thermal actuation with vibrotactile actuation can induce the effect of wetness [33]. With a low intensity and frequency of vibrotactile feedback, a rain effect can be changed to represent falling snow (see Fig. 6). Particle-based feedback can also be used to represent swarms of living organisms such as insects or bats (see Fig. 7).

To simulate the temperature of an environment such as a desert, all thermal actuators should be activated simultaneously. The direction of natural heat sources such as warm sun rays on the user's skin can be approximated with individual thermal actuators. The high resolution of vibrotactile feedback also allows to simulate the natural turbulence of a storm.

Three exemplary effects of this category were chosen for the user study: a sprinkler (see Fig. 5), falling snow (see Fig. 6), and a swarm of bats (see Fig. 7).



Fig. 5. Cold water is spraying from the ceiling as the player passes by.



Fig. 6. As the train passes a mountain site snow flakes are falling on the player's face.

5.2 Game Events

Game events include game-specific effects that can not be attributed to physical forces such as a notification of the player gaining a level. Typically such effects are presented via the acoustic and visual channel being the only available sources. *Face/On* is capable of generating directed and animated haptic feedback, allowing designers to guide the user's attention towards a certain direction or encode more information into a notification via a complex feedback pattern. The design of *Face/On* allows the use of various matching feedback patterns such as directed swipes that can for example serve as notifications.



Fig. 7. A swarm of bats is attacking the player and is perceived as many single impact points.

5.3 Forces

With its high density of vibrotactile actuators, Face/On is able to approximate the point of impact of small objects with haptic feedback. The ‘funneling illusion resulting from the small gap between the actuators allows to simulate high speed forces such as the pressure of an aircraft turbine (see Fig. 8). The additional inclusion of thermal feedback further enhances the design space of feedback patterns as well as the possibilities to enhance VR experiences. The combination of hot thermal feedback with a short burst of vibrotactile feedback can for example be used to simulate the blast of an explosion (see Fig. 9). By adding cold thermal feedback, however, the effect of a falling avalanche can be created (see Fig. 10). For the user study, three exemplary effects of the ‘forces’ category have been created: the pressure of an aircraft turbine, an explosion, and an avalanche.



Fig. 8. A hostile aircraft is flying over the train at high-speed generating a strong turbulence.

5.4 Player State

Among others, the representation of the internal state of a player can include a health bar and various status effects such as being wounded or frozen. A common effect in games to represent a critical health level is the acoustic feedback of a beating heart. Since an elevated blood pressure increases the perception of one’s heartbeat throughout the body [26], Face/On can support this effect with a vibrotactile heartbeat pattern. Since the actuators are activated simultaneously during this effect, they are perceived as one large entity rather than multiple individual actuators. By adding hot and cold thermal feedback, player states such as burning or being frozen can be represented, respectively. As an example for player states, a heartbeat pattern that can represent different heart rates has been integrated into Face/On.



Fig. 9. A hostile aircraft is being chased and shot down by another aircraft. The explosion can be felt by the player from afar as heat and a blast of wind.

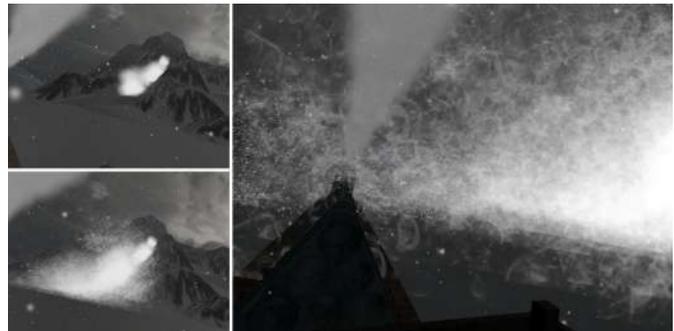


Fig. 10. After a lightning bolt strikes a nearby mountain top, a massive avalanche is threatening to crush the train. The player perceives a cold and turbulent wind with snow.

6 ACTUATION MODES

To create the effects described above, a set of complex vibrotactile feedback patterns is necessary. A naive approach would result in a high number of serial-commands to control each vibrotactile actuator individually. This amount of traffic could increase the response time for haptic feedback although it has been shown to be even more sensitive to delays than visual feedback [18]. In addition, sending such serial commands requires in-depth knowledge of the underlying implementation. This circumstance makes it difficult for application designers to integrate additional feedback into an application. Based on the presented application examples different modes were developed, which abstract from the underlying complexity of serial commands. These actuation modes were created to trigger the feedback by a single command in JSON format and are then interpreted on the micro-controller as a series of actuations. The resulting actuation modes *continuous*, *pulse*, *heartbeat*, *random*, and *dash* are able to cover all effects described in Sect. 5.

6.1 Continuous Mode

As the name implies, the *continuous* mode provides continuous actuation on all specified vibrotactile actuators. The list of parameters expects an intensity value between 0 and 100 for each of the 16 actuators. It is therefore possible to vary the local intensity of vibration, allowing to create sensations such as a continuous, one-sided collision of the user’s head. An actuation command for the example in Fig. 11 can be now expressed as:

```
{
  "id": 0,
  "mode": "continuous",
  "values": [0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 70, 100, 100, 70, 0, 0]
}
```

6.2 Pulse Mode

The *continuous* mode requires a separate message to stop the actuation resulting in a delay for short actuation. To cover short collisions and

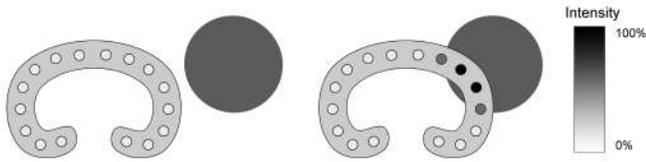


Fig. 11. A visualisation of vibrotactile feedback during a collision. Actuators closest to the point of impact receive a higher intensity than neighbouring actuators.

fast repetitive impulses, the *pulse* mode was implemented to accept additional parameters for the pulse width (*OnDurationsMs*), pulse frequency (*IntervalMs*), and *repetitions* (see Fig. 12). Interpreting the example in Fig. 11 as a short collision the corresponding command could be:

```
{
  "id":0, "mode": "pulse", "repetitions":1,
  "values": [0,0,0,0,0,0,0,0,0,70,100,100,70,0,0,0],
  "OnDurationsMs":100,"intervalMs":0}

```

This would result in a single short (100 ms) impulse of the selected vibrotactile actuators.

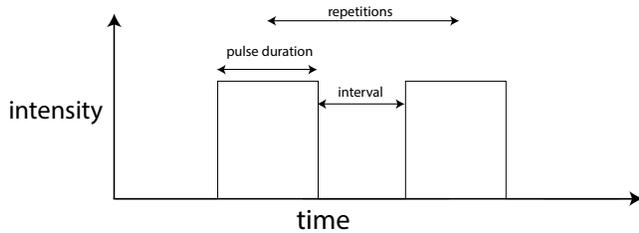


Fig. 12. Pulses can be defined via pulse width, intensity, interval, and repetitions.

6.3 Heartbeat Mode

An often used design element of virtual experiences is the acoustic representation of the user's heartbeat to convey a sensation of panic or high concentration. Previous work has shown that vibrotactile feedback can be sufficient to convey a heartbeat [9] and, thus, influence the user's emotional state [1]. As heartbeat feedback requires a distinct pattern to simulate the beginning and the end of the systole, a separate *heartbeat* mode was implemented as a variation of the *pulse* mode to accept a pulse duration (*OnDurationMs*) for both pulses, an intensity value between 0 and 100 for each of the 16 vibrotactile actuators, and an interval value (*intervalMs*) between consecutive pairs of pulses (see Fig. 13). The interval between the pulses that represent the systole was set to 280 ms which is within the typical range reported in the literature [2]. The parameters are passed in the following form:

```
{
  "id":0, "mode": "heartbeat",
  "values": [60,60,60,60,60,60,60,60,60,60,60,60,60,60,60,60],
  "OnDurationsMs":100,"intervalMs":400}

```

6.4 Random Mode

Simulating environmental particle-based effects such as rain, hail or snow requires an actuation mode that seems random. Therefore a separate continuous mode was implemented that randomly selects two vibrotactile actuators and activates them for a given duration (*OnDurationMs*). This process is repeated after a predefined interval (*intervalMs*). The intensity values range from 0 to 100. A light summer rain could thus be simulated via:

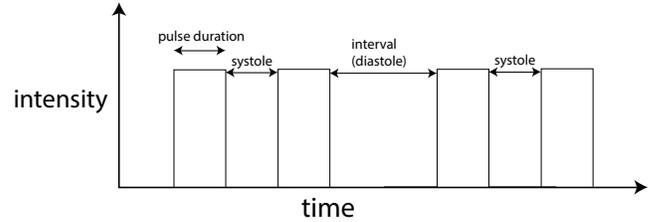


Fig. 13. In *heartbeat* mode, the cardiac cycle is modelled via two consecutive pulses (systole) and intervals between each pair (diastole).

```
{
  "id":0, "mode": "rain",
  "values": [60,60,60,60,60,60,60,60,60,60,60,60,60,60,60,60],
  "OnDurationsMs":100,"intervalMs":40}

```

6.5 Dash Mode

To simulate high-speed movement such as a strong wind directed at the users' face, the *dash* mode creates a dynamic wave-like pattern that originates from the centre of the cushion and moves outwards symmetrically (see Fig. 14). With 16 vibrotactile actuators this results in four states with four actuators being active at the same time. The parameters for intensity (a value between 0 and 100) and duration (*OnDurationMs*) control the intensity and speed of the wave. There are no intervals between the states to create a smooth transition between actuators and leverage the funneling illusion. A fast wave with three repetitions can be created via:

```
{
  "id":0, "mode": "dash", "repetitions":3,
  "values": [60,60,60,60,60,60,60,60,60,60,60,60,60,60,60,60],
  "OnDurationsMs":100}

```

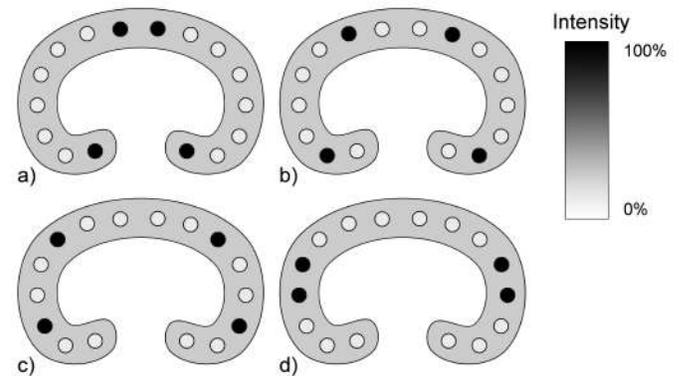


Fig. 14. A symmetrical wave simulates a frontal wind in *dash* mode.

7 PRE-STUDY

7.1 Procedure

To evaluate comfortable intensity parameters for the vibrotactile and thermal actuators, a pre-study with 8 participants (3 female) from our institution was performed. Participants were seated in a room with constant temperature. The participants were equipped with an HTC Vive HMD and the described prototype. The virtual scene was created in Unity3D and was only showing textual instructions on a white neutral background. In a randomised order, participants were asked to increase the intensity of the current actuator type to a noticeable level using

the touchpad of a Vive controller. Vibration was increased in steps of 10%, temperature in steps of 1°C in a safe range from 20°C up to 30°C starting from the participants' individual skin temperature. Temperature was divided in cold and hot actuation, changing temperature levels below and above skin temperature, respectively. Participants were free to increase and decrease the intensity until satisfied with the level. With the trigger button of the controller participants confirmed their selection and were asked to select the maximum comfortable intensity. After a confirmation the next actuator type was selected.

7.2 Results - Vibration

The median for the minimum level of vibration intensity was 40% and 95% for the maximum level. A comfortable range satisfying all participants was found at an intensity between 60% and 80% which is consistent with frequencies used in related work [23] (see Fig. 15).

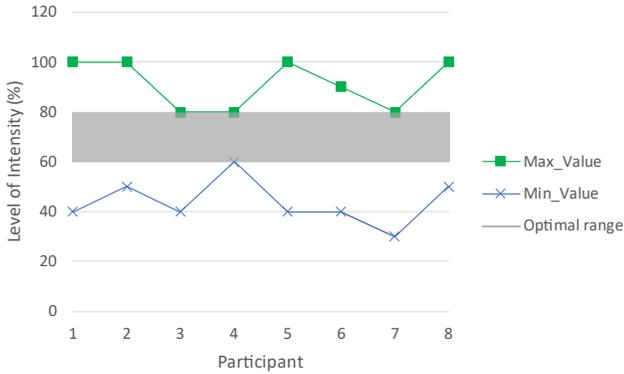


Fig. 15. Ranges of vibration intensity selected by participants.

7.3 Results - Temperature

All values are reported relatively to participants' skin temperature. The median for the minimum level of hot actuation was +0.5°C and +1.5°C for the maximum level. With the exception of participant 6, a comfortable range for hot actuation was found to be between +0.5°C and +1.5°C. The median for the minimum level of cold actuation was -1.0°C and -7.5°C for the maximum level. A comfortable range for cold actuation for all participants was found to be between -0.5°C and -4.5°C (see Fig. 16).

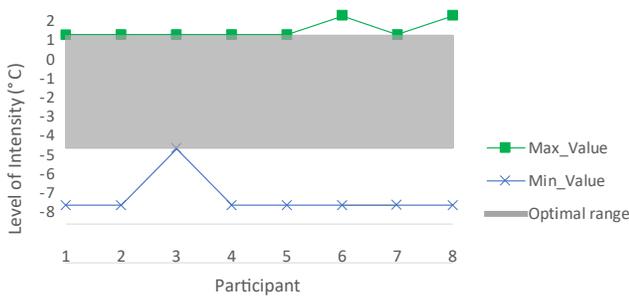


Fig. 16. Comfortable temperature ranges relative to participants' skin temperature.

8 USER STUDY

To evaluate the effect of multi-modality and synergies between both actuator types on the sense of presence, enjoyment, and simulator sickness score, a repeated measures 2×2 factorial design study was conducted with 16 participants. Both actuators were defined as variables with two states: on and off. As described in Sect. 5, the range of effects

that can be created with Face/On is broad. Therefore, only a partial quantity of exemplary effects were chosen for the user study. The study was approved by the local ethics committee. An informed consent was obtained from all individual participants included in the study.

8.1 Study Design and Measures

The study had two independent variables *vibration* and *temperature* with two levels (*on, off*) which resulted in 4 conditions.

For every condition, each participant watched the three scenes described below in a still standing position in a room with constant temperature without taking off the HMD. The scenes used *Face/On* for haptic feedback and an HTC Vive for visual and auditory feedback. All scenes and conditions were fully counterbalanced by a Latin-square. The baseline condition was [*vibration_off, temperature_off*] in which the scenes were viewed without any additional stimuli. After each condition, the participants completed the SSQ questionnaire [24], the E^2I questionnaire (immersion, engagement and enjoyment) [30] as well as Slater et al.'s SUS questionnaire [41] to measure presence. In a final questionnaire, participants were asked to rank the actuator combinations and provide optional responses on if and how they would like to use *Face/On* haptic feedback along with general comments. The study took on average 60 minutes and participants received 10 €. The vibration motors created a noticeable noise but it was barely heard due to the acoustic effects of the scenario playing inside the headphones. All intensity levels used in this study were based on the comfortable ranges found in our pre-study (see Sect. 7).

8.2 Participants and Procedure

Four of the 16 participants were female. They were aged between 22 and 40 years ($M = 27.13, SD = 4.12$) and were recruited from our institution. Participants reported their average time spent in VR between 0 and 8 hours per week ($M = 0.94, SD = 2.08$).

Using the exemplary effects described in Sect. 5, three different scenes were implemented for the user study. To ensure that each participant experiences all effects in the same way, the scenes were designed as a passive train ride. To prevent simulator sickness due to forward or angular acceleration, the train followed a straight path with constant speed [38]. The intensity settings for all effects were based on ranges found in the pre-study (see Sect. 7). At the beginning of the first scene, participants enter a tunnel where they are soon attacked by a swarm of bats (see Fig. 7). The *dash* mode was applied here to simulate the high speed of both, player and bats. Before leaving the tunnel, the train passes a sprinkler that showers the player with cold water. This effect is achieved using the *random* mode while actuating the thermal sources at minimum temperature settings.

At the exit of the tunnel, the train is teleported into a snowy mountain site (see Fig. 6). Similar to the sprinkler, the effect of falling snow was created with a combination of short bursts of cold actuation and the *random* mode. The vibrotactile intensity, however, was kept very low to create the sensation of light snowflakes landing on the participant's skin. As the train passes a mountain, a heavy avalanche hits the train (see Fig. 10). To convey the sensation of heavy snow masses, all 16 vibrotactile actuators were activated via the *continuous* mode.

After passing a portal, the train arrives at a foreign planet where the participant is soon attacked by an aircraft (see Fig. 8). During a nosedive, the aircraft creates a strong pressure with its turbine that is conveyed via the *dash* mode and a high vibrotactile intensity setting. Soon after, the aircraft gets shot out of the sky by another aircraft and crashes on the rocks (see Fig. 9). The hot blast of the explosion is simulated with a hot actuation of all thermal sources at the highest comfortable setting and a short vibrotactile actuation in the *dash* mode. After the explosion, the train gets teleported back to a train station and the participant receives a text prompt to take off the HMD. This concludes the trial.

8.3 Results

8.3.1 Enjoyment

A Friedman ANOVA revealed significant differences in Enjoyment for the four different conditions, $\chi^2(3) = 22.804, p < .001$. Post hoc anal-

ysis with Wilcoxon signed-rank tests was conducted with a Bonferroni correction applied, resulting in a significance level set at $p < 0.0083$. Median (IQR) Enjoyment levels for the baseline, vibration, temperature and vibration+temperature trial were 3.0 (2.5 to 4.0), 4.13 (2.88 to 4.75), 4.38 (3.13 to 5.38) and 5.0 (3.31 to 5.88), respectively. There was a significant difference between the vibration+temperature and the baseline trials ($Z = -3.370, p = .001$), the vibration+temperature and vibration trials ($Z = -2.994, p = .003$) and the vibration and the baseline trials ($Z = -3.066, p = .002$).

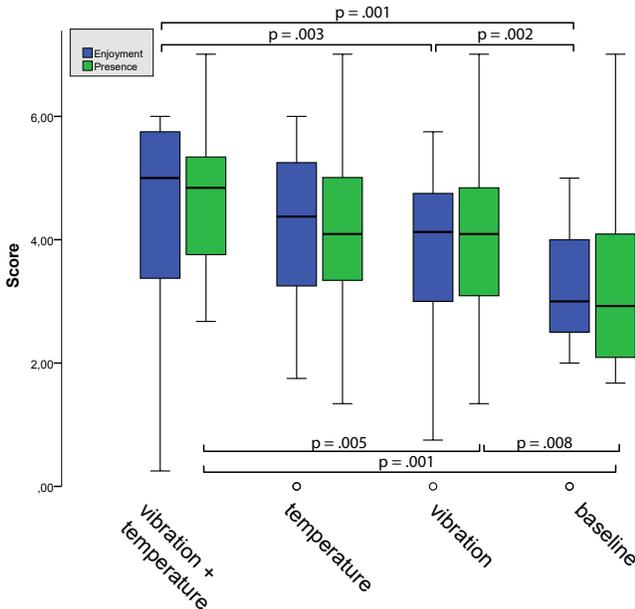


Fig. 17. Box plots of enjoyment and presence scores for all four conditions.

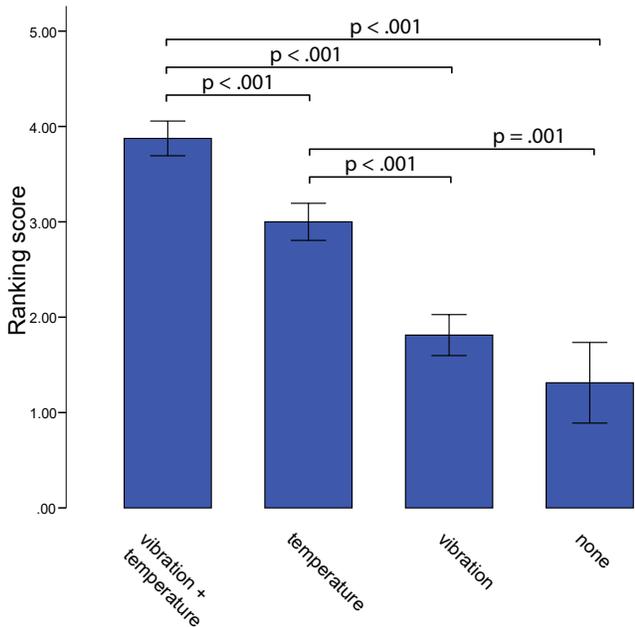


Fig. 18. Bar chart of condition ranking sorted by user preference in descending order.

8.3.2 Presence

A Friedman ANOVA revealed significant differences in Presence for the four different conditions, $\chi^2(3) = 18.120, p < .001$. Post hoc analysis

with Wilcoxon signed-rank tests was conducted with a Bonferroni correction applied, resulting in a significance level set at $p < 0.0083$. Median (IQR) Presence levels for the baseline, vibration, temperature and vibration+temperature trial were 2.92 (2.04 to 4.13), 4.08 (3.04 to 4.83), 4.08 (3.25 to 5.08) and 4.83 (3.71 to 5.42), respectively. There was a significant difference between the vibration+temperature and baseline trials ($Z = -3.234, p = .001$), vibration+temperature and vibration trials ($Z = -2.787, p = .005$), and vibration and baseline trials ($Z = -2.643, p = .008$).

8.3.3 Simulator Sickness

An analysis of the SSQ revealed no significant difference in simulator sickness scores over all conditions ($M = 9.875, SD = 12.851$) compared to the control condition ($M = 8.65, SD = 10.1$).

8.3.4 Correlations

Fig. 18 shows the user ranking across all conditions in a descending order which suggests a correlation with the enjoyment and presence scores in Fig. 18. This correlation was analysed using Spearman's correlation coefficient. There was a significant positive correlation between *ranking* and *enjoyment* ($p = .004, \rho = 0.352$) and *ranking* and *presence* ($p = .001, \rho = 0.389$). Further more we found significant positive correlations between *enjoyment* and *presence* ($p < .001, \rho = 0.556$). A Friedman ANOVA revealed significant differences in the ranking scores of the four different conditions, $\chi^2(3) = 38.625, p < .001$. A Kendall's W test revealed a high concordance value for the ranking scores, $W = 0.805, p < .001$. Post hoc analysis with Wilcoxon signed-rank tests was conducted with a Bonferroni correction applied, resulting in a significance level set at $p < 0.0083$. Median (IQR) ranking score levels for the baseline, vibration, temperature and vibration+temperature trial were 1.0 (1.0 to 1.0), 2.0 (2.0 to 2.0), 3.0 (3.0 to 3.0) and 4.0 (4.0 to 4.0), respectively. There was a significant difference between the vibration+temperature and temperature trials ($Z = -3.5, p < .001$), the vibration+temperature and vibration trials ($Z = -3.753, p < .001$), the vibration+temperature and baseline trials ($Z = -3.646, p < .001$), the temperature and vibration trials ($Z = -3.755, p < .001$) and the temperature and baseline trials ($Z = -3.256, p = .001$).

8.4 Discussion

Our results indicate that the presence of two forms of feedback - vibrotactile and thermal - demonstrates better results in terms of presence and enjoyment. The combination of both modalities was ranked higher than single-modality conditions which also resonates in the participant responses where participants stated for example that 'the combination of temperature and vibration reinforces the overall impression more than the individual actuators' (P15) and 'vibration and temperature work very well together' (P2). These synergy effects were described with the fact that 'the cold doesn't feel punctual when combined with vibration but is spread' (P10). This is consistent with previous work and indicates that multi-modality has a positive impact on user presence. Adding further modalities such as kinesthetic feedback generators could further increase the benefit and could be evaluated in the future. The SSQ scores did not change significantly possibly due to a rather small sample size.

9 LIMITATIONS

Although the copper heat pipes improved heat dissipation for the Peltier elements drastically, temperature actuation was limited to a bare minimum. Tests with continuous cold actuation over short periods of time ($t = 30s$) showed an accumulation of heat in the heat pipes of over $40^\circ C$. Shortly after the actuation period ($t < 3s$), the actuator side facing the users' skin reached a peak temperature of $32^\circ C$ which was higher than the comfortable maximum value reported in the pre-study (see Sect. 7). Therefore, thermal actuation was provided in short impulses rather than continuous actuation. A more sophisticated and active cooling system such as fans or liquid cooling could mitigate the heat dissipation issue. As stated in Sect. 4.1, the temperature change rate was approximately $3^\circ C/s$ which resulted in a noticeable delay. Providing feedback for sudden, non-scripted events therefore requires an approach as reported

in HapticTurk [6]. Here, the authors implemented a mechanic that probes the environment for incoming user-environment events such as collisions to compensate for feedback delay. Similarly, events such as projectile impact could be predicted via ray-casting to synchronise the haptic and visual feedback. Although no participant complained about hearable vibrations or any other sounds affecting the experience in a negative way, there is the possibility of bone conducted sound affecting the experience.

10 DESIGN CONSIDERATIONS

The findings of this work have implications on the design of haptic feedback for VR. Designers of VR experiences may consider the following three aspects when creating haptic feedback for the facial area.

10.1 Hardware Design

The results of our study validate the benefit of a multi-modal design. We expect that adding further modalities like kinesthetic feedback (as done in e.g. [15]) would create additional synergies and increase the range of effects that can be generated. To keep the compact form factor of the current prototype, additional actuators should be mounted on the contact area between cushion and skin or within the remaining space inside the cushion. An alternative would be to create interchangeable cushions with different actuator constellations that can be changed depending on the current content.

Most effects presented in this work would not have been feasible with a low-resolution design. Therefore, we argue that an increased resolution of actuators results in a larger design space for haptic feedback. However, not all types of actuators require the same level of resolution. In this work, we have demonstrated how low-resolution thermal feedback can be combined with high-resolution vibrotactile feedback. Similar asymmetric constellations might be feasible for other types of actuators and require further exploration.

10.2 Software Design

In this work, we created complex effects by using feedback modes that can be triggered by a single command. This on one hand reduces communication traffic between software and prototype and therefore reduces the delay of haptic feedback and on the other hand allows for easier integration into VR applications. The level of abstraction allows to keep the code clean and to rapidly implement and evaluate new effects. Designers of effects for Face/On or other haptic feedback devices could consider adapting a similar abstraction layer for any new actuator type. Since our experiment was limited to a few exemplary effects out of a broad range of possibilities, there might be value in evaluating more effects regarding their impact on user presence and enjoyment.

10.3 Application Design

From our experience, haptic feedback in the facial area should be kept sparse to stay comfortable. If continuous or long effects (e.g. precipitation) are necessary, the intensity should be kept low and the effect subtle. Big effects like an explosion should use multiple modalities to create a strong impression. Effects like these can create an impressive presentation of the virtual world. To create more intricate haptic feedback, future VR designers could translate audio signals into haptic feedback. Especially low frequencies could result in haptic feedback that leverages an audio signal. Due to the high resolution of vibrotactile actuators, Face/On could represent the direction of the audio signal by actuating the corresponding face region.

11 CONCLUSION

In this paper, we have presented the design and evaluation of Face/On, a multi-modal haptic feedback device for VR HMDs. By combining high-resolution vibrotactile haptic feedback with thermal sources inside the compact form factor of a face cushion, complex feedback patterns can be generated to create unique effects for virtual environments. We implemented exemplary effects for three virtual scenes, that have demonstrated and validated how complex haptic feedback can increase user presence and enjoyment. In the future, Face/On can be extended

by additional actuators to create more synergies and more complex feedback patterns.

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