Sensory VR: Smelling, Touching, and Eating Virtual Reality

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ABSTRACT
We present two proof of concept sensory experiences designed for virtual reality (VR). Our experiences bring together smell, sound, taste, touch, and sight, focusing on low-cost, non-digital materials and on passive interactions. We also contribute a design rationale and a review of sensory interactions, particularly those designed for VR. We argue that current sensory experiences designed for VR often lack a broader consideration of the senses, especially in their neglect of the non-digital. We discuss some implications of non-digital design for sensory VR, suggesting that there may be opportunities to expand conceptions of what sensory design in VR can be.

Author Keywords
Tangible and embodied interaction; virtual reality; interactive narratives; diegetic design; sensory design; non-digital.

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• **Human-centered computing~Virtual reality** • *Human-centered computing~Interaction design theory, concepts and paradigms* • *Software and its engineering~Interactive games.*

INTRODUCTION
As the visual and aural fidelity of consumer virtual reality (VR) continues to improve, recent industry and academic work has examined digitally-mediated touch, taste, and smell in VR. Citing the effects of immersion [32], presence [60, 76] or engagement [8], physical experiences are often said to lend a sense of realism in VR (cf. Denisova et al. [14], who suggest that there are overlaps and gaps in the ways we assess these effects). However, sensory experiences within digitally-mediated virtual environments can lack broader considerations of bodies and environments. Active haptic interactions with physical objects, for example, may neglect the passive haptics of that same object, let alone its other sensory characteristics, such as its taste and smell. While we do not expect all virtual environments to be touched, smelled, or tasted, we argue that design for the virtual can include a consideration of the rich affordances of the non-digital world.

In this paper, we contribute two proof of concept sensory experiences designed for VR that include smell, sound, taste, touch, and sight. We draw on the notions of diegetic [21, 22] design and intersensory [39] design, asking how a contextually situated interplay of sensory qualities might contribute to the overall narrative experience. Our two VR environments each explore the sensory qualities of a moment: a moment at the beach, including heat, sunscreen, sand underfoot, and a fruit drink; and a moment in a forest inspired by the storyworld of Little Red Riding Hood, with the looming presence of a virtual wolf, real wind, grass underfoot, and freshly baked bread in a basket nearby.

We argue that low-cost, non-digital, diegetic interactions (e.g., Figure 1) can help to reconceptualize sensory VR design practices, offering a contrast to technologically-driven VR experiences. We also contribute a review of several current trends in digitally-mediated design for the senses, a design rationale, and lessons learned from our sensory workshops. We conclude with a discussion of some of the implications of our work, suggesting that sensory VR could allow players to co-construct experiences that take into account the multiple variations of their sensory needs and preferences, and the sensory variations of their real-world environments.

Figure 1. Engaging with the non-digital for sensory VR.

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RELATED WORKS

While consumer VR is primarily a visual and aural medium, it also includes the tracked, embodied actions of players' head and hand movements. These sensory, embodied modalities—the visual, the aural, and some physical movement—form the basis of consumer VR. In this section, we review some work that attempts to fill in VR's missing modalities. In later sections, we reflect on how these trends appear to conceptualize the body, and what this may mean for sensory VR design.

Smell & Taste

For Ghinea et al., smell is a modality that is yet to be "conquered" by multimedia [18]. As the authors note, designers face the challenge of a modality that can be perceived in different ways based on age, gender, culture, and lived experience. In the attempts to address the challenge of smell as controlled "data" that will "drift, diffuse, and linger," the work reviewed by the authors implicitly suggests neutral, smell-free environments modified by the planned "emission of scents." Under this conceptualization, the environment, and the people in it, are part of the design problem. Murray et al. also note the unpredictability of human olfactory perception in their review of "olfaction-enhanced multimedia" [42], but argue that the inclusion of smell and taste will "make multimedia applications more reflective of reality." As "olfactory displays" (e.g., pumps, fans, and cannons that blow or shoot smells) have a relatively tenuous connection to reality, the goal may be, more accurately, a "sense of reality" [18].

Narumi's review of taste in VR echoes this conception with its focus on the "pseudo-gustatory" [46]. In MetaCookie+, for example, the headset overlays a virtual cookie onto a plain cookie and then pumps a scent into the user's nose through a set of tubes, resulting in a reported change in taste [47]. The fallibility of human perception is similarly exploited in projects such as the "tongue interface" [54]. With a design inspired by other "objects that people use to interact with their mouths," the tongue interface uses two electrodes, one under the tongue and the other on top, to produce sour, bitter, sweet, and salty sensations. Just as smell interfaces appear to exclude organic materials, taste interfaces appear to exclude food, although some examples of food in VR do exist. You Better Eat to Survive is a two-player game in which one player in VR must occasionally eat or the screen fades to black. A second non-VR player acts as the VR player's arms, feeding them when necessary. A microphone picks up the sound of chewing, restoring the VR player to life [3] (cf. the eat, chew, smile interaction sequence of the non-VR Food Practice Shooter [33]).

Touch

Generally, we can categorize touch in VR as employing either passive or active haptics. In Metaspace II [63] and Real Virtuality [9], the passive haptics are the physical characteristics of an object, like its weight or texture, are said to lend realism to a virtual environment. In Metaspace II, the user carries a large box that represents a shining virtual cube; in Real Virtuality the player carries a rod that represents a virtual torch. Active haptics, like the vibrotactile feedback of a mobile phone or a VR controller, are more common. Systems can combine passive and active haptics, as in Tangible VR, using a stuffed animal for the passive haptics of its fur and weight, and the active haptics of a "heartbeat" and head movement triggered by the interaction [22]. Zenner and Krüger [78] suggest the additional category of dynamic passive haptics, in which active haptics change the passive haptic properties of an object. This is demonstrated by a handheld rod that shifts its weight depending on the corresponding virtual object.

Touching virtual objects can employ haptic controllers and wearables, as with the handheld "haptic shape controller" of TextureTouch and NormalTouch [7]. Holding the controller, the user puts a finger on a 6 DOF pad that moves to simulate the contours of a virtual object. Similarly, Schorr and Okamura [58] present two fingertip-mounted devices that press on the pads of the user's fingers to simulate a change in the virtual object's weight and texture. The authors suggest that such work could enable users to interact more "directly" with virtual environments, with their "bare hands" rather than a "physical tool" (cf. the "real contact" of VR Touch [19]).

Since handheld, worn, and mounted devices constrain the user's hands, tangible proxies offer an alternative approach. Snake Charmer [2] uses a robot arm with an attached tangible object to present physical proxies in place of virtual counterparts. The authors demonstrate examples of tangible objects outfitted with textures, buttons, Peltier pads, or fans (cf. the "realistic touch sensations" of Axon VR [4]). The authors show that these tangible "endpoints" of the robot arm can be exchanged and used as passive, active, or input-based interactions. Leveraging the affordances of both the virtual and physical is also a design goal of Sparse Haptic Proxy [13], in which a wall-like prop is used as a surface for virtual content as well as for its passive haptic qualities.

Flying objects can also act as proxies. Knierim et al. [35] present quadcopters as proxies for virtual objects that hit the user: first virtual bumblebees and arrows, then virtual bricks, wood, and skulls. While there is no mention that the user may want to swat the quadcopter away, a cage around the quadcopter helps to shield the user from the propellers. The potential for physical pain in virtual worlds is also explored with Impacto, a wearable device that simulates the impact of a hit using electrical muscle stimulation (EMS) to trigger involuntary muscle contractions [37].

Movement

Many touch-based interactions imply additional movement on the part of the user: reaching, grasping, pointing, even kicking. The same can be said of the physical movement implied by the tracked controllers of consumer VR. The wearable puppet of VRSurus [16] is an extension of this kind of movement, with the user's arm controlling an in-game character. As with passive haptics, physical actions are often said to lend a degree of embodied realism. Shadow Shooter [77], aims to align embodied actions with virtual feedback using a real archery bow modified with sensors and a mobile projector to project virtual content onto a wall (cf. the movement implied with the physical proxies of VR Zone [74], or VIRZOOM [69]).

Consumer VR [e.g., 29] can track the user's position to allow walking and kneeling, but not climbing. Solutions for climbing appear to range from the passive haptics of small ridges on the floor to simulate stepping on virtual stairs [43] to boots connected to motorized stilts to simulate climbing steps in VR [56]. In the latter case, some users did report that the heavy prototypes made regular walking feel "less natural" (cf. the "natural movement" of Virtuix [68]). These interactions contrast non-VR foot-based interactions, which appear to conceptualize the feet and legs as input devices [67]. Kickables [57], for example, presents tangible interactions for the feet using common interaction models like sliders and buttons, striving for precision and control.

Movement in VR must include a consideration for the available physical space (compare, e.g., the tracked walking in Anvio VR [1] with the pod-like chair of VRGo [72]), while also addressing medium-specific design challenges: with 360-degree movement, users can potentially look or walk away from the designed experience. In response, the SwiVRChair directs the user's gaze by automatically rotating or halting rotation to point the user in the direction of story content [20], with scenarios that include spinning the user, or having monsters sneak up and surprise the user with a virtual punch to the face. A larger-scale example of working within constraints is TurkDeck, in which a group of people move a set of wall panels around to simulate physical rooms and corridors for a VR user [12]. The system consists of 65 physical props in all. With the "workers" moving the pieces in tandem with player movement, the physical space can appear larger than it is. This illusion echoes the contributions of redirected walking in VR [38, 64] with the added opportunity to touch the virtual world.

Ambient effects

Ambient effects, including simulated wind and heat, have been explored for added "realism," as demonstrated by the felt heat and wind of a virtual desert, volcano, living room, chimney, and a train [31]. The authors use eight axial fans and three infrared lamps that can reach temperatures up to 100 degrees Celsius, with sensors that trigger a shut off if the temperature rises higher than 45 degrees Celsius. Similarly, Ambiotherm seeks to simulate "real-world conditions" with two fans mounted on a Gear VR and two Peltier elements secured to the back of the user's neck with a strap around the throat [53]. The authors claim that this placement of the Peltier elements was chosen for its "high levels of comfort" and for the "perception of overall temperature change (similar to the effects of induced hypothermia)." The VaiR prototype uses a head mounted set of 10 nozzles that can blow short blasts of air or steady streams up to 25km/h while rotating around the user's head [55]. As the authors note, however, the head is not the only part of the body to experience wind (cf. work that focuses only on the "frontal region of the head" to examine the perception of wind direction [45], or ViveNChill [70] for another motivation: to cool a sweaty player down).

Mixed Reality VR

In their attempts to draw on physical as well as virtual affordances, much of the work already described could be classified as mixed reality. There are some advantages to this approach. As suggested by the makers of Oscillate, a physical swing within a virtual environment, "physical reality is replete with interesting kinaesthetic experiences" [65]. Like passive haptics, mixed reality interfaces can include the sensory, embodied qualities of the physical environment. CarVR leverages the kinaesthetic motion of a passenger in a car with virtual content mapped to a predefined route [25] (cf. VR roller coasters [36, 59]). Meehan et al. [40] use a wooden plank above a virtual pit, grounding the experience with a low-cost, tangible object (cf. the physical props of Project iCan [52], or the props and ambient effects designed for The Void [71]). Annexing Reality predicts possible overlays of virtual objects onto the nearest physical match in the player's view, like a bottle representing a light-saber [24]. IRIDiuM+ includes the active and passive "walkable haptics" of vibrating carpet-like materials and the "air haptics" of actuated fans [34]. Work that considers both the user and the environment begins to resemble interactive theatre (e.g., Sleep No More [51]), in which a user interacts within the bounds of a constructed space. Flatland [75] is a recent example, using a tangible object to guide the user through darkened spaces with particular smells and tactile qualities.

DESIGN RATIONALE

Within the work we reviewed, we found conceptual gaps that reflect implicit and explicit decisions made prior to design. We noticed that, first, much of the research simulates sensory experiences using digitally-mediated solutions. Second, the designer often creates structured experiences for a neutral body in a neutral environment. And third, a focus on one or two sensory modalities often ignores the rest of the body or the environment. A naive reading could suggest a common set of design assumptions: i.e., that (a) a digital solution (with its implicit promise of control and reproducibility) is better than a non-digital solution; (b) we need not consider the multiple variations of a player's sensory needs and preferences, or the variations of their environment; and further, (c) design that focuses on discrete sensory experiences will not be affected by our environment or our other senses. As a design prompt, we propose to challenge these apparent assumptions.

We draw on the field of tangible, embedded, and embodied interaction (TEI), for the reminder to better assess the physical medium of the digital experience. In her critique of Paul Dourish's conception of embodied interaction, Hornecker argues that "the human body is strangely missing, as well as the materiality of the world we live in." Hornecker broadens the scope of "tangible" interaction, attempting to include embodied interactions within shared physical spaces [27]. The notable absence of the digital in design tools like Ideating in Skills [61], or the focus on the physical form of a "hybrid object" [50] is an attempt to draw attention to the situated, embodied practices with tangible objects as well as the interplay between digital and non-digital. In their theoretical framework, van Dijk and Hummels [15] argue for design that "radically rejects" the Cartesian frame, which undergirds "the bulk of interactive technology." They aim to reconceptualize "embodied" design in TEI as something that requires a consideration of the physical and social interplay between people, places (what they refer to as the "lifeworld"), and things (e.g., artifacts), with an emphasis on open-ended design that can respond to changing contexts.

Our designed experiences, therefore, attempt to challenge the taken-for-granted theoretical stance suggested by related VR work. We draw on tangible and embodied design in order to include a consideration of the sensory experience as shaped by the digital and the non-digital. To consider the people, places, and things that create the interplay between the digital and non-digital, we also draw on notions of "intersensory" design and "diegetic" design. McBride and Nolan [39] emphasize that any individual sense must be understood as part of an "intersensory" whole, not just within our bodies but also as "a relational and contingent part of the total social, cultural and environmental ecology" (190). Diegetic design [21, 22] conceptualizes all aspects of the designed, narrative experience as belonging within its story world. Bringing these perspectives together in our design process, we asked: "What are the intersensory characteristics of these narrative environments?"

In the following sections, we describe the interaction scenarios and implementation of our two proofs of concept in more detail. We sought to examine non-digital sensory interactions within a digitally-mediated environment in order to better understand how we might conceptualize sensory VR. For this preliminary work, we chose to design around the sensory qualities of a single narrative moment to narrow and constrain the sensory interactions in each proof of concept.

INTERACTION SCENARIOS

Our two proofs of concept explore sensory experiences for VR focusing on a single moment. The first is a moment at the beach and the second is a moment in Little Red Riding Hood. Both scenarios suggest a number of sensory characteristics that are not typically available in VR. There are smells and tastes, things to feel and touch, ambient effects, and embodied actions. In addition to the constraint of the narrative moment, the experience is constrained by the technology: in both experiences, the player is seated and cannot move within the virtual environment, and because of the limitations of the Oculus DK2 and the Gear VR, they do not see a representation of their body or the objects.

Despite the similarity of interactions in our environments, both scenarios are also open-ended, i.e., we conceptualize experiences that players co-create: modifying, replacing, or using the sensory affordances of their environments. For example, in the beach experience, the sand replaces the feeling of tiles underfoot, while the forest environment uses the wind and grass of a nearby park. Finally, both scenarios conceptualize some planning on the part of the player. We present possible choices here; note that these choices are provocative rather than prescriptive. As we discuss later, a narrative moment can contain many sensory qualities, which can be shaped by players' own lived experiences.

The Beach

The goal of this scenario is to recreate some of the sensory qualities of being at the beach. The player prepares sunscreen, a drink of choice, a lawn chair, a space heater, and a plastic storage container of sand to accompany their VR experience. The player adjusts the temperature and the placement of the space heater to simulate the warmth of the wind, and sits in a lawn chair. The player puts on sunscreen. The smell is reminiscent of a hot day at the beach. In advance, the player has warmed some of the sand separately and spread it as the top layer of sand in the container. The player puts their feet in the sand, puts on the headset and the headphones. They see an empty beach and hear the waves and the seagulls (Figure 2). To match their virtual drink, the player has a drink in the cup holder of their chair.

Figure 2. The beach environment, featuring sand underfoot.

Little Red Riding Hood

This interaction scenario draws inspiration from Little Red Riding Hood, recreating the moment before Red's encounter with the Wolf in the forest. Red stops to sit a while to rest and pick flowers. The player prepares the basket of food that is meant for Grandma, and walks to an outdoor area that has some of the sensory qualities of the story. Being in the city, this version uses a nearby park. The player takes off their shoes and puts their bare feet in the grass. It is summer and it is warm. There is a gentle breeze and the smell of the fresh air. The player puts on a mobile headset and headphones, transforming the sights and sounds of the park into the sights and sounds of the fairy tale forest (Figure 3). The player dawdles as Red does and eats the bread, even though it is meant for Grandma. Virtual fog rolls in and the sky darkens. The mood changes: there is the sound of breathing in the woods nearby and eyes looking out at Red. The wolf is nearby.

Figure 3. The forest environment, with wind, grass, and the smell of the outdoors "simulated" by a city park.

IMPLEMENTATION

We designed our VR experiences to work alongside technology, using non-digital solutions for sensory interactions. We used an Oculus DK2 for the beach environment and a Gear VR for the forest environment. Out of the box, neither headset supports hand tracking or object tracking. In keeping with the focus on low-cost materials, we did not add any peripheral tracking to match the placement of the real and virtual objects, though each of the physical objects did have a virtual counterpart. Players wore headphones for the soundscapes, which we created to emphasize the mood and atmosphere of the environments. We used Unity3D to create the environments and to place the spatialized sound sources. For the beach environment, we sampled and looped sounds of waves, seagulls, and wind; for the forest environment, we sampled and looped sounds of a forest and the creaking sounds of wind through trees. The fog, a darkening sky, and the sound of the wolf's breathing nearby signal a mood change.

Sensory objects of the forest environment included a basket with fresh bread and apples, and in one iteration, various tangible objects drawn from the story, like Red's hooded cloak, pine needles, and dirt from outside. In this environment, the breeze of the wind, the temperature, and the feeling of grass on bare feet are all from reality. In the city, these sensory characteristics are even more readily available than those we used for the beach environment. These are examples of the simplest non-digital solutions: the wind simulates the wind. Sensory objects for the beach environment included a lawn chair, a space heater, fruit juice, sunscreen, and a plastic storage container filled with sand. Each of these allows for embodied, sensory actions: the act of putting on sunscreen, with its characteristic scent; the act of settling into the deep seat of a lawn chair; the warm "wind" of a space heater; the taste of a fruit juice; and the feeling of sand between toes (Figure 4). Together, these objects create a relatively complex VR environment that engages several senses at once. Trying the environment ourselves for the first time, we noticed one thing did not feel "right." The sand was too cold, so we warmed a few cups in the microwave. Now the top layer was warm, as if exposed to the sun, with cool layers below.

Figure 4. A tropical drink to match the drink in VR, and the smell and embodied action of putting on sunscreen.

SENSORY DESIGN WORKSHOPS & EVALUATION

We began our design process by brainstorming the sensory details of particular moments and environments in our own lives. We used the concept of diegetic design to think about how each sensory detail might contribute to an overall narrative whole, and the concept of intersensory design to think about how each sensory detail might work with or against another. To examine the varied and interdependent contexts of sensory interactions, we organized several informal design workshops, often including members of our lab. Workshops with our lab included as many as 25 people. We make no claims of generalizability as to our process or the feedback we received; instead, we discuss this preliminary design process in order to document how it challenged our own design assumptions and to better understand how we might conceptualize sensory VR. In our first set of workshops, we set aside VR to focus on the non-digital. In our second set of workshops, we focused on the ways that the non-digital could contribute to VR design.

Workshops without VR

Inspired by guidelines outlined in McBride and Nolan's work [39], our goal in our first set of workshops was to examine our own sensory practices, expectations, and beliefs. In one workshop, we reflected on the tangible, sensory qualities of oranges, smelling, peeling and tasting the fruit. We discussed the smell of the rind on our fingers, the stickiness of the juice. When we repeated this exercise with members of our lab, conversations turned to a variety of culturally situated food practices that were beyond those that we had discussed—a reminder of individual preferences and experiences. The reminder that a single organic object has a number of sensory characteristics, though obvious in retrospect, was necessary. It was a reminder that any single distilled smell, like that of an essential oil, is also a removal of several other sensory, embodied characteristics, like the act of peeling an orange.

We continued these conversations in the following workshops, discussing and smelling several essential oils. We hoped to critically examine our own assumptions about these smells: where do they come from, what might these smells communicate about a narrative environment, and what are the other sensory qualities of this smell in its original context? We did the same with tangible objects in another workshop. We brought in and discussed the physical attributes of several objects, asking what they might communicate. These ranged from a dried seahorse found on a beach to a packaged latex condom. Conceptualizing individual objects as diegetic was a design prompt: what do these objects tell us about their environments or their story worlds? Engaging with the non-digital in these workshops became a valuable resource for design, offering low-cost sensory explorations. When we prepared to include VR, we found that the same questions applied: what are the sensory characteristics of our VR environments and what might we gain or lose by introducing a particular modality?

Workshops with VR & informal user feedback

When we began prototyping our proofs of concept, we organized additional workshops with members of our lab to elicit informal feedback. For the first iteration of the forest environment, we presented all the modalities separately: a red cloak; apples; dirt, grass, and pine needles; a soundscape; and a VR forest. We discussed the sensory qualities of each, asking for feedback on the modalities and the narrative mood. Some guessed that it was based on Little Red Riding Hood; for those who did not, we noted how reactions varied. Some were drawn to the sounds, some were drawn to the smell of the dirt and pine needles. We realized that like much of the work reviewed above, we were still choosing the sensory modalities for the player, asking them to ignore one thing while paying attention to another, with the implicit promise of immersion.

In industry rhetoric about "immersion" (e.g., Holovis's "immersive" and "transformative journeys" [26] or VRCade's "immersive gaming experiences" [73]), it is the system that immerses the player. The player's suspension of disbelief is assured by the power and illusion of the system. Disconnected and embodied aspects of the experience, like the awkwardness of donning a heavy headset, must be ignored. For Murray [41], this could be an opportunity to use the headset as a "threshold object"; i.e., using it as a stand-in for a physical object worn by the player-character, like an astronaut's helmet. But what about environments in which a headset is not diegetic, like a beach or a forest? A large VR sunhat, or Red's hood could help make the headset a threshold object, but the weight and heat of the headset would still have to be ignored by the player, which is also to say that the weight and heat are not diegetic.

These reflections led us to reconceptualize "immersion" as player-driven rather than system-driven. If the player chooses the sensory qualities that they want to experience, the interaction can begin before the player puts on the headset. This can help to break down other taken-for-granted assumptions about the designed experience. Since we do not know the sensory qualities of the player's home, the players can look to include particular sensory aspects of their own environments. This also suggests that the experience does not have to happen in one place, and does not have to happen exclusively indoors. The player could become an active participant in their own immersion, knowingly co-constructing their virtual reality experience. As this also requires players to make choices that impact the story, designers could help create more player-driven experiences by offering suggestions for sensory modalities or by helping to scaffold the experience.

Similarly, when showing the beach environment to our lab colleagues in another workshop, we found that our efforts in controlling the experience and acting as helpers were largely unnecessary. After putting on sunscreen, the headphones, and the headset, each volunteer looked around briefly, sat back in the chair and then curled their toes in the sand. Like the helpers in TurkDeck [12] and You Better Eat to Survive [3], we had focused on the player's experience rather than on that of the helpers. (The helpers' experience is, however, a consideration in work that provides the "human actuators" with goals and feedback of their own [10, 11], suggesting that their role(s) could also be made diegetic.) While there are certainly occasions for heavily structured and monitored experiences, in this sensory moment, the sand was enough. Seeing a virtual drink on a virtual table, one player said, "All I need now is that drink over there." We promptly handed him a fruit punch.

DISCUSSION

VR presents an opportunity for TEI because virtual reality is never merely a visual/aural experience. The embodied negotiation of the potential mismatch between what we see and what we feel is, in many ways, a question for the TEI community. We have made a point to include industry work in an effort to show trends and similarities between industry and academia. In both, we find "sensory" attachments for headsets, vibrating wearables that claim to increase "immersion," and finger-mounted haptic devices for "realistic" touch. As we have noted in our design rationale, these parallels suggest several design assumptions that, in turn, suggest gaps. In this section, we return to these apparent assumptions: (a) digital solutions are superior to non-digital solutions; (b) we should design for a neutral body in a neutral environment; and (c) we should design for discrete sensory experiences. Challenging these assumptions, we find opportunities to reconsider the non-digital as a design resource, leading to a reconceptualization of players, their environments, and their roles within sensory VR. These considerations can be a fruitful avenue as the TEI community continues to contribute an examination of the whole body within digitally-mediated environments, raising important questions: how much of our bodies and our physical environments do we include and how much do we exclude? How do we conceptualize the body in VR design?

Limitations

As our work was tested in informal settings, we make no claims of generalizability or reproducibility. We suggest the value of our contribution is primarily in its "criticality" [5] in the sense that it questions current design trends in VR and requires us to confront our own taken-for-granted assumptions. In the same vein, the overall goal in our exploratory workshops, both with core members of the design team and with members of our lab, was to better understand how we might conceptualize sensory VR. We do not suggest that it will be possible or advisable to recreate what we have created, nor do we suggest that every player or every designer will have the same experiences that we document. Such recommendations are beyond the scope of this work and beyond our design intentions. For example, while we suggest that "co-constructed" experiences may offer opportunities for VR design, these are, at present, conceptual rather than practicable suggestions as we did not engage in participatory design practices. Nevertheless, we do suggest that a consideration for the non-digital, for player-driven experiences, for an examination of how we simulate the senses and what technologies we use, are each a potential opportunity to examine and expand on current design practices.

The non-digital as design challenge

As our related work suggests, digitally-mediated sensory simulations are assumed to offer control and reproducibility, often negating the prospect of the non-digital. Challenging such taken-for-granted assumptions in our design process led us to reflect on some the broader ramifications of conventional reproducibility: Must reproducibility necessarily include technology? Must every interaction be planned or controlled? From an interaction design perspective, our inclination is often to provide feedback to "confirm" the user's actions, guiding them towards the "right" actions, and helping the user "know what to do" [49]. But there is no need to think about technologically enabled feedback in the case of one's feet in the grass—the feedback of the cool passive haptics of the grass in the heat of the afternoon sun is immediate and complex (Figure 5).

Similarly, the idea of "knowing what to do" implies knowing what to do next: a procession from one interaction to another. There is nothing to "do" in our beach environment. There is no sequence of planned interactions with planned results. Presenting our proofs of concept in our workshops, we were aware of the potential for shallow engagement with novel technologies [28] and our players' potential expectation of wanting to know what they were supposed to "do" next. Yet, as demonstrated by the player who requested a fruit punch to go with the beach experience, there may be an opportunity to allow the player to co-construct their experience (e.g., by placing the heater, warming the sand, or preparing a drink). Reflections such as these helped us to reconceptualize "immersive" experiences as player-driven rather than system-driven.

Figure 5. Using grass for the feedback of its passive haptics.

Including the player

We chose to explore a single narrative moment in order to constrain the experience and narrow our focus. Yet, as our proofs of concept suggest, one narrative moment can have several sensory qualities and can last as long as the player wants to experience them. Designers face additional challenges if they hope to create longer narratives with distinct transitions between sensory experiences. Smell, for example, is a difficult modality to work with, having numerous practical and ethical challenges [see, e.g., 23]. Related work that assumes a neutral body within a neutral environment might bypass these challenges by disregarding the complex contexts of a designed experience. For us, challenging this assumption started with the admission that we could not assume to know the needs and preferences of the player or the sensory conditions of their environment.

Conceptualizing the experience as player-driven allows us to reintegrate the player and the player's sensory environment. Designing interactions in which the player chooses for themselves what diegetic smells, tastes, atmospheres, and tangible objects accompany a narrative could help to personalize the experience while also helping to circumvent some of the difficulties that designers face when attempting anything to do with smell or taste, like the risk of an allergic reaction. Integrating the player begins to overcome some of the challenges of the reproducibility of the non-digital. A video game that plans for a player to eat baked goods does not have to provide baked goods as long as the player knows to get the ones that suit them ahead of time. In this way, designers can work to enable players to co-construct a variety of possible narratives in ways that are most meaningful to them.

Reconsidering the bounds of sensory VR

A reconsideration of the beginning of the designed experience to include any preparatory actions (e.g., putting on sunscreen, or choosing an appropriate time and location outside, or eating baked goods) could go still further. The interaction could begin when the player contemplates the available sensory affordances of their own environment. With some foreknowledge of a desired experience, the player can ask, as we did, "What are the sensory qualities of the environments available to me? What are the diegetic qualities of my environment?" In turn, the designed experience could help players to incorporate their physical environments. This begins to suggest a spectrum of sensory, diegetic possibilities that could be available to the player. In our version of Little Red Riding Hood, for example, a player with a nearby forest might have a more diegetic sensory experience than our player in a city park. Yet both experiences are valid if they meet the player's needs and preferences.

Giving the player more control over a designed experience acknowledges some of the uncontrollable aspects of those spaces, while also offering more opportunities for design. The assumption that discrete sensory experiences will not be affected by our environment or our other senses limits the designed experience, both intentionally and unintentionally. For example, it is probably safe to assume that most video games designed for VR make no consideration for what is in the player's mouth, or what the player is tasting. This is to say that the player and the designer have implicitly agreed that what the player might be tasting is outside the story world. The player must implicitly agree to ignore some senses and pay attention to others. How might designed experiences change if players did not have to ignore some of their senses? How might these experiences change if both players and designers implicitly agreed that all of the player's senses and their environments could be diegetic? Every physical space lends its ambient sensory qualities to virtual worlds, just as every player has differing needs and preferences within those spaces.

Reconsidering technology

The absence of any technological innovation in our proofs of concept is not intended as a dismissal of technology. Rather, using low-cost sensory materials is an attempt to (re)consider the real-world aspects of a designed experience, filled with organic and inorganic materials. As VR is a digital simulation, work that explores other digital simulations appears to be a natural fit. Attempts, for example, to deliver "augmented" or "electric" taste [44] complement work that aims to "digitize" smell and taste [62] (cf. the "super realistic smells" of Vaqso [66] or the "deep immersion" and "simulated effects" of the Feelreal helmet and mask [30], or the "new senses" of the Neo Sensory Vest [48]). However, some of the trends in VR that we have touched on in this paper suggest an ironic turn away from the body in order to achieve embodiment. Our proofs of concept are a reminder that the design of sensory VR should include a consideration of sensory experiences that are non-digital, readily available, and chosen by users.

Examining the taken-for-granted in the technologies we use offers opportunities for future work. Following van Dijk and Hummels [15], it can be "radical" to focus on the sensory affordances of an environment before a technological intervention. For embodied experiences, it can also be practical. For those working on technological solutions to sensory VR, explorations like ours may be useful for prototyping digitally-mediated sensory design. Contrasting a contextually situated sensory experience with its digital, virtual, or synthetic counterpart can simply be an exploration of what we gain or lose in the process of mediation. At the very least, the non-digital can allow designers to better assess the sensory, embodied qualities of a particular environment. As Gaver et al. suggest, it can be useful to consider the ambiguous, open-ended experience as it may help to position the user in an active, interpretive role [17]. Open-ended experiences in VR could also benefit from a consideration of the "trajectory" of the user's experience: what are the possible paths through which the user navigates physical/digital spaces, as well as through planned moments of an experience? [6]

CONCLUSION

We have argued that much of the current work that aims to bring sensory experiences to VR does so while ignoring the non-digital. Drawing on design practices that strive for an interrelated conception of our bodies and environments, we created two proof of concept sensory VR experiences. We offer a consideration for taste, touch, and smell, as well as ambient effects like heat and wind to the more conventional modalities of sight and sound. Both experiences are barefoot and open-ended, one indoors, the other outdoors, exploring the sensory details of a moment. In our VR and non-VR workshops, we used diegetic and intersensory considerations as design prompts: how does a particular modality contribute to the environment, the story, and the player? In response, we emphasize the inclusion of the passive, experiential aspects of the non-digital. Neither experience requires sophisticated programming or physical prototyping, yet both deliver an array of sensory affordances that are rarely offered in VR. Technological solutions to these sensory interactions would be prohibitively complex and expensive, for our lab and for a general audience. We conclude by suggesting that the incorporation of the non-digital is a challenge to sensory design and technology, but not a dismissal of either. Instead, it offers opportunities to expand the design space, allowing players to co-construct designed experiences that best suit their own environments and their own bodies.

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REFERENCES

1. Anvio VR. 2017. Retrieved from: https://en.anviovr.com/
2. Bruno de Araujo, Ricardo Jota, Varun Perumal, Jia Xian Yao, Karan Singh, and Daniel Wigdor. 2016. Snake Charmer: Physically Enabling Virtual Objects. In Proceedings of the TEI ‘16: Tenth International Conference on Tangible, Embedded, and Embodied Interaction (TEI ‘16). ACM, New York, NY, USA, 218-226.
3. Peter Arnold. 2017. You Better Eat to Survive! Exploring Edible Interactions in a Virtual Reality Game. In *Proceedings of the 2017 CHI Conference Extended Abstracts on Human Factors in Computing Systems (CHI EA '17).* ACM, New York, NY, USA, 206-209. DOI: https://doi.org/10.1145/3027063.3048408
4. AxonVR. 2017. Retrieved from: https://axonvr.com/
5. Jeffrey Bardzell and Shaowen Bardzell. 2013. What is "critical" about critical design?. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems* (CHI '13). ACM, New York, NY, USA, 3297-3306. DOI: https://doi.org/10.1145/2470654.2466451
6. Steve Benford, Gabriella Giannachi, Boriana Koleva, and Tom Rodden. 2009. From interaction to trajectories: designing coherent journeys through user experiences. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems (CHI '09).* ACM, New York, NY, USA, 709-718. DOI: https://doi.org/10.1145/1518701.1518812
7. Hrvoje Benko, Christian Holz, Mike Sinclair, and Eyal Ofek. 2016. NormalTouch and TextureTouch: High-fidelity 3D Haptic Shape Rendering on Handheld Virtual Reality Controllers. In *Proceedings of the 29th Annual Symposium on User Interface Software and Technology (UIST '16).* ACM, New York, NY, USA, 717-728. DOI: https://doi.org/10.1145/2984511.2984526
8. Jeanne Brockmyer, Christine Fox, Kathleen Curtiss, Evan McBroom, Kimberly Burkhart, and Jaquelyn Pidruzny. 2009. The Development of the Game Engagement Questionnaire: A Measure of Engagement in Video Game Playing: Response to Reviews. Journal of Experimental Social Psychology 25, 4 (March 2009), 624-634. DOI:http://dx.doi.org/10.1016/j.jesp.2009.02.016
9. Sylvain Chagué and Caecilia Charbonnier. 2016. Real Virtuality: A Multi-User Immersive Platform Connecting Real and Virtual Worlds, VRIC 2016 Virtual Reality International Conference - Laval Virtual, Laval, France, ACM New York, NY, USA.
10. Lung-Pan Cheng, Patrick Lühne, Pedro Lopes, Christoph Sterz, and Patrick Baudisch. 2014. Haptic turk: a motion platform based on people. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems* (CHI '14). ACM, New York, NY, USA, 3463-3472. DOI=http://dx.doi.org/10.1145/2556288.2557101
11. Lung-Pan Cheng, Sebastian Marwecki, and Patrick Baudisch. 2017. Mutual Human Actuation. In *Proceedings of the 30th Annual ACM Symposium on User Interface Software and Technology* (UIST '17). ACM, New York, NY, USA, 797-805. DOI: https://doi.org/10.1145/3126594.3126667
12. Lung-Pan Cheng, Thijs Roumen, Hannes Rantzsch, Sven Köhler, Patrick Schmidt, Robert Kovacs, Johannes Jasper, Jonas Kemper, and Patrick Baudisch. 2015. TurkDeck: Physical Virtual Reality Based on People. In *Proceedings of the 28th Annual ACM Symposium on User Interface Software & Technology (UIST '15).* ACM, New York, NY, USA, 417-426. DOI: https://doi.org/10.1145/2807442.2807463
13. Lung-Pan Cheng, Eyal Ofek, Christian Holz, Hrvoje Benko, and Andrew D. Wilson. 2017. Sparse Haptic Proxy: Touch Feedback in Virtual Environments Using a General Passive Prop. In *Proceedings of the 2017 CHI Conference on Human Factors in Computing Systems* (CHI '17). ACM, New York, NY, USA, 3718-3728. DOI: https://doi.org/10.1145/3025453.3025753
14. Alena Denisova, A. Imran Nordin, and Paul Cairns. 2016. The Convergence of Player Experience Questionnaires. In *Proceedings of the 2016 Annual Symposium on Computer-Human Interaction in Play* (CHI PLAY '16). ACM, New York, NY, USA, 33-37. DOI: https://doi.org/10.1145/2967934.2968095
15. Jelle van Dijk and Caroline Hummels. 2017. Designing for Embodied Being-in-the-World: Two Cases, Seven Principles and One Framework. In Proceedings of the Eleventh International Conference on Tangible, Embedded, and Embodied Interaction (TEI '17). ACM, New York, NY, USA, 47-56. DOI: https://doi.org/10.1145/3024969.3025007
16. Ruofei Du and Liang He. 2016. VRSurus: Enhancing Interactivity and Tangibility of Puppets in Virtual Reality. In *Proceedings of the 2016 CHI Conference Extended Abstracts on Human Factors in Computing Systems* (CHI EA '16). ACM, New York, NY, USA, 2454-2461. DOI: https://doi.org/10.1145/2851581.2892290
17. William W. Gaver, Jacob Beaver, and Steve Benford. 2003. Ambiguity as a resource for design. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems* (CHI '03). ACM, New York, NY, USA, 233-240. DOI=http://dx.doi.org/10.1145/642611.642653
18. Gheorghita Ghinea and Oluwakemi A. Ademoye. 2011. Olfaction-enhanced multimedia: perspectives and challenges. *Multimedia Tools Appl.* 55, 3

(December 2011), 601-626. DOI=http://dx.doi.org/10.1007/s11042-010-0581-4

19. GotouchVR. 2017. Retrieved from: https://www.gotouchvr.com/
20. Jan Gugenheimer, Dennis Wolf, Gabriel Haas, Sebastian Krebs, and Enrico Rukzio. 2016. SwiVRChair: A Motorized Swivel Chair to Nudge Users' Orientation for 360 Degree Storytelling in Virtual Reality. In *Proceedings of the 2016 CHI Conference on Human Factors in Computing Systems* (CHI '16). ACM, New York, NY, USA, 1996-2000. DOI: https://doi.org/10.1145/2858036.2858040
21. Daniel Harley, Jean Ho Chu, Jamie Kwan, and Ali Mazalek. 2016. Towards a Framework for Tangible Narratives. In Proceedings of the TEI '16: Tenth International Conference on Tangible, Embedded, and Embodied Interaction (TEI '16). ACM, New York, NY, USA, 62-69. DOI=http://dx.doi.org/10.1145/2839462.2839471
22. Daniel Harley, Aneesh P. Tarun, Daniel Germinario, and Ali Mazalek. 2017. Tangible VR: Diegetic Tangible Objects for Virtual Reality Narratives. In *Proceedings of the 2017 Conference on Designing Interactive Systems* (DIS '17). ACM, New York, NY, USA, 1253-1263. DOI: https://doi.org/10.1145/3064663.3064680
23. Victoria Henshaw, Dominic Medway, Gary Warnaby, and Chris Perkins. 2016 Marketing the 'city of smells'. 16 2 (June 2016), 153-170. DOI: http:dx.doi.org/https://doi.org/10.1177/1470593115619970
24. Anuruddha Hettiarachchi and Daniel Wigdor. 2016. Annexing Reality: Enabling Opportunistic Use of Everyday Objects as Tangible Proxies in Augmented Reality. In *Proceedings of the 2016 CHI Conference on Human Factors in Computing Systems* (CHI '16). ACM, New York, NY, USA, 1957-1967.
25. Philipp Hock, Sebastian Benedikter, Jan Gugenheimer, and Enrico Rukzio. 2017. CarVR: Enabling In-Car Virtual Reality Entertainment. In *Proceedings of the 2017 CHI Conference on Human Factors in Computing Systems* (CHI '17). ACM, New York, NY, USA, 4034-4044. DOI: https://doi.org/10.1145/3025453.3025665
26. Holovis. 2017. Retrieved from: http://www.holovis.com/
27. Eva Hornecker. 2006. Physicality in tangible interaction: bodies and the world. First Steps in Physicality, 21.
28. Eva Hornecker. 2008. "I don't understand it either, but it is cool"-visitor interactions with a multi-touch table in a museum. In Horizontal interactive human computer systems, 2008. TABLETOP 2008. 3rd IEEE International Workshop on, pp. 113-120. IEEE, 2008.
29. HTC Vive. 2017. Retrieved from: https://www.vive.com
30. Feelreal. 2017. Retrieved from: http://feelreal.com/.
31. Felix Hülsmann, Julia Fröhlich, Nikita Mattar, and Ipke Wachsmuth. 2014. Wind and warmth in virtual reality: implementation and evaluation. In *Proceedings of the 2014 Virtual Reality International Conference* (VRIC '14). ACM, New York, NY, USA, Article 24, 8 pages. DOI=http://dx.doi.org/10.1145/2617841.2620712
32. Charlene Jennett, Anna L. Cox, Paul Cairns, Samira Dhoparee, Andrew Epps, Tim Tijs, and Alison Walton. 2008. Measuring and defining the experience of immersion in games. *Int. J. Hum.-Comput. Stud.* 66, 9 (September 2008), 641-661. DOI=http://dx.doi.org/10.1016/j.ijhcs.2008.04.004
33. Takayuki Kosaka and Takuya Iwamoto. 2013. Serious dietary education system for changing food preferences "food practice shooter". In *Proceedings of the Virtual Reality International Conference: Laval Virtual* (VRIC '13). ACM, New York, NY, USA, Article 23, 4 pages. DOI: https://doi.org/10.1145/2466816.2466841
34. Maggie Kosek, Babis Koniaris, David Sinclair, Desislava Markova, Fraser Rothnie, Lanny Smoot, and Kenny Mitchell. 2017. IRIDiuM+: deep media storytelling with non-linear light field video. In *ACM SIGGRAPH 2017 VR Village* (SIGGRAPH '17). ACM, New York, NY, USA, Article 10, 2 pages. DOI: https://doi.org/10.1145/3089269.3089277
35. Pascal Knierim, Thomas Kosch, Valentin Schwind, Markus Funk, Francisco Kiss, Stefan Schneegass, and Niels Henze. 2017. Tactile Drones - Providing Immersive Tactile Feedback in Virtual Reality through Quadcopters. In *Proceedings of the 2017 CHI Conference Extended Abstracts on Human Factors in Computing Systems* (CHI EA '17). ACM, New York, NY, USA, 433-436. DOI: https://doi.org/10.1145/3027063.3050426
36. Kuka. 2017. *Kuka Coaster*. Retrieved from: https://www.kuka.com/en-ca/industries/other-industries/entertainment/kuka-coaster
37. Pedro Lopes, Alexandra Ion, and Patrick Baudisch. 2015. Impacto: Simulating Physical Impact by Combining Tactile Stimulation with Electrical Muscle Stimulation. In Proceedings of the 28th Annual ACM Symposium on User Interface Software & Technology (UIST '15). ACM, New York, NY, USA, 11-19. DOI: https://doi.org/10.1145/2807442.2807443
38. Keigo Matsumoto, Yuki Ban, Takuji Narumi, Yohei Yanase, Tomohiro Tanikawa, and Michitaka Hirose. 2016. Unlimited corridor: redirected walking

techniques using visuo haptic interaction. In *ACM SIGGRAPH 2016 Emerging Technologies* (SIGGRAPH '16). ACM, New York, NY, USA, , Article 20 , 2 pages. DOI: https://doi.org/10.1145/2929464.2929482

39. Melanie McBride & Jason Nolan. (2016). “Including smell: An intersensory curriculum, by design.” In Victoria Henshaw, Kate MacLean, Dominic Medway, Chris Perkins, & Gary Warnaby (eds.). *Designing with smell: practices, techniques and challenges*. New York: Routledge.
40. Michael Meehan, Brent Insko, Mary Whitton, and Frederick P. Brooks, Jr. 2002. Physiological measures of presence in stressful virtual environments. In Proceedings of the 29th annual conference on Computer graphics and interactive techniques (SIGGRAPH '02). ACM, New York, NY, USA, 645-652. DOI: http://dx.doi.org/10.1145/566570.566630
41. Janet Murray. 2005. Did it make you cry? Creating dramatic agency in immersive environments. In Virtual Storytelling. Using Virtual Reality Technologies for Storytelling (pp. 83-94). Springer Berlin Heidelberg.
42. Niall Murray, Brian Lee, Yuansong Qiao, and Gabriel-Miro Muntean. 2016. Olfaction-Enhanced Multimedia: A Survey of Application Domains, Displays, and Research Challenges. *ACM Comput. Surv.* 48, 4, Article 56 (May 2016), 34 pages. DOI: http://dx.doi.org/10.1145/2816454
43. Ryohei Nagao, Keigo Matsumoto, Takuji Narumi, Tomohiro Tanikawa, and Michitaka Hirose. 2017. Infinite stairs: simulating stairs in virtual reality based on visuo-haptic interaction. In *ACM SIGGRAPH 2017 Emerging Technologies* (SIGGRAPH '17). ACM, New York, NY, USA, Article 14, 2 pages. DOI: https://doi.org/10.1145/3084822.3084838
44. Hiromi Nakamura and Homei Miyashita. 2011. Augmented gustation using electricity. In *Proceedings of the 2nd Augmented Human International Conference* (AH '11). ACM, New York, NY, USA, , Article 34 , 2 pages. DOI=http://dx.doi.org/10.1145/1959826.1959860
45. Takuya Nakano, Shota Saji, and Yasuyuki Yanagida. 2012. Indicating wind direction using a fan-based wind display. In *Proceedings of the 2012 international conference on Haptics: perception, devices, mobility, and communication - Volume Part II* (EuroHaptics'12), Poika Isokoski and Jukka Springare (Eds.), Vol. Part II. Springer-Verlag, Berlin, Heidelberg, 97-102. DOI=http://dx.doi.org/10.1007/978-3-642-31404-9_17
46. Takuji Narumi. 2016. Multi-sensorial virtual reality and augmented human food interaction. In *Proceedings of the 1st Workshop on Multi-sensorial Approaches to Human-Food Interaction* (MHFI '16), Anton Nijholt, Carlos Velasco, Gijs Huisman, and Kasun Karunanayaka (Eds.). ACM, New York, NY, USA, Article , 6 pages. DOI: https://doi.org/10.1145/3007577.3007587
47. Takuji Narumi, Shinya Nishizaka, Takashi Kajinami, Tomohiro Tanikawa, and Michitaka Hirose. 2011. Augmented reality flavors: gustatory display based on edible marker and cross-modal interaction. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*(CHI '11). ACM, New York, NY, USA, 93-102. DOI: https://doi.org/10.1145/1978942.1978957
48. Neo Sensory. 2017. Retrieved from: http://neosensory.com/
49. Don Norman. 2013 The design of everyday things: Revised and expanded edition, New York City, NY: Basic Books.
50. Daniela Petrelli, Alessandro Soranzo, Luigina Ciolfi, and John Reidy. 2016. Exploring the Aesthetics of Tangible Interaction: Experiments on the Perception of Hybrid Objects. In Proceedings of the TEI '16: Tenth International Conference on Tangible, Embedded, and Embodied Interaction (TEI '16). ACM, New York, NY, USA, 100-108. DOI: https://doi.org/10.1145/2839462.2839478
51. Punchdrunk. 2017. *Sleep No More.* Retrieved from: https://www.punchdrunk.org.uk/sleep-no-more/
52. ProjectiCan. 2017. Retrieved from: https://project-ican.com/
53. Nimesha Ranasinghe, Pravar Jain, Shienny Karwita, David Tolley, and Ellen Yi-Luen Do. 2017. Ambiotherm: Enhancing Sense of Presence in Virtual Reality by Simulating Real-World Environmental Conditions. In *Proceedings of the 2017 CHI Conference on Human Factors in Computing Systems* (CHI '17). ACM, New York, NY, USA, 1731-1742. DOI: https://doi.org/10.1145/3025453.3025723
54. Nimesha Ranasinghe and Ellen Yi-Luen Do. 2016. Digital Lollipop: Studying Electrical Stimulation on the Human Tongue to Simulate Taste Sensations. *ACM Trans. Multimedia Comput. Commun. Appl.* 13, 1, Article 5 (October 2016), 22 pages. DOI: https://doi.org/10.1145/2996462
55. Michael Rietzler, Katrin Plaumann, Taras Kränzle, Marcel Erath, Alexander Stahl, and Enrico Rukzio. 2017. VaiR: Simulating 3D Airflows in Virtual Reality. In *Proceedings of the 2017 CHI Conference on Human Factors in Computing Systems* (CHI '17). ACM, New York, NY, USA, 5669-5677. DOI: https://doi.org/10.1145/3025453.3026009
56. Dominik Schmidt, Rob Kovacs, Vikram Mehta, Udayan Umapathi, Sven Köhler, Lung-Pan Cheng, and Patrick Baudisch. 2015. Level-Ups: Motorized Stilts that Simulate Stair Steps in Virtual Reality. In

Proceedings of the 33rd Annual ACM Conference on Human Factors in Computing Systems (CHI '15). ACM, New York, NY, USA, 2157-2160. DOI: https://doi.org/10.1145/2702123.2702253

57. Dominik Schmidt, Raf Ramakers, Esben W. Pedersen, Johannes Jasper, Sven Köhler, Aileen Pohl, Hannes Rantzsch, Andreas Rau, Patrick Schmidt, Christoph Sterz, Yanina Yurchenko, and Patrick Baudisch. 2014. Kickables: tangibles for feet. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems* (CHI '14). ACM, New York, NY, USA, 3143-3152. DOI=http://dx.doi.org/10.1145/2556288.2557016
58. Samuel B. Schorr and Allison M. Okamura. 2017. Fingertip Tactile Devices for Virtual Object Manipulation and Exploration. In *Proceedings of the 2017 CHI Conference on Human Factors in Computing Systems* (CHI '17). ACM, New York, NY, USA, 3115-3119. DOI: https://doi.org/10.1145/3025453.3025744
59. Six Flags. 2017. *Galactic Attack.* https://www.sixflags.com/overtexas/newsroom/galactic-attack-vr-coaster
60. Mel Slater. 1999. Measuring Presence: A Response to the Witmer and Singer Presence Questionnaire. *Presence: Teleoper. Virtual Environ.* 8, 5 (October 1999), 560-565. DOI=http://dx.doi.org/10.1162/105474699566477
61. Dorothé Smit, Doenja Oogjes, Bruna Goveia de Rocha, Ambra Trotto, Yeup Hur, and Caroline Hummels. 2016. Ideating in Skills: Developing Tools for Embodied Co-Design. In *Proceedings of the TEI '16: Tenth International Conference on Tangible, Embedded, and Embodied Interaction* (TEI '16). ACM, New York, NY, USA, 78-85. DOI: https://doi.org/10.1145/2839462.2839497
62. Charles Spence, Marianna Obrist, Carlos Velasco, and Nimesha Ranasinghe. 2017. Digitizing the chemical senses: possibilities & pitfalls. *International Journal of Human-Computer Studies* (2017), 1071-5819. DOI:http://dx.doi.org/https://doi.org/10.1016/j.ijhcs.2017.06.003
63. Misha Sra, and Chris Schmandt. 2015. MetaSpace II: Object and Full-body Tracking for Interaction and Navigation in Social VR. arXiv preprint arXiv:1512.02922. DOI: http://dx.doi.org/10.1145/2815585.2817802
64. Evan A. Suma, Mahdi Azmandian, Timofey Grechkin, Thai Phan, and Mark Bolas. 2015. Making small spaces feel large: infinite walking in virtual reality. In *ACM SIGGRAPH 2015 Emerging Technologies* (SIGGRAPH '15). ACM, New York, NY, USA, Article 16, 1 pages. DOI: https://doi.org/10.1145/2782782.2792496
65. Paul Tennent, Joe Marshall, Brendan Walker, Patrick Brundell, and Steve Benford. 2017. The Challenges of Visual-Kinaesthetic Experience. In Proceedings of the 2017 Conference on Designing Interactive Systems (DIS '17). ACM, New York, NY, USA, 1265-1276. DOI: https://doi.org/10.1145/3064663.3064763
66. Vaqso. 2017. Retrieved from: https://vaqso.com/
67. Eduardo Velloso, Dominik Schmidt, Jason Alexander, Hans Gellersen, and Andreas Bulling. 2015. The Feet in Human--Computer Interaction: A Survey of Foot-Based Interaction. *ACM Comput. Surv.* 48, 2, Article 21 (September 2015), 35 pages. DOI=http://dx.doi.org/10.1145/2816455
68. Virtuix. 2017. Retrieved from: http://www.virtuix.com/
69. VIRZOOM. 2017. Retrieved from: https://www.virzoom.com/
70. ViveNChill. 2017. Retrieved from: https://www.indiegogo.com/projects/vivenchill-vr#/
71. The Void. 2017. Retrieved from: https://www.thevoid.com/
72. VR Go. 2017. Retrieved from: http://www.vrgochair.com/
73. VR Studios. 2017. *VRCade.* Retrieved from: https://www.vrstudios.com/vrcade/
74. VR Zone. 2017. Retrieved from: https://vrzone-pic.com/en/
75. Sarah Wiseman, Janet van der Linden, Ad Spiers, and Maria Oshodi. 2017. Control and Being Controlled: Exploring the use of Technology in an Immersive Theatre Performance. In *Proceedings of the 2017 Conference on Designing Interactive Systems (DIS '17).* ACM, New York, NY, USA, 3-14. DOI: https://doi.org/10.1145/3064663.3064694
76. Bob G. Witmer and Michael J. Singer. 1998. Measuring Presence in Virtual Environments: A Presence Questionnaire. *Presence: Teleoper. Virtual Environ.* 7, 3 (June 1998), 225-240. DOI=http://dx.doi.org/10.1162/105474698565686
77. Masasuke Yasumoto and Takehiro Teraoka. 2015. Shadow Shooter. In *Proceedings of the 2015 Virtual Reality International Conference* (VRIC '15). ACM, New York, NY, USA, Article 17, 2 pages. DOI: https://doi.org/10.1145/2806173.2806193.
78. Andre Zenner and Antonio Kruger. 2017. Shifty: A Weight-Shifting Dynamic Passive Haptic Proxy to Enhance Object Perception in Virtual Reality. *IEEE Transactions on Visualization and Computer Graphics* 23, 4 (April 2017), 1285-1294. DOI: https://doi.org/10.1109/TVCG.2017.2656978.