FaceHaptics: Robot Arm based Versatile Facial Haptics for Immersive Environments

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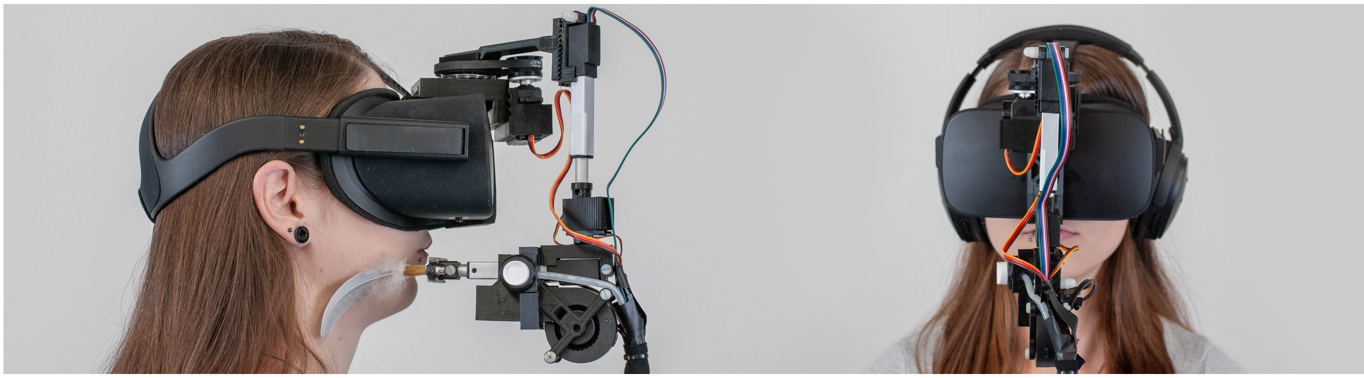

Figure 1. The FaceHaptics system, showing a side and frontal view of the setup for face haptic feedback, affording various sensations including touch, texture, warmth, air flow, or wetness. The left image depict one of many possible touch/texture feedback elements, which can easily be exchanged.

ABSTRACT

This paper introduces FaceHaptics, a novel haptic display based on a robot arm attached to a head-mounted virtual reality display. It provides localized, multi-directional and movable haptic cues in the form of wind, warmth, moving and single-point touch events and water spray to dedicated parts of the face not covered by the head-mounted display. The easily extensible system, however, can principally mount any type of compact haptic actuator or object. User study 1 showed that users appreciate the directional resolution of cues, and can judge wind direction well, especially when they move their head and wind direction is adjusted dynamically to compensate for head rotations. Study 2 showed that adding FaceHaptics cues to a VR walkthrough can significantly improve user experience, presence, and emotional responses.

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Author Keywords

Haptics; robot arm; immersive environments; virtual reality; user study; perception; presence; emotion

CCS Concepts

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

INTRODUCTION AND MOTIVATION

Over the last decade, Virtual Reality (VR) systems have been massively improved, in particular driven by the gaming industry but increasingly also other industry sectors. Predominantly, advances have been made in providing affordable yet high quality visual displays. However, non-visual cues can be a key factor in immersive systems, for example to improve overall simulation and perceptual fidelity [36] or to invoke emotional reactions [14, 27]. While rendering audio cues is well supported, haptic feedback is still challenging, and foremost targeted towards the hands [31]. In this paper, we look at how haptic feedback can be provided towards the face rather then the hands. We explore how this feedback could be of value in an immersive environment while wearing a head-mounted display (HMD). The reason why we choose the face is that it is highly sensitive to haptic cues and can perceive different kinds of haptic feedback well, as other areas of the body are often covered by clothes. For example, wind is often sensed by the face or hands. Moreover, due to the high number of receptors in the face, it is quite sensitive [56]. While the provision of haptic feedback towards the head can enable the support of events associated with direct object interaction, it often also has an ambient nature. We refer to ambient feedback as feedback that is focused on the overall environment condition instead of a specific object or event. We assume both types of events can potentially enhance the user experience (e.g., fun or awe [58]), which we assess through our system and studies.

Previously, researchers have attached different output devices to HMDs, including olfactory displays [41, 18], fans [7], or even flywheels to simulate inertia [16]. While demonstrating the potential of face feedback, most systems have a number of technical limitations. Namely, actuators and other haptic feedback elements are generally integrated in the HMD cushioning around the eyes or directly under the HMD. As such, feedback localization and directionality (the angle at which feedback is provided towards the face) is limited. Thereby, the majority of systems do not (or can not) take into account head movements - e.g. the changing sensations of wind on the face when turning one's head - as they are constrained by the number and locations of fixed feedback elements. Most systems also offer a limited number of actuation types and are not easily extensible. While systems have been announced that integrate different feedback modalities (e.g., the FeelReal system, https://feelreal.com) they have yet to become available and still are limited by feedback range, resolution (localization) and directionality. Finally, only very few systems (e.g., [63]) focused on direct object feedback. Even more so, these systems are mainly based on sensory substitution. Here, haptic (force) events are "translated" into tactile cues instead of being presented as real forces, leading to perception limitations [22].

To overcome the limitations of previous feedback systems, we present **FaceHaptics**. FaceHaptics consists of a small custom-made robot arm attached to an HMD that can move different feedback elements along and against the face to most areas not covered by the HMD (Figure 1 and Figure 2). As such, it is not limited to the cushioning area in the HMD. Rather, it covers a large part of the face around the HMD. The system offers an integrated fan and interchangeable heads to attach different feedback devices or materials that can touch and brush the face, offering a high level of modularity and customization to interface designers. We provide both ambient and direct object feedback through the system. To illustrate the capacities of the system, we currently provide wind, warmth, soft single-point and moving touch (real forces instead of vibration), and air-water spray (wetness) towards the face. FaceHaptics thereby can also change the directionality of haptic cues dynamically, for example to indicate a specific wind direction while compensating for head movements, or to simulate moving objects. Through our studies, we will show that users can interpret well the directionality of cues, and that cues significantly contribute to both presence and especially emotional response.

Perception and potential application

The head offers a high density and variety of receptors, mostly distributed over the eyes, ears, nose, mouth and skin. With FaceHaptics, we foremost stimulate receptors in the skin. When we regard the face as a sensory organ [56], we can identify various perceptual events that are related to the receptors in the human face. These receptors cover both haptic and other events. Generally, the face receives sensory information from the environment and transmits it to the cortex. Over 17.000 corpuscles (receptors) can be found in the facial skin that contribute to different sensory functions. The different corpuscles are sensitive to stretch (Ruffini corpuscles), stroking and fluttering of the skin (Meissner corpuscles), pressure and texture (Merkel disk receptors and to a lesser extent hair follicle fibers), and temperature and pain (free nerve endings). Furthermore, as the head is supported by an intricate musculoskeletal system, also stronger forces can be experienced, for example through receptors in muscles. Though we mostly focus on the skin, we will also discuss feedback to the mouth and nose later.

The different cues can take various roles in a virtual environment. Generally, skin-related face feedback can include, but is not limited to the following stimuli and events:

- **touch:** light touch and soft pressure (e.g., wind, objects strafing the face, intimacy like sensual touch or kissing), hard impact or pressure (e.g., objects hitting face)
- **temperature:** ambient temperature, direction and temperature of single heat source (e.g., light, sun, glowing object)
- **texture:** texture / material properties (e.g., clothes, fingers or leafs touching face)
- **pain:** events associated with stimuli that surpass the pain threshold (e.g., objects hitting or pinching the face, skin protrusion, or high/cold temperature)

It is useful to note that some perceptions combine different types of stimuli. Wetness, for example, is a perceptual construct of cold temperature and tactile sensations such as pressure and texture [15]. In our studies, we mainly look into events related to light touch, texture and temperature, as these are safer to use and can more easily be integrated to augment a wide range of VR experiences.

Research questions and contributions

With FaceHaptics, our research is driven by the following research questions (RQs) that are centered around the premise of understanding the role of haptic actuation on the face while being immersed in a virtual environment.

RQ1. How well can users perceive directional haptic stimuli towards the face? Can dynamic head movements help to improve direction perception? Exemplified by wind, we explore how events caused by a feedback element that does not touch the skin directly could be perceived. Here, we specifically explore how well users can judge the direction of stimuli, to investigate the potential of the full directionality of the system, in contrast to other systems that have a limited number of fixed feedback elements. Sound localization ability (which has low directional accuracy similar to wind direction detection) can be greatly improved with dynamic head rotations [5]. We hypothesized wind direction estimates might be similarly improved, extending previous research like [39]. Head rotations naturally occur in VR, hence assessing their impact on direction discrimination (and comparing it to a static baseline) is essential. We focused on wind, as warmth takes longer to detect (and was confounded with wind), mist perception has little directionality, and direct touch is already well understood.

RQ2.How does adding different face-haptic stimuli to HMD-based VR affect user experience? With this research question, we regard user experience as a combination of presence and emotional response, following similar dimensions as previous work [27]. While perception of individual cues has been explored in previous work, it is not always clear how and to what extent face stimuli affects overall user experience. While we assume the feedback will improve fidelity [36], most previous studies only provide general indications towards the effect of cues. This leaves open questions such as the perceptual differentiation of cues, the effect of cues on presence or different emotional responses [46]. We hypothesize that adding face-haptic stimuli improves user experience in terms of enhanced emotional response, memorability, convincingness, believability, enjoyment, and presence/immersion. However, we do not have a clear prediction about the relative effectiveness of different cues as we assumed them to be highly context-dependent.

RELATED WORK

With the increasing interest in using HMDs as gaming platform, researchers for some time have extended head-worn displays with different types of actuation, or targeted the face directly or indirectly by using devices around the user. Most of the work has been focused on ambient (environment-centered) cues, while also object-centered cues have found some application. The majority of systems opt for adding multisensory feedback devices external to the user, e.g., mounted on a table [27] or on a large frame around the walking area of an immersive systems [14], while others (see our wind discussion below) attached actuators directly to or in [61] the HMD itself. Finally, some work has also focused specifically on low-cost passive solutions (especially props) to integrate multisensory feedback into VR system, e.g., as presented in [17].

With respect to haptic cues, researchers have explored (partially multi-directional) wind as through fans attached to the HMD [7] or using external devices [14, 27, 38]. Notably, in [28] a full-body steerable wind display is demonstrated, integrated with a multi-screen VR projection and tiltable force-feedback linear treadmill setup. Other studies combined fans with temperature display [48]. Directional temperature was explored by integrating multiple thermal elements in an HMD [45], while [63] combined directional thermal with directional vibrotactile feedback and also looked to some extent into direct object interaction feedback. Directional (vibro)tactile feedback has also been demonstrated in other systems using vibrotactors [4, 35, 43] or suction mechanisms [23]. Tactile wetness sensations was focused on in [44]. Stronger forces on the head related to inertia where explored in the flywheel-based system described in [16], while also pressure [8] and soft touch to the face provided by ultrasonic soundwaves [9] has been experimented with. Finally, the face is often associated with intimacy, which has been explored to some extent in the frame of social touch [19], in part with focus on kissing and hugging [51].

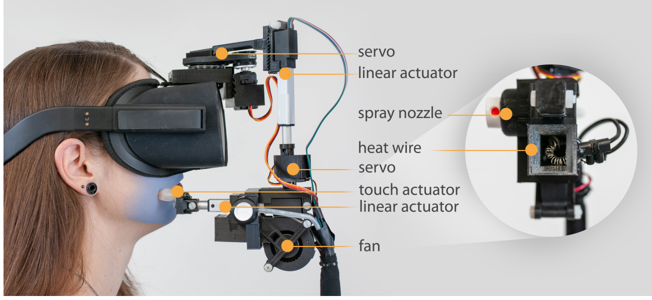

Figure 2. System overview: elements of the robot arm with different feedback elements. The close up shows a frontal view of lower robot arm with fan, heat wire in front of fan, and spray nozzle. The blue overlay over the face shows the approximate area that can be reached using touch events (wind can be sensed over the whole face).

Regarding chemical senses, smell has been provided externally [64] and through devices directly connected to the HMD [40]. Researchers have also explored taste including biting simulation [21]. With regards to vestibular cues, galvanic stimuli have been used to trigger the human balance system [33].

Some previous work has looked into actuation (position, orientation) of computer or tablet displays, e.g. TouchMover [57] or Forcetab [34]. In contrast, Mobilimp [59] integrated a small finger-like robot arm to a cellphone, exploring tangible aspects, yet towards the hands. Furthermore, other body locations have been focused on, including the torso and feet (e.g., [26]) - see [31] for an overview. Our system also relates to various alternative robotic solutions that can provide haptic feedback to a user's body, in particular those that are mounted on tables, body-worn, or attached to drones. For example, SnakeCharmer [3] made use of a table-mounted robot arm and demonstrated how an actuator can be moved to the user's hand to render texture, position, and temperature, illustrating flexibility in changing stimuli using a single device. The system is similar to VRRobot [60] where a robot-arm was used to move props towards the user. Robot-arms have also been attached to the user's body, somewhat like an exoskeleton. While these systems focused on extending the body with limb extensions, they could be repurposed to afford haptic feedback. Particular examples including Metalimbs [53] and Fusion [52]. Drones have also been used to enable interaction with physical objects, for example by mounting objects on the drone [2] or using the drone to "hit" the user [1]. Finally, full body solutions like HapticTurk [10] afford the provision of haptic feedback by manually moving the body (or objects against the body), but relies on multiple trained experimenters to provide feedback.

Overall, previous work indicates improvements in presence in immersive environments due to added multisensory stimuli. Yet, the majority of studies does not necessarily pinpoint underlying perceptual mechanisms and more detailed effects (e.g., the effect of cues on emotional response), which we aim to look closer at in our studies. Furthermore, from a technical stance, we are unaware of any system that can provide a high variety of haptic cues in a fully localizable and multi-directional manner to the uncovered parts of the face.

FACEHAPTICS SYSTEM

Our FaceHaptics system (Figure 2) consists of a custom-made robot arm attached to a commercial HMD, currently an Oculus Rift CV1. The arm supports 4DOF and the kinematics allow to reach points on the face in a range of ±67.5° from the center (total 135°). Events that need to be provided orthogonal to the face can be provided in a ±35° range, due to restrictions of the movement of the arm. The areas are highlighted in Figure 2. The arm construction is comprised of two linear actuators (Actuonix L12, 3 and 5cm respectively) and two servo motors. One servo motor (DSS-M15S, 2:1 gear using belts) is mounted on top of the HMD and turns the arm around the front of the face, the second servo (HS-5070MH) rotates the lower arm towards the face. The robot arm and further feedback elements attached to the arm are driven by an Arduino Mega and an external power supply (12v/4A, for fan and heat wire). Intensity of the fan and wire can be controlled in 256 steps. A step-down module lowers the voltage to 6V, for usage with the other feedback elements. Feedback elements are described here after. The arm is controlled using inverse kinematics (IK Constructor Unity Plugin) through Unity (2018.3). In Unity, two targets are used: one to control the overall rotation of the upper arm, the second target to register exact locations and directions towards the skin. We choose to use linear actuators in contrast to a fully servo-based arm, as the linear actuators proved to be much more resistant against head shakes than an initial version we built using servos only.

The system can provide both head-centered (egocentric, the feedback element stays stable at a fixed location in front of the head) or world-centered cues, where the arm can compensate for head rotations. In this way, we can keep the source of the actuation (e.g., wind) stable from an allocentric (world or simulated scene) perspective. The system affords head rotations of up to 167 degrees / second (yaw), though the maximum rotation afforded by the arm is, as noted before, 135°. We support calibration of the system for different face geometries through up to 10 points chosen on strategic locations on the face (e.g., mouth). These points are triggered in a step-by-step procedure that extends the lower linear actuator towards the face until it touches the skin, storing the face positions in a config file. Currently, this procedure is done manually - a future iteration foresees the usage of a pressure sensor.

For our studies, we connected multiple feedback elements to the robot arm. To simulate airflow and wind, a fan (DF5015, 12V, nominal 5000RPM, 5.55 CFM) is permanently attached. To simulate warmth/heat, the fan is extended with a heat element, comprised of a gauge nichrome 80, that can reach around 55 degrees Celsius (gauge wire temperature). This can be clearly noticed at 3cm from the skin (the distance from the wire to the skin). Both fan and heating element are controlled by a transistor, which allows smooth adjustments. To provide wetness sensations, we attached a spray nozzle to the side of the fan, to which a flexible tube is connected to a Philips Sonicare Airfloss device. To enable a direct control of the Philips Sonicare Airfloss from within the application, a relay was connected to the trigger switch. The nozzle can spray small amounts of an air-water mixture towards the face. Finally, a magnet is mounted at the front of the lower linear actuator. Using the magnet, different types of contraptions can be flexibly and quickly mounted as needed while using an exchangeable head. Currently, we make use of a soft rubber tip that, when pressed against the face, delivers a quite firm touch event, and while moved along the face softly touches the face. To counterbalance the weight of the robot arm (405gr) and cables, a small weight-bag of 654gr is attached to the back of the HMD. We measured our system with full payload using a 240 fps camera. Maximum speeds are 136/187 °/s for the top respectively bottom servo, and 23 mm/s for linear actuators. We designed studies to avoid speeds of >45 °/s to avoid vibrations at higher speeds, which we will further discuss later in the paper. Force measurements using a Vogel digital force measurement device of the horizontal linear actuator pressing against a surface showed we can provide forces of around 5.05N - forces were measured with a fixed robot arm until the point where the arm starts deforming. Finally, the small water container affords 50+ sprays, and has a delay of 600 ms (caused by the Philips Sonicare).

USER STUDIES

To assess the FaceHaptics system, we performed two user studies. During both studies, users were seated comfortably on a (non-swivel) chair. They wore noise-cancelling headphones and the HMD with added FaceHaptics. The simulated environment was a rain forest scene created in the 3D game engine Unity. Many haptic cues could be easily included to match events in the scene (e.g., sunlight, leafs brushing the face). We explicitly designed the environment to elicit a "positive experience", and added FaceHaptics cues were expected to trigger positive emotional responses (e.g., happiness, surprise, wonder), instead of the negative ones (e.g., anger, disgust, fear). Prior to the studies, we calibrated the system to adjust for participants' facial geometry, to ensure users could well perceive the stimuli. As we only made use of a minimal number of direct touch points, a single-point calibration sufficed, which sped up the procedure considerably (<1 min). Based on the calibration, we could easily and quickly exchange the rubber-tip head with longer or shorter versions as needed, as this was the only feedback type directly affected by face geometry (head, wind, and water spray were provided without direct touch of the robot arm).

Sixteen participants (19-47years old, mean age = 32, SD = 7.7, 5 female) participated in both user studies. The majority was experienced in video-gaming and plays video-games at least weekly (81.3%), while the experience with HMDs was less common as 75% of the participants have used it only a few times, and one person never (6.3%). Before the first study, participants received written and oral instructions, signed the informed consent form, and answered questions related to their demographic background. The studies were performed according to declaration of Helsinki.

Study 1 - Directional wind cue perception

The goal of study 1 was to investigate how well participants could judge the direction of wind (airflow) provided through the fan attached to the FaceHaptics system, depending on if they moved their head, and if the FaceHaptics robot arm compensated for head rotations or not.

Methods

Users saw the same environment as used for study 2 (a rainforest, see Figure 4) but from a static location. The environment did not include any specific auditory or visual cues on wind direction. Users would receive a wind cue from different directions, provided by the fan. Directions were grouped in three angles covering a $\pm 35^\circ$ area (0° straight ahead, and $\pm 25^\circ$ for left and right). In this range, the robot arm can be moved orthogonal to the face. A random offset between -10° and $+10^\circ$ was used to vary directions and avoid learning effects. Based on pilot testing, the wind cue lasted for 8s to ensure that it could be clearly perceived.

Participants judged wind direction in 4 different conditions: (a) **static head**, where participants were instructed to keep their head stationary, and the fan provided air flow from a given fixed angle per trial; (b) **oscillating head and compensating wind direction**, where participants were instructed to make slow oscillating head movements at a predefined angular velocity (as if gesturing "no"), while the fan attached to the robot arm counteracted the head rotation in order to provide a fixed world-centered wind direction. To provide consistent head oscillations across participants, they were asked to rotate their head to always face a simulated butterfly that flew at a fixed radius and sinusoidal profile around the user's head, at a frequency of 1Hz and $\pm 30^\circ$ amplitude around the users' forward direction. We only considered jaw for rotation and cue provision; (c) **oscillating head and static wind direction**, where the fan stayed at a fixed position relative to the head and HMD, while participants were instructed to make oscillating head motions as in (b); and (d) **free head movement with actuator compensation**, where participants were free to rotate their head as they wished while the robot arm compensated for head rotations. We predicted that being able to rotate ones head, in particular during the free head movement condition, should improve wind direction judgment performance, but only if the robot arm compensated for the head rotations so as to provide a constant world-centered wind direction. While condition c seems counterproductive, we included it to simulate static wind systems that cannot compensate for head movements as reported in related work. After 8s the wind stopped, and participants used a method of adjustment to indicate the perceived wind direction by rotating their head to orient a visually simulated laser pointer in the virtual scene until it matched the perceived wind direction. Afterwards, they verbally rated pointing direction certainty on a 0-100 scale (100 being completely sure).

Each participant completed 24 trials, consisting of a factorial combination of 3 wind directions $\{0^\circ$ straight ahead, and $\pm 25^\circ$ for left and right$\}$ including a random offset between -10° and $+10^\circ \times 4$ movement conditions as described above $\times$ 2 repetitions per condition. Trials were blocked by movement condition, but otherwise randomized. Note that left and right directions were included to avoid bias towards one direction, but data was pooled across left and right trials before data analysis. After finishing study 1, users provided ratings on the difficulty of the task, presence in the scene, and perceived realism on an analog scale ranging from 0 (=very low) to 100 (=very high) for each condition.

Results

A repeated measures ANOVA was used to study the effect of the independent variables movement direction and wind direction on the absolute and the signed pointing error and certainty ratings. Planned contrasts were applied to analyze differences between factor levels. In analyzing pointing data we realized there was a systematic leftward bias in the pointing direction from all participants, of about 15° on average. When manually checking and measuring the offset using a woolen tuft mounted at the centre-lower side of the fan outlet, we could confirm this left-ward bias in the data, which was likely caused by the mounting of the fan and the air flow direction which was slightly offset. Also, we noted the outflow was not symmetrical. To correct for this overall bias, we subtracted the median offset (15 degrees) from the pointing direction data before further data analysis. The movement condition showed a significant effect on the **absolute pointing error** ($F(3,45) = 3.0, p = .04, \eta_p^2 = .0167$). The absolute pointing error was lowest for the free head dynamic wind condition ($M = 7.25^\circ, SD = 4.29$) as indicated in Figure 3 and highest for the condition with oscillating head and static wind ($M = 14.50^\circ, SD = 13.9$) (left). Planned contrasts showed that the two conditions that allowed for head movements and provided dynamic wind direction compensation resulted in lower absolute pointing errors that the two conditions that had static wind direction, i.e., where head movements were not compensated for, as in most other wind systems.($p = .021$). Additional planned contrasts showed that pointing errors did not differ between the two static wind conditions ($p = .30$), nor the two conditions with dynamic wind ($p = .14$). Interestingly, absolute pointing errors showed no significant main effects of wind direction or interactions between movement condition and wind direction (all $p's > .57$). The **variability in the pointing data** showed a similar data pattern (Figure 3 (middle)): The standard deviation of the signed point error differed significantly between movement conditions ($F(3,45) = 3.1, p = .036$) with a lower pointing error in conditions with head movements and dynamic wind than conditions with static wind ($p = .01$).

Overall **certainty of judging wind directions** was affected by movement condition ($F(1.89, 28.3) = 6.34, p = .006, \eta_p^2 = .0297$). Descriptively, it was highest for the free head dynamic wind condition ($M = 84.9\%, SD = 8.95\%$) and lowest for the oscillating head and static wind condition ($M = 69.6\%, SD = 18.7\%$), see Figure 3 (right). Planned contrasts showed that the two conditions that allowed for head movements and provided dynamic wind direction compensation resulted in higher certainty ratings than the two conditions that had static wind direction ($p = .011$). When comparing the two static wind conditions, certainty ratings were higher for the static head compared to oscillating head condition ($p = .0045$). When comparing the two dynamic wind conditions revealed a marginally significant trend towards higher certainty ratings for the free head movement condition compared to the oscillating head condition ($p = .086$). Interestingly, wind direction did not show any main effects on certainty ratings ($p = .80$), although there was a significant interaction between movement condition and wind direction on certainty

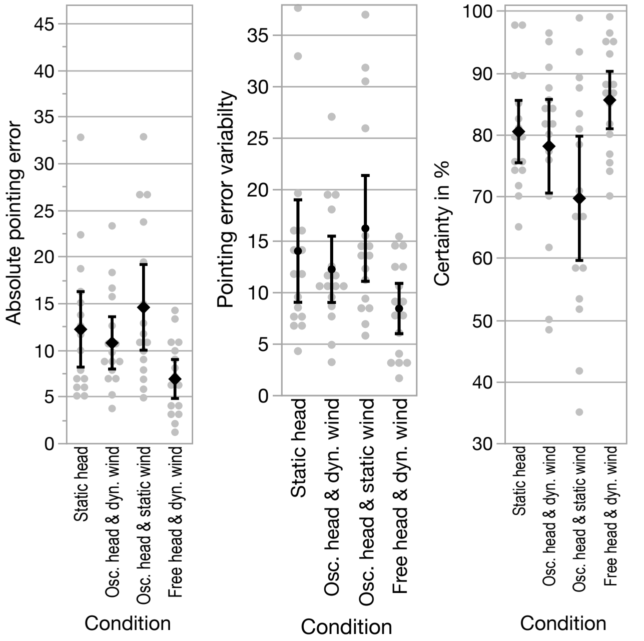

Figure 3. Mean performance for the different conditions, averaged over the two repetitions. Gray dots indicate participant mean data, whiskers indicate 95% confidence intervals.

ratings, $F(3,45) = 3.47, p = .024$. Contrast slices showed that participants' certainty in judging the wind direction was significantly higher for the side than center condition for the "free head and dynamic wind" condition ($p = .017$), whereas the other movement conditions showed no such difference ($p's > .05$). Finally, computing the mean signed pointing error in the forward direction (wind directions from $-10°$ to $+10°$) and the side directions (where wind came from $\pm 25° \pm 10°$) showed that participants overall pointed quite accurately (Center: $M = 0.58°, SD = 6.57°$, Side: $M = 0.15°, SD = 5.63°$), with no systematic tendency to point inwards or outwards for either central wind directions $t(15) = .353, p = .729$) or side wind directions ($t(15) = .011, p = .915$).

Discussion

Overall, the results indicate that users could well judge directionality, especially if head movement was compensated. We were initially concerned about the offset caused by the fan output, as previous work shows there could be an effect of direction (centre versus left/right) on the pointing error [38]. However, though wind direction affected the error, we showed there was no significant effect. Results can be compared to the experiment reported by Nakano et al. in [39], where both a 3×3 ventilator array and a single ventilator were used. Both configurations were attached to a platform that could be moved on an arc rail centered around the head. The two systems were used to detect differences in just noticeable differences (JNDs, instead of pointing errors) for uniform (ventilator array) and localized (single ventilator) wind stimuli, that were thought to affect perception. In the real world, wind is rather uniform instead of localized. JNDs were low, with 5.55° degrees for the array, and 1.68° degrees for the moving wind source. Notable, participants judged wind direction by either direction (uniform stimuli) or the area on the face touched by the wind (local stimuli). Generally, and as also supported by the JND results, users found it harder to judge direction with uniform wind. In comparison to our study, we made used of a similar setup, as our single ventilator also moved around the face, albeit much closer to the face. Interestingly, our absolute pointing errors of 7.25° are rather more comparable to the uniform wind than the local wind condition in [39]. This may indicate that the shape of our wind stimulus is also wider and perhaps non-uniform, as we also noted during initial tests. A further assessment is necessary to address the actual wind shape and velocities produced by the ventilator. Finally, in their previous experiment with a rigid setup, Nakano et al [38] noted some left/right perception switches. In comparison, in our study in 4.3% or 11 of the 256 trials total where wind directions came from the side, participants pointed in the left-right reversed direction, e.g., they pointed toward the left side when wind came from the right sight and vice versa. They were apparently unaware of this, and rated their certainty overall fairly high ($M = 68.6\%, Median = 80\%, SD = 28.3\%$). Most of these reversed trials occurred during the first repetition per condition (8/11 trials), with overall 5 in the oscillating head and static wind condition, 4 in the oscillating head and dynamic wind condition, and 2 in the static head condition, and none in the free head dynamic wind condition. This further suggests that allowing for free head movements reduces not only pointing errors but also cardinal errors.

Figure 4. Feedback elements with sample events: ventilator depicts fan, wire for heat, leaf is the rubber tip and spray the water-air spray.

Study 2 - User experience of face haptics

The goal of the second study was to investigate the effect of the different FaceHaptics cues, namely soft touch, wind, warmth, and wetness, on presence and emotional response in a compelling immersive environment walkthrough.

Methods

We created an appealing tropical rainforest VR scenario (see Figure 4) that contained 16 events along a 3 minute pre-defined walkthrough. Each participant completed one trial with additional face-haptic feedback for these 16 events, and another

feedback	haptic event	scenario event
fan	wind (medium to high speed)	wind gusts
	cold temp. (high speed)	walk along cold wall
heater & fan	warm temp.	walk in sun / heat fire
soft rubber tip	soft touch (pressure)	insects flying into face
	sliding touch	leafs brushing face
spray nozzle & fan	mist (brief air-water gust)	waterfall spray

Table 1. Feedback elements with associated haptic events and representative scenario events. These events were also used in the questionnaire to ask for specific effects.

IPQ items	Audio-visual	Multisensory
In the computer generated world, I had a sense of being there	4.2 (1.2)	5.3 (1.1)**
Somehow I felt that the virtual world surrounded me	4.0 (1.3)	5.2 (1.2)**
I had a sense of acting in the virtual space, rather than operating something from outside.	3.7 (1.5)	4.6 (1.3)
I felt present in the virtual space	4.3 (1.2)	5.4 (1.1)**
I felt like I was just perceiving pictures (reversed)	4.6 (1.7)	5.3 (1.5)
I was not aware of my real environment.	4.1 (1.4)	3.9 (1.8)
I still paid attention to the real environment. (reversed)	5.1 (1.5)	5.1 (1.7)
I was completely captivated by the virtual world.	4.1 (1.3)	5.5 (1.4)**
The virtual world seemed more realistic than the real world.	1.9 (0.9)	2.6 (1.4)*
How aware were you of the real world surrounding while navigating in the virtual world?	4.8 (1.4)	5.3 (1.4)
How real did the virtual world seem to you?	4.1 (1.2)*	3.3 (1.4)
How much did your experience in the virtual environment seem consistent with your real world experience?	3.4 (1.3)	4.8 (1.2)**

Table 2. Mean IPQ ratings on a 7 point Likert scale [1-7] and standard deviations for the audio-visual and multisensory walkthrough. Wilcoxon signed rank tests were used to compare ratings between conditions. $^{*} = p < .05, ^{**} = p < .01$.

one without (hence, only audio-visual cues), in counterbalanced order. We designed the environment such that events would be interesting and could be clearly noticed also in the audio-visual condition. Both paths contained the same events and followed the same path, yet in the inverse direction (counterbalanced) to avoid learning effects. Table 1 provides an overview of the feedback elements, haptic stimuli and representative events in the scenario. To ensure comparability across participants and conditions, events were scripted and users were passively moved along the pre-defined path. Furthermore, users were instructed to look at a butterfly that flew ahead of them to maintain consistent viewpoints across trials and participants. Movement speed was piloted to minimize potential motion sickness and resembled a slow walking pace. To limit hearing the slight noises produced by the servos and linear actuators, we displayed pink noise over the noise-cancellation headphones, mixed in with the environmental sound. During piloting, we tuned this such that the noise was subtle and well integrated in the environmental sound. In interviews, users noted no negative effect of the pink noise.

After each walkthrough, participants took off the HMD, were interviewed about their experience of the different events, and filled out an online questionnaire. Here, participants rated the different types of events on a 0-100 scale in terms of convincingness (realism) and memorability. We used the standard 9-point Self-Assessment Manikin (SAM) scale to rate emotional response in terms of valence and arousal. SAM is a widely used affective rating system [6, 30]. SAM ranges from a frowning, unhappy figure to a smiling, happy figure when representing the valence dimension. For the arousal dimension, SAM ranges from a relaxed, sleepy figure to an excited, wide-eyed figure. High ratings represent high pleasure/arousal on each dimension. Furthermore, users rated their overall experience with respect to the 6 primary emotional responses (anger, disgust, happiness, fear, surprise, sadness [37]) on a 1-5 scale. Following, we asked participants to rate the overall believability and enjoyment of the walkthrough (0-100 scale). Next, we asked if adding FaceHaptic cues improved awareness of events in the scenario; if the directionality helped to associate cues to visual events; and if the cues had a positive effect on the visual experience of the scene. Finally, users answered the IPQ presence questionnaire on a 7-point Likert scale [54], followed by an interview for open comments.

Results

Wilcoxon pairwise comparisons were used to compare questionnaire ratings between the audio-visual (HMD and headphones) and multisensory (added FaceHaptics) experience. Results are summarized in Table 2 (presence) and Table 3 (mean ratings by event). Analysis of IPQ revealed that **presence** was significantly higher in most (6/12) categories for the multisensory condition, with only one exception were users were asked about how "real" the environment felt (see Table 2). Similarly, as indicated in Table 3 participants rated the multisensory condition where FaceHaptics cues were added as consistently and significantly more **convincing** and **memorable** for each of the events than the audiovisual condition without FaceHaptics (each $p < .01$). While mean convincingness ratings in the audio-visual condition ranged from 15.44 ($SD = 18.54$) in the "Walking along cold rock wall" to 31.13 ($SD = 29.64$) in the "Wind gusts" event, ratings in the multisensory walkthrough ranged from 39.88 ($SD = 33.51$, "Walking along cold rock wall") to 83.37 ($SD = 15.53$, "Water mist from waterfall"). Similarly, mean ratings of the memorability of events were rather low in the audio-visual condition, ranging from 13.75 ($SD = 13.63$, "Walking along cold rock wall") to 34.25 ($SD = 29.96$, "Plant brushing face") and significantly higher for multisensory events, ranging from 44.38 ($SD = 32.79$, "Walking along cold rock wall") to 85.63 ($SD = 32.79$, "Water mist from waterfall"). As such, overall users seemed to be impressed most by the waterfall event and least by walking along the cold rock event. Regarding haptic event types, this means that wetness scored well, while coldness was not rated highly, supposedly because it was not easily noticeable using the fan alone. Touch and wind (tactile) events roughly scored equally well on memorability and convincingness.

The overall **believability** was also rated significantly higher for the multisensory experience ($M = 78.88, SD = 4.38$) than the audio-visual condition ($M = 43.75, SD = 23.05$), $t(15) = -5.4, p > .001$. Accordingly, there was a similar patterns of higher **enjoyment** ratings when the VR walkthrough was accompanied with multisensory FaceHaptics cues

	Audio-visual				Multisensory			
Event	Memorability	Convincingness	Valence	Arousal	Memorability	Convincingness	Valence	Arousal
Plant brushing face	34.3 (30.0)	27.3 (20.3)	5.3 (1.3)	3.5 (2.1)	74.0 (16.3)**	61.6 (20.5)**	6.3 (2.0)	5.9 (2.4)**
Butterfly touching face	18.2 (18.0)	17.8 (17.7)	5.2 (1.2)	2.6 (1.4)	71.8 (31.9)**	64.9 (30.8)**	6.9 (2.1)*	5.9 (2.6)**
Wind gusts	19.2 (21.1)	31.1 (29.6)	4.9 (1.1)	2.8 (1.7)	77.9 (19.0)***	80.1 (19.4)**	7.4 (1.3)**	5.6 (2.3)**
Walking in warm sun	23. 3 (26.5)	23.3 (24.6)	5.0 (1.5)	2.5 (1.7)	76.6 (26.1)**	74.8 (29.2)**	7.4 (1.9)**	5.6 (2.8)**
Walking along cold rock wall	13.8 (13.6)	15.4 (18.5)	4.8 (1.0)	2.1(1.4)	44.4 (32.8)**	39.9 (33.5)**	5.9 (1.7)	3.9 (2.6)**
Water mist from the waterfall	31.9 (25.3)	29.4 (24.0)	5.9 (1.7)	3.6 (2.2)	85.6 (18.0)**	83.4 (15.5)**	7.4 (2.2)*	6.7 (2.5)**
Specific emotions	Happiness, 44%, 57.4 (29.4); Surprise, 31%, 44.6 (31.3)				Disgust, 31%, 35.2 (38.0); Happiness, 88%, 62.1 (26.8) Surprise. 81%, 56.9 (24.8)			

Table 3. Ratings and standard deviations by event for the audio-visual and multisensory condition: (Top) Memorability and convincingness on a scale from 0-100, SAM valence and arousal on a 9-point scale. (Bottom) Percentage of users who reported feeling a specific emotion and its intensity on a scale from 0-100. Ratings were compared between conditions using the Wilcoxon signed rank test. $^* = p < .05, ^{**} = p < .01, ^{***} = p < .001$.

$(M = 81.06, SD = 26.74)$ compared to the standard audio-visual condition $(M = 49.44, SD = 6.29)$, $Z = -3.0, p = .003$.

With regards to **emotional response**, SAM scale ratings for valence and arousal were consistently higher for all of the multisensory compared to the equivalent audio-visual events, see Table 3. These differences were significant except for valence ratings for the events "Plant brushing face" and "Walking along cold rock wall". Regarding the role of stimuli we could observe that in particular the integration of wind and the warm wind resulted in more positive feelings when experiencing the respective situations "wind gusts" and "walking in warm sun" compared to the audio-visual condition $(p < .01)$. While the soft touch of the butterfly event and the water spray in the waterfall event also elicited more positive feelings than audio-visual stimuli alone, the slightly higher valence ratings for the events with the integrated sliding touch and the cold wind did not reach significance. A closer look at the ratings reveals that while valance ratings are still reasonably high for the audio-visual condition $(M = 5.1, SD = 1.03)$, the level of arousal was relatively low $(M = 2.83, SD = 1.47)$. Specific emotions that participants reported were surprise and happiness in particular, in both conditions (see Table 3, bottom. In the audio-visual trials, 44% of the users reported feeling happiness and 31% surprise, while sadness or anger were not felt at all, fear by two and disgust only by one user. With multisensory cues almost all users experienced happiness (88%) or surprise (81%), one user also felt anger, one felt fear, and 5 users disgust (31%). In our questionnaire, we did not ask explicitly about the match between events and emotional responses. Previous work has shown this is often hard to judge [27] as emotions are often not directly bound to a specific event but occur over time [37]. Nonetheless, in the structured interview we asked if people felt that specific events has affected their emotional responses. On the one hand the waterfall event elicited in particular surprise which is reflected in user statements such as as "The water which suddenly landed on my face surprised me" or "I was surprised due to the water splash in my face", but on the other hand also "disgust from being sprayed with water for the first time ..." which was stated by another user. Disgust was also elicited due to touching events, "because plants, butterflies were touching my face", although "I do not want to be touched in my face". At the end, though, only one participant noted negatively on direct face-touch stimuli and explained that this was directly related to the actual visual stimuli itself (fear of insect). Other users were also surprised by touching events, going through plants was described as "a bit surprising", other users said "I have not seen that touching event coming" or "brushing plants was surprising". The feeling of happiness was often explained by users as a result from the overall experience, which is reflected in statements such as "Who is not happy to walk through the jungle when the sun is shining?" or "I was happy with the environment" and "no negative associations in any way". Sometimes users were more specifically referring to certain parts of the multisensory walkthrough. Users referred to feeling of warmth in particular, stating "I felt happiness due to the sunny and warm part of the tour" or "Warmth was very pleasant".

Finally, in accordance with the higher ratings for multisensory events, users showed strong agreement (scale ranged from 1 to 11) that "haptic cues had a positive effect on the visual experience and realism of the scene" $(M = 9.75, SD = 1.61)$. Furthermore, it was stated that "the directionality of haptic cues helped to associate haptic cues to visual events in the environment" $(M = 8.63, SD = 1.54)$.

Discussion

Based on previous work, the finding that adding multisensory stimuli can improve presence and emotional responses was certainly not unexpected. While the improvements in **presence** were often significant, there is still room for improvement, e.g., by creating even more visually realistic environments and more compelling and realistic matching FaceHaptics cues. Even more so, it will be necessary to study the effect of multisensory cues on presence by comparing situations that also involve direct user interaction. Currently, users were moved along the path and could not directly interact with objects to ensure comparability across conditions and participants and avoid confounds. Previous work has shown that direct interaction could further improve presence [49], so we expect a noticeable increase. Interestingly, IPQ ratings also showed that users reported a higher level of realism ("how real did the virtual world seem to you") for the audio-visual compared to the multisensory condition, yet a higher level of consistency with the real world for the multisensory condition. We currently do not have a direct explanation for this besides that users may have had predominantly visual aspects in mind when answering the first question, while focusing more on the multisensory aspects of the real world in the second.

What also surprised us was the level of **convincingness and memorability** of events especially when FaceHaptics was added, and the extent the stimuli affected emotional responses. As we stated before, we implemented the audiovisual environment such that events were memorable and audio-visually pleasing even without the added haptic cues. It has to be said, though, that one event was more difficult to judge in audio-visual conditions, namely the walking along a "cold wall". There was no audio-visual indication of coldness, in contrast to, e.g. sunlight, which could be easily noticed because of the shadows. In designing this study we had the challenge of creating events that are both noticeable and memorable in the audio-visual condition alone, yet can be accompanied by an added haptic event to the face while maintaining ecological validity. We show that representing those events beyond their audio-visual nature can have a large impact on user experience. One event, though, did not work well - the walking along the "cold" wall was not even reliably noticed in the multisensory condition. Though previous work [38] indicates that coldness can be achieved through wind flow (the "ventilator chill effect"), it did not have the expected effect. As such, other or stronger types of cooling may be necessary. While we experimented with Peltier-elements for cold/warm sensations, they did not work well enough during pilot testing, which is why we choose our alternative approach. Future work could consider alternative and more effective types of cooling.

The improvement in **emotional response** (valence and arousal) is rather striking, and seems to be stronger than the effect of the multisensory cues on presence. It was somewhat surprising as this effect has not been clearly noticed in previous work on multisensory VR systems [14, 27]. Our results may point towards a higher level of engagement. User engagement can be defined as the quality of user experience that may depend on the aesthetic appeal, usability and novelty of the system, the ability of a user to attend to and become involved in the experience. Engagement depends on the depth of participation the user is able to achieve with respect to each experiential attribute [42]. Thereby, user engagement can be associated with emotional, cognitive and behavioral processes [29]. As such, measurement of these processes, e.g., through biosensor analysis or attention tracking using an eye tracker, would be beneficial as a next step. The novelty effect, as part of engagement, may also mean that after longer periods of exposure, users will adjust to the haptic feedback, lowering the level of engagement. This will require user tests over a longer period of time. In line with was reported in [27], what turned out to be a difficult again is to pinpoint which type of actuation can cause which type of emotional response. Our results indicate that a generalized answer will not be possible. Nevertheless, while we noted an overall stronger arousal for multi-sensory events, the higher ratings of valence in the multisensory condition were not equally strong for all events.

Another noteworthy outcome is to what extent multisensory cues were thought to influence the **visual experience and realism**. While the rating may be related to or interpreted as the overall fidelity of the simulation [36], cross-modal effects may also come into play, where one sensory channel may affect perception in another perceptual channel [55]. Initial work has shown that sound can affect visual realism [20], also particularly in immersive games [50]. It has also been shown that vision frequently dominates the integrated visual-haptic percept, for example when judging size or shape, but in some cases the percept is clearly affected by haptics [13]. While in immersive environments, the interaction between haptic and visual perception has gained some interest (e.g,[32]), the effect of haptics on visual realism in immersive environments is still not well understood and warrants further study. Interestingly too, the answer to the realism question does not necessary coincide with the IPQ question about how "real" the world felt, for which currently we have no explanation.

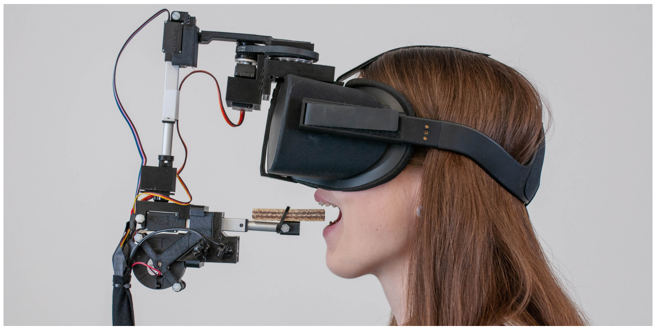

Figure 5. Adding biting functionality to FaceHaptics - showing the potential of extensibility, but also the limitations regarding reloading.

Finally, **directionality** of haptic feedback can potentially have an effect on associating the cues with visual events. Subjective feedback showed that providing multi-directional feedback can be important for scenarios where feedback needs to be associated to specific objects to adjust interaction, for example to improve reaction time. This topic warrants further research.

TECHNICAL CONSIDERATIONS AND LIMITATIONS

Through our iterative design of the robot arm, we improved its construction to be more robust and resistant against head rotations. However, a closer look reveals that – although the arm can be well used – there are some limitations. Here, we list those limitations and considerations, and compare our system to other systems that are body-worn (e..g., [52], table-mounted (e.g., [3]) or attached to a drone (e.g., [24]). The comparison is summarized in Table 4 - here, we discuss the main issues. One of the first issues that should be noted is the weight of the device on the head. While added actuators can potentially improve UX, the additional weight can bother the user over time. As such, trade-offs should be regarded. Weight would likely be an issue for longer-term, non-seated usage. Our participants did mention weight in debriefings, but none saw it as a critical issue, likely because studies had breaks an not overly long, the setup was reasonably well balanced, robot arm movements were deliberately slow, and users were seated instead of walking. Here, solutions that mount robot arms on the body, or externally could have an advantage. Inertia and vibrations, related to weight, also become a problem once the arm moves faster. While this could be improved by reducing robot arm weight, actuators attached to other body locations or externally may have an advantage. Generally, the operation speed (and response time, limited by faster speeds causing vibrations) of our current system suffices for many events, but should be improved. The types, strength and accuracy of stimuli is reasonably good for our system - while

	head	body	surface	drone
Weight issues (on head/body)	-	+/-	+	+
Inertia issues (on head/body)	+/-	+/-	+	+
Vibration issues (on head/body)	-	+/-	+	+
Directionality	+/-	+/-	+/-	-
Operation speed	+/-	+/-	+	-
Accuracy	+/-	+	+	-
Safety	+	+/-	+/-	-
Exchange actuator (runtime)	+/-	+	+	+/-
General extensibility	+	+	+	-
Reload actuator (runtime)	+/-	+/-	+	+/-
General cue intensity/force	+/-	+	+	-
Ergonomics	+/-	-	+	+
Suitability for walking	+	+/-	-	+

Table 4. A comparison of issues with different systems (rows) that could (theoretically) provide feedback to the user's head, including head and body-worn solutions, robot arms mounted on tables or other ground surfaces, and actuators mounted on drones (columns). "+" and "-" indicate advantages vs. disadvantages of the different feedback systems.

a body-worn or grounded robot arm could be more precise and could also hold other types of actuators, they come with other limitations, including safety, ergonomics and limitations while walking around. This is especially a knock-out argument against surface-mounted robot arms, which can hardly be used with users moving through a larger space. While drones offer an interesting solution for walking users, they have a limited range (incl. type, force, reloading) of actuation - for example, HapticDrone [1] only provide 1D forces 1.53 N upwards and 2.97 N downwards. Finally, while our arm can be quite easily extended with other stimuli, exchanging and reloading stimuli during runtime is somewhat challenging - here, body-worn and surface-mounted arms are advantageous.

CONCLUSION AND FUTURE WORK

In this paper, we presented a novel robot arm actuation system for providing spatialized haptic cues to the human face. In two user studies, we explored how well users can perceive directional cues, and how different haptic cues are perceived in relation to presence and emotional response. Results indicate that users can judge well the directions of cues external to the face (wind), especially when actuation compensates for head movement. This aspect speaks strongly for our hardware design, in comparison to other multisensory HMD solutions with fixed or a limited number of actuators or other haptic feedback elements: also in study 2, the direction of cues was reported to positively affect the tie to a visual cue.

While we explored light touch, texture and temperature as actuation channels, FaceHaptics can be easily extended towards other types of sensory stimulation. Our system approach has both the advantage but also the limitation that it can reach parts of the face not covered by the HMD, in contrast to systems that embed actuators inside the HMD. However, our system comes with a higher level of flexibility and fewer technical limitations caused by the space available inside the HMD to mount additional devices. Furthermore, a combination of in-HMD and FaceHaptics can easily be envisioned - e.g., to generate apparent motion of a cue over the face, by combining external and in-HMD cues.

With respect to perception, future work could investigate how UX is affected by spatial, directional or temporal mismatch, or non-directional stimulation (like the just-released FeelReal system). Furthermore, future work could address directional discrimination for other modalities besides wind. We are currently also considering other types of perceptual events, like slight pain or other annoying events. It may prove an interesting feedback channel in games and has hardly been explored in user interfaces (e.g., [25]). In a next step we will also test the system triggering other emotional responses. As our environment mainly focused on positive emotions, using the FaceHaptics system for fear-inducing or other adverse situations would be very interesting, e.g., phobia treatment or immersive horror games. Conversely, combining subtle soft feedback of warmth, wind, or touch with suitable narrative structure and audio-visual stimuli could also be used to enhance positive profound experiences such as awe, compassion, or love [11, 12, 46]. Finally, among the other considerations is also inclusion of smell. While not being a haptic stimulus by itself, it could be an interesting channel to support emotional responses, or augment food-related stimuli, and can support haptic events such as touch, drinking, and eating (biting, licking, touching with tongue etc.). An olfactory device could be connected and provide olfactory cues directly to the nose, thus reducing the amount of smell that needs to be provided, and making it easy and faster to clear the air from the smells as needed. Such an interface could also be combined with a food or drink dispenser interface. Initial experimentation with biting pieces of food were successful (see Figure 5), underlining the easy extensibility of the system, but also the need for a reloading mechanism or dispensing system (e.g., candy dispenser).

Extension of FaceHaptics through its modular construction can also lead to exciting new research opportunities and possibilities. We tried numerous light materials, from soft woollen balls to semi-sharp plastic parts. Most of these materials offer a unique experience, while some others - e.g., our rubber tip - can be used for different simulation types. Yet, as noted earlier, further system optimization is necessary. One possibility to flexibly exchange stimuli types is to make use of a rotating head that can mount multiple types of feedback elements, rotating the currently needed element towards the head, similar to the haptic revolver [62] and SnakeCharmer [3] interfaces. Another possibility would be to use exchangeable electromagnetic blocks to exchange the head of the robot arm, similar to Topobo [47], attaching blocks to the HMD. Furthermore, we currently experiment with adding dampening material to limit vibrations when rotating the arm faster. We will also investigate the usage of relocated actuators with wires to limit off-center weight/inertia, or suspending the system from the ceiling similar to DisneyQuest Aladdin, for stationary users. Finally, although the FaceHaptics system might not be feasible for all VR applications, it provides a flexible research prototype that allows to investigate a large variety of stimuli beyond audio-visuals, thus providing guidance for future VR hardware and experience designs.

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