Playing by Ear: Designing for the Physical in a Sound-Based Virtual Reality Narrative

Daniel Harley
University of Waterloo, Waterloo, Ontario, Canada
dharley@uwaterloo.ca

Aneesh P. Tarun
Synaesthetic Media Lab, Ryerson University, Toronto, Ontario, Canada
aneesh@ryerson.ca

Bonnie J. Stinson
Synaesthetic Media Lab, Ryerson University, Toronto, Ontario, Canada
bonnie.j.stinson@ryerson.ca

Tudor Tibu
Synaesthetic Media Lab, Ryerson University, Toronto, Ontario, Canada
tudor.tibu@ryerson.ca

Ali Mazalek
Synaesthetic Media Lab, Ryerson University, Toronto, Ontario, Canada
mazalek@ryerson.ca

ABSTRACT

We present two proof-of-concept narrative VR experiences with a focus on sound-based physical interactions. Responding to a call to expand upon current design conceptualizations, we draw on tangible sound-based design in order to develop considerations for the body and physical environments within VR narratives. We propose that a focus on the actions the player is asked to perform (e.g., touch, stand, kneel, grasp, walk, listen, reach, dance) can contribute to an understanding of VR as a sensory, embodied medium that offers ways to playfully engage with physical reality rather than simulate it entirely.

CCS CONCEPTS

• **Human-centered computing** → Human computer interaction (HCI); Interaction paradigms; Virtual reality; • **Software and its engineering** → Software organization and properties; Contextual software domains; Virtual worlds software; Interactive games.

KEYWORDS

Virtual reality, mixed reality, sound, design, tangible, embedded, embodied, narrative, storytelling

ACM Reference Format:

Daniel Harley, Aneesh P. Tarun, Bonnie J. Stinson, Tudor Tibu, and Ali Mazalek. 2021. Playing by Ear: Designing for the Physical in a Sound-Based Virtual Reality Narrative. In *Fifteenth International Conference on Tangible, Embedded, and Embodied Interaction (TEI '21), February 14–17, 2021, Salzburg, Austria.* ACM, New York, NY, USA, 9 pages. https://doi.org/10.1145/3430524.3440635

1 INTRODUCTION

In his 1965 vision for the "ultimate display," Ivan Sutherland wrote, "If the task of the display is to serve as a looking-glass into the mathematical wonderland constructed in computer memory, it should serve as many senses as possible" [42]. At the time, research into virtual reality (VR), including Sutherland's "head-mounted 3D display" [43], offered early signs of this vision of the future of computing. Decades later, despite popular efforts that appeared to strive for more comprehensive sensory displays (see e.g., the DataGlove at VPL Research in the 1980s [54]), consumer VR arrived as a visual display. In the Kickstarter for the Oculus Rift, a product which contributed to the recent consumer push for virtual reality technologies, the advertised "immersive experience" of the headset was said to be due to its visual qualities [25].

Current research, however, continues to offer many examples of technologies that extend the physical interactions of a VR display [1, 5, 22, 36, 49–52], raising important questions about the physical and sensory characteristics of VR design. For example, in contrast to Sutherland's vision, Marshall and Tennent [28] argue that striving towards a "complete" simulation of reality constrains designers. They demonstrate ways that designers can create sensory experiences beyond those provided by the system, including deliberately disrupting or "breaking" the simulation, and designing for multiple concurrent "realities" rather than a single "immersive" simulation. As such, Marshall and Tennent have identified a broad design space that requires further examination: VR that decenters the importance of the visual simulation by including a deliberate consideration for the sensory world outside the headset.

We propose that related design practices outside VR can contribute to this expanding design space. Drawing on narrative and sound-based interaction design, we use a research through design (RtD) approach to present two VR narratives that include diegetic physical objects and playful engagements within a sound-based installation (Figure 1). We detail our design process, which includes an informal workshop, narrative design, and a user test, in order to contribute to a discussion about the conceptual tools that shape VR experiences. We conclude with a reflection on future work.

2 RELATED WORK

In this section, we review current design trends for VR, especially pertaining to designing tangible and/or embodied experiences, followed by research that proposes physical, sound-based interactions. These two sections situate our contribution: the first section outlines a design space that is relatively underexplored from a narrative design perspective; the second section outlines non-VR sound-based

TEI '21, February 14–17, 2021, Salzburg, Austria

ACM ISBN 978-1-4503-8213-7/21/02…$15.00
https://doi.org/10.1145/3430524.3440635

Figure 1: Exploring sound-based tangible, embedded, and embodied interaction in VR.

design that we apply to VR in order to extend considerations for engaging with the physical space outside the headset.

2.1 Playing with/in VR

Marshall and Tennent [28] argue that current conceptualizations of VR, XR, and MR—including Milgram and Kishino's [31] mixed reality continuum—can constrain designers by overemphasizing the visual and by insisting upon a simulation of "reality." For Marshall and Tennent, such overarching conceptualizations are untenable in part because a "complete" sensory simulation is not necessarily the goal, since it is possible to simultaneously engage with senses and realities beyond what is simulated by the headset or the controllers. In a subsequent paper, Marshall et al. [27] propose a model of classifying sensory experiences in VR based on the "level of sensory alignment," i.e., the degree to which digital stimulation aligns with non-digital stimulation, ranging from alignment to misalignment. Whatever the degree of alignment, an important consideration for designers is to evaluate what is stimulated by the digital system and what is "open to physical stimulation by the outside world" [27].

While this reconceptualization primarily positions sensory misalignment as a design space [45–47], it also begins to offer a framework to better understand playful work that cannot be neatly categorized along polarized axes. For example, a renewed focus on the sensory stimulation of the "outside world" might include asymmetrical play in VR (one player in VR and another player out) [2, 8, 37, 53]. Or it might include design that incorporates the non-digital [13], or that focuses on the embodied sense of being in an environment, whether by attention to breath [35], or through site-specific design [11]. Beyond HCI, there are important examples of installation-based work in which artists incorporate physical objects, themed set design, and/or live performers [24]. Just as these playful design examples do not fit within the bounds of normative (and/or consumer) VR design, they also might not typically be grouped together. What this work has in common, however, is an interest in the interplay between the physical and the digital. In order to continue to expand the design space that explores the physicality of the "outside world" within VR design, we suggest there is an opportunity to apply lessons learned from alternate design traditions.

2.2 Playing with Sound

One example of design work that decenters the visual while also focusing on the physical is sound-based tangible and embodied interaction. In their review of tangible user interfaces (TUIs) Orit Shaer and Eva Hornecker characterize sound-based applications as "one of the oldest and most popular areas for TUIs" [40]. We review a selection of such applications to highlight how physical interactions might be complemented by the digital. Although there is an important parallel history of music-based tangible applications (e.g., [20, 21, 23]), as well as musical instruments designed for virtual reality [39], we are interested in playful interactions rather than applications that aspire towards musical expression or mastery.

Within a playful context, we find objects that can gain sound-making properties [33], bottles that "contain" sound [17], or a wand that can record, remix, and play back sound in real time [30]. These interactive systems embed sound into tangible objects, offering collaborative, embodied interactions that employ the physical affordances of the objects for sonic interaction design. There is, for example, the Audio Shaker [16] "a tactile container to capture, shake up and pour out sounds," making the sounds "physical" after shaking the container. Similarly, Matti Niinimaki's work over the last ten years demonstrates a variety of tangible objects made into sound installations and sonic interactions [32]. For example, Niinimaki's Beat Blender project presents household objects (a blender, an iron) converted into objects that remix music. Dropping fruit toys into the blender creates beats and sounds that change depending on the fruit; hitting "blend" or "mix" or "grate" and other buttons on the blender each affect the composition.

In order to apply this focus on the physical within a narrative context, Ella Dagan's Cloakroom [6] could be used as an exemplar. In Dagan's work, a number of coats hang in a room, which the player is invited to wear. Each coat has objects in the pockets, and every object triggers an audio narrative when it is placed in a basket. In this work, there is the embodied feeling of wearing these coats, with their weight, texture, and smell; the physical characteristics of the objects; and stories embedded in physical, everyday objects. To help develop considerations for the physical within a VR design process, we ask, how might we employ lessons learned across these sound-based interactions for VR design? How might the physicality of these interactions contribute to new conceptualizations of narrative VR design?

3 DESIGN APPROACH: PLAYING BY EAR

We present two sound-based proof of concept narrative experiences in VR (N1 and N2), which we designed with attention to physical environments, movement, and touch. We employ a research through design (RtD) approach as a means to examine the contours of this design space and to put our conceptual considerations into practice. According to Gaver [7], the purpose of this approach is not to provide concrete generalizations, but rather to produce design objects that "embody theory." For Gaver, "[T]he goal of conceptual work in research through design is not to develop theories that are never wrong, it is to create theories that are *sometimes right*" [7] (emphasis in original), and as such we intend to ask and explore speculative questions about the design space as outlined by Marshall and Tennent [28]. In this section, we describe how we began with an informal workshop without VR to better focus on tangible design and the connections to past TUIs; we outline our proofs of concept, the first of which offers a linear narrative and interaction sequence, while the second offers a non-linear, exploratory setting; we then describe how the narrative design and technical design of our implementation both strive to highlight the physicality of the experience; and finally we describe a formal evaluation of N2 with eight participants. Importantly, we view this evaluation as an extension of our iterative design process rather than a culmination. Throughout, our goal is to explore facets of these design stages (and the process as a whole) in order to look for opportunities for future work.

Although there are differences in terms of methodology and output for the various RtD approaches [3], a common feature that helps to define the contribution of the work is the interpretation of the designed object, whether that be through an elucidation of process, or an analysis of resulting themes and effects. We contribute the "intermediary knowledge" [14] of our design with the understanding that the purpose of such work is generative rather than explanatory. In other words, our goal is to raise questions for design that bridges TUIs and VR, asking how we might learn from other domains as well as what new considerations this may require for VR design. Documenting the process of design explorations is important for future research. For example, despite evidence of innovative VR design outside academia [24], work that was featured at festivals and events[1] is often difficult to access or experience, and the design process often does not receive formal attention. We make our process more explicit using RtD so that our examples may help lay the groundwork for further scholarly analysis, including taxonomies that consider tangible and embodied interactions in VR. By annotating facets of our design that might otherwise be implicit [29], we aim to make the "theory" [7] of our design work more explicit. We also contend that the RtD process offers insight that may help future work that strives towards more generalizable interactions by providing an account of the pitfalls and early successes within our design process. Our design choices throughout show a process with false starts, missteps, and limitations; we argue that detailing such processes is needed for early explorations of new conceptualizations. Even as we contribute novel narrative applications for VR, our goal in testing these experiences in formal and informal settings is less a process of refining the narrative experience, and more an effort to illustrate broader themes for future work that might begin with physical experiences in VR.

3.1 Initial attempts and informal workshop

We started by sketching ideas that aimed to incorporate the physicality of sound-based tangible and embodied interactions in VR. Conscious of some of our own aesthetic preferences, we took note of our own visual biases as our initial interaction ideas seemed to culminate in visual rewards: e.g., visual effects like sparks and fireworks, or virtual windows that each opened to a visual representation of the sound-based environment. For us, ideas such as these seemed to come easily when brainstorming for a visual medium. We felt it was important to question our assumptions about what VR "should" look like and we refocused our design goals: decentering the visual, designing for the physical reality in addition to the virtual reality, and designing for sensory experiences beyond what the system normatively provides.

Rather than begin with the virtual, we discarded our initial sketches to begin again with the physical. With a deliberate focus on tangible objects, we invited approximately 20 members of our lab (all university students with no prior knowledge of the project) to participate in an informal design workshop as a preliminary means to test and expand our initial plans. The students were split into smaller groups to facilitate conversation, and one team member was placed in each group to take notes. We brought in a number of everyday objects (e.g., a water pitcher, a stuffed animal, a wooden toy) to invite discussions about their physical characteristics and how these objects might be used for sound-based interactions. The objects were selected to cover a range of possible sensory experiences and interactions, e.g., light/heavy, transparent/opaque, solid/squishy. In our discussions, we found that sound-based work provided a precedent to inform and identify initial design ideas from the workshop. As some people focused on remediating the physical affordances of the objects (e.g., putting sound into a container and trapping it or letting it loose) we were reminded of Niinimaki's work [32]; as others used the affordances for representation (e.g., using the surfaces of a wooden toy as buttons to produce sound) we were reminded of AudioCubes [38].

In a sense, these were VR workshops without VR. Because VR and its visual possibilities seemed to overly influence our initial ideas, removing VR was an effort to begin with the physicality of the experience. Based on these workshops, we settled on a bottle as interface for sound-based interaction for our first proof of concept, which also has a precedent [17]. For our second proof of concept, in addition to objects that offer sound-making possibilities, we extrapolated on these lessons to design a physical space that "contained" particular sounds, represented by "zones." Overall, these workshops offered a rough baseline for our design of physical interactions, helping to inform an approach that prioritizes the physicality of the experience.

3.2 Interaction Scenarios

After our workshops, we designed N1 and N2 to explore physical and sound-based interactions within VR. Both experiences employ a similar narrative scenario: a wizard offers the player magical objects that relate to the weather and aural environments. However, while N1 follows a linear sequence of events guided by an audio narrative, N2 uses narrative as an orienting device to structure more open-ended interactions. In both, listening to audio also requires and/or is complemented by particular kinds of action.

3.2.1 N1: The Wizard's Workshop. In the first proof of concept, players begin in a magical workshop that contains only a table, a jug, and a rubbery blob. The player hears the voice of a wizard, who explains that he has been turned into a blob by magic gone wrong. He was trying to change the weather in a land in which

[1]See, for example, the installation-based design and physicality of Carne y Arena, which was premiered at the Cannes Film Festival: https://docubase.mit.edu/project/carne-y-arena/

Figure 2: A tabletop and tangible objects become part of a spell to create rain.

Figure 3: Handling a physical/virtual orb that contains birdsong. Kneeling to remove and isolate the sound of grass.

there has been no rain in a thousand years. The wizard enlists the player to help create rain using the objects of his magical workshop (Figure 2). The wizard guides the player through three interactions, ultimately producing a rainy soundscape.

The wizard invites the player to create wind by touching and moving their hands across the surface of the worktable. Doing this, the player begins to hear wind. The faster the player's hands move, the stronger the wind becomes. The player is then asked to add water to the spell. Picking up and shaking the jug creates a sloshing sound. The wizard tells the player to pour the water out, which sounds as if it splashes around the workshop. Now distant thunder can be heard; the spell is almost complete. The wizard asks the player to pick him up and to dance—"That's it! Keep your head moving!"—until the sound of the wind and thunder are joined by the sound of rain. The wizard congratulates the player as they listen to the sound of the rain.

3.2.2 N2: The Wizard's Time Off. In the second proof of concept, the player is handed a note as they enter a play area consisting of three zones, delineated in physical space by a carpeted area, a hanging cardboard shelf, and a grass-like outcropping made of craft materials. The note is from the wizard, who explains that this is where he comes to relax and to listen to the sounds of his favorite places. He has prepared two zones, and has left one zone empty, where the player can bring sounds from the other zones. In the note the wizard tells the player that the VR headset is a mask that he made so that others would be able to see what he sees and hear what he hears.

Putting on the headset, the player sees the three zones represented as glowing cylinders of different sizes and colors. There is a faint hum between zones. Inside the green zone, the player hears the sound of a forest, with creaking trees, wind, and birds. In this zone, there is a green orb on a shelf. It feels as if it is covered in soft pine needles. If the player takes the orb out of the zone, the birdsong from the forest becomes localized in the orb. Taking the orb to other zones will add the birdsong to those zones. The player must kneel to enter the blue zone, in which they hear the sound of an ocean coast, wind, and barking sea lions in the distance. The glowing object in this zone is a bundle of grass (Figure 3). Taking the grass out of the blue zone removes and localizes the sound of the wind in the tangible object. Without any glowing objects, the empty, purple zone is silent, but the player can add sounds from the other zones and sit on the carpet to listen to their creation.

3.3 Implementation

This subsection details our narrative design and technical implementation. As these are proofs of concept, we do not aim for a high degree of polish across the design, but instead focus our efforts on exploring possibilities for design that begins with the physical.

3.3.1 Narrative Design. In order to define the specific characteristics of our interactions, we draw on diegetic design [9, 10, 12, 13, 44] to situate the objects and the environment within the world of the story. The magical setting establishes the wizard in N1 as both tangible blob and narrator; in N2, the physical note that the player receives defines the headset as a "mask" built by the wizard to better see and hear his magical world (Figure 4). These diegetic prompts and objects established the playful conditions for a variety of physical interactions. The note and the "mask" from the wizard offer a way to transition from the physical to the virtual, attempting to transform the mundane qualities of the physical installation into a magical play space while also establishing the conditions of its open-ended interactions.

As with our tangible interaction design, beginning with the physical within a diegetic setting offers a way to define actions (e.g., that requires players to reach, to kneel) before supplementing those actions with visual affordances. When we felt that the linearity of the audio narrative in N1 unnecessarily constrained the possibility for exploration, refocusing on the physical helped to call attention to the affordances of the space as well as possible movement within that space. For N2, we began by identifying ways to incorporate physical interactions, designing an experience in which the player is asked to touch, stand, kneel, grasp, walk, reach, and "dance" in what is otherwise a listening experience in VR. Rather than enhance a VR experience by adding the physical, we asked how we might enhance a physical experience by adding VR.

3.3.2 Technical Design. Our proofs of concept use the HTC Vive head-mounted display with the attached headphones, and we created VR environments in the Unity game engine. Our interactive

Figure 4: Employing diegetic design to situate the headset, physical actions, and tangible objects in the storyworld.

audio experiences use the Wwise sound engine in N1 and Unity's built-in audio tools and interaction scripts in N2. We use online creative commons audio sources for the nature sounds in both N1 and N2. In N1 we wrote and recorded the wizard's dialogue; in N2, we layered sounds from real locations (Chile and Argentina) to create natural, contextual soundscapes.

We embedded a microphone in the tabletop to capture the touch interaction in N1, and in both N1 and N2 we attached the two wireless controllers into or onto the tangible objects (the wizard blob and water jug in N1, a green orb and grass in N2). Since we designed N2 after N1, in addition to technical improvements, the open-ended experience of N2 offers more interaction variables. The main difference in implementation between the two, however, is that in N1, interactions are dictated by controller movement, and in N2 interactions are dictated by controller placement. In N1, the type and intensity of the controller movement triggers the progression of specific narrative elements within the interaction experience. For example, the pouring interaction and the "dance" with the wizard in N1 (with the player holding the wizard blob) is captured by tracking the position and movement of the controller. In N2, the controllers both represent the presence of sound within particular zones, and are spatialized sound objects outside the zones, which become louder the closer they are to the headset (to one's ears). In N2, the interactive elements have slight animations: a floating particle effect around the zones, and a slow rustling movement for the tangibles.

We aligned the shape, size, and position of the passive physical objects (a small table in N1; a ledge and a platform in N2 made with foam, cardboard, felt, and other craft materials) to their 3D virtual counterparts. Each zone in N2 has distinct visual and aural characteristics that are designed to encourage particular kinds of movement. The green zone is represented by the tallest cylinder to draw the eye upwards toward the ledge holding the green orb. The top of the cylinder in the blue zone is only a few feet from the ground, requiring the player to kneel to interact with the objects inside. The purple empty zone has no top as a subtle suggestion that a tangible object could be brought into this zone. In contrast to N1, N2 is designed as an open-ended experience. The player can move the tangibles between zones to add and remove sound.

3.4 Evaluation

We conducted a formal user study of N2 with 5 female-identified (F) and 3 male-identified (M) participants (P), ages 20-35, recruited from the local community using flyers, university mailing lists, and by word of mouth, striving for gender parity among the participants. We chose to evaluate N2 because it iterates on N1 on a technical level and because it offers a wider array of physical interactions. The study lasted less than an hour and participants were compensated $10 for their time. Before they signed the consent form, we asked participants whether they had any concerns about VR or the study. Each participant then familiarized themselves with the technology as we explained how to put on and tighten the headset, what the boundary system would show, how to avoid tangling the cable, what to do if they felt discomfort or nausea, and that we would be nearby to help if necessary.

To establish the narrative, we told participants that they had met a wizard and were staying in his home and he left a note describing what they could do while he was away. We explained that there was no ending to the experience, that they could explore as long or as little as they liked, but we would let them know when five minutes had passed. Participants read the note and put on the headset. After the experience, we conducted semi-structured interviews to allow for a discussion about particular actions, choices, and impressions based in part on our observation of the participant (e.g., "Could you describe what you did in VR?" or, "I noticed you smiled after you touched the green object. Could you describe what that was like?"). Participants then completed a questionnaire that repeated some of the more general interview questions (e.g., "What did you like most about the experience?") to give participants a chance to expand on their comments.

3.5 Results

We coded and analyzed our observation notes, interviews, and questionnaire responses and identified four key themes using an inductive, grounded approach [41]: *senses*, in order to reflect the sensory language participants used; *experience*, in order to note what participants thought of the interactions; *expectations*, for the ways that the experience did or did not conform to participant expectations; and *physicality,* for the ways that participants moved and interacted within the narrative. In keeping with our goals and the exploratory nature of an RtD approach [7], as well as the scope of the study, we do not make claims of replicability. Indeed, the many idiosyncratic variables of our design (e.g., the narrative, sound design, tangible object design, and design of the physical space) could prohibit more generalizable findings. Our aim with this feedback is to reflect on the experiences with our narrative design and to help raise questions for future design work as well as future analytical work.

The findings will draw primarily on our qualitative data. We use quantitative data only to provide a general sense of our participants' enjoyment and experience with VR. For instance, none of the participants stated that they used VR regularly (for 3/8 it was their first time with movement-based VR), 7/8 stated that they would like to try a longer version of our narrative, and 7/8 stated that they enjoyed the experience. Since VR is relatively new to these participants, we can interpret these positive sentiments to be due to the novelty of VR rather than our work (e.g., two participants noted that they liked the grid of the boundary system, which is a default feature of the HTC Vive). We turn to our qualitative data to examine how our design choices seemed to shape the experience. Following Marshall and Tennent [28], we avoid presence questionnaires that are common in VR studies both because the experience begins before the player puts on the headset, and because presence questionnaires can assume that a "convincing" simulation is the ultimate goal.

3.6 Analysis: Interacting with the Sounds of N2

Senses: When discussing their favorite parts of the experience, participants each described sensory experiences. P1M and P2F both described using their "senses" to explore; for P3M, P4F, P6F, and P7F it was the ability to touch and interact with the tangible objects; for P5M and P8F it was the sounds of the zones. P3M summed up the experience succinctly: "The sounds were interactive—I'm still fascinated by that. Different objects did different things in different areas." For many participants the experience was described as if it could be used for relaxation, calling it "soothing" (P1M), saying that it could relieve stress (P1M, P2F), that it was "pleasant" (P2F, P3M) and "calming" (P3M, P7F). When asked about what other sounds they might like to hear in the environment, most described natural environments; for two participants (P1M, P7F), other possible sounds related to their family homes, which they said they would like to listen to when feeling nostalgic or homesick.

Experience: Predictably, given our design approach, the visuals were overall the least favorite part of the experience (6/8), either as a general comment (3/8) or because of a perceived mismatch in how near or how far away objects should be represented (3/8). Yet for two of those participants (P2F, P7F), the sounds combined with the lack of visual finesse seemed to encourage imagination. P7F said that she "visualized birds and trees" and that the sound "painted a picture, but not too much of a picture, so it left room for imagining more." P2F said that the sound objects "connected" the zones together, saying that she imagined first going to the beach (coastal zone), then walking to the lighthouse (forest zone), where she heard the sound of walking up wooden steps (which is how she interpreted the creaking sound of trees) and could hear the birds outside.

Expectations: Given that most of our participants are not regular VR users and some had never tried movement-based VR, we knew that we might have to prompt them to let them know that they could touch and pick objects up. We prompted six of the eight participants (e.g., we might say, "Didn't the wizard say something about moving the sounds around?"). Whether prompted verbally or not, there was often surprise. P1M, who was hesitant at first, later said, "The note said something about moving stuff, that I could move stuff. So, I reached out and touched the plant, and that was like—*woah*—[laughs] yeah, yeah that really surprised me. I wasn't expecting that, to be able to physically touch it." Such instances of playful surprise are a reminder that a better understanding of player expectations may contribute to design that might alternately adhere to or disrupt those expectations. For instance, after finding out that objects were interactive, P4F pulled the foam holder (a passive, non-interactive object) out of the ground and placed it elsewhere in the scene. We quietly put it back, worried that she would trip on it since it was not tracked; when she found it again, she pulled it out again, thinking it was intentional. Afterwards she said it was one of her favorite parts of the experience. As Marshall and Tennent [28] observe, there can be enjoyment even when the simulation is "broken."

Physicality: Although there is no right or wrong way to engage with an open-ended interaction, we observed a sense of hesitation for most participants: not daring to touch the environment, or if they touched it, not daring to pick anything up. A simple improvement might be to offer a variety of visual and aural affordances (e.g., a flashing glow around the tangible objects; a magical blip when it is plucked from its zone), but purely virtual improvements might never be sufficient. Although all of our participants kneeled, reached, walked, touched, grasped, etc., there was one action that we tried ourselves but that our participants did not: sitting in the carpeted zone. Asking our participants about this, P1M and P3M said that they were too engaged in moving between zones to want to sit; P5M and P7F were worried that the cable might tangle or not be long enough; and P8F was worried that the floor was dirty. What is particularly interesting is not only the variety of responses but how they each relate to the body and the physical space, suggesting a need to better engage with the interplay between physical and virtual affordances.

Consider, for example, the difference between a more experienced user and a novice user within our study. P7F, one of the few who had tried VR before said, "Having used VR before, I'm not used to being able to physically grab things with my hands, it's always with the remotes." For this participant, due to previous experience with VR, the controllers had already defined (and limited) the expected physicality and tactility of the interactions. In contrast, for P2F, who was trying VR for the first time with our experience, described VR by saying, "It's very different from other games, because of all the senses that you have involved, you can touch things, you can interact with them." With our experience as the first, she defined VR as a medium that offered the possibility of touch, an environment that can engage a range of sensory experiences. If VR is defined by the experiences it provides, how might we make those experiences begin with "all the senses"?

4 DISCUSSION

In this paper, we present a response to Marshall and Tennent's [28] call to include a deliberate consideration for sensory stimulation beyond the headset. Using an RtD approach, we focused on a sound-based narrative as a general use case, both to contrast an emphasis on visuals in VR and to learn from the rich history of interactive sound-based work. Although an RtD process can sometimes culminate in design guidelines, it is important to acknowledge not only the limitations of our user test (e.g., 8 participants, short playtimes, the use of convenience sampling), but also that generalizable outcomes are not necessarily the goal of RtD. While one opportunity for future work will be more formalized testing and implementation to assess the various forms of tangible and embodied interactions that are possible with VR, the primary contribution of this work is the documentation of our design process through the creation of N1 and N2. More specifically, we contribute a process that demonstrates the following overlapping considerations: 1) subjective benefits of beginning with the physical (rather than the virtual) using diegetic design; 2) an approach to apply design lessons from an alternative domain; and 3) preliminary themes that may inform future design and testing. In this section, we briefly expand on these considerations.

Beginning with the physical: We propose that VR design that begins with a focus on the body and the physical settings of digital interactions is a reminder that a VR experience is never purely digital. For us, prioritizing the physical helped to draw links between current VR design and prior work that considers physical-digital interactions and spaces. Rather than ask what the physical might add to VR, we asked what VR might add to a physical interaction. An advantage of looking at sound-based work was that it helped us to frame the digital as a design resource, as a way to supplement or remediate possible interactions with objects. This offered an action-oriented language to design physical interactions centered on objects (e.g., shake, remove, listen, pour, scratch, etc.), as well as a prompt to look beyond the immediacy of tangibles. For example, we also asked how we might design for physical movement within that space (walking, kneeling, reaching, sitting, etc.). This also reveals a key limitation of our design examples: they require a particular ease of mobility. We stress that the purpose of our documentation is not to endorse our subjective choices. Future work should include the option to modify actions to meet specific needs and preferences. Further, while we used narrative design as a way to structure our interactions and to explore the diegetic contours of a limited "tracked sensory simulation device" [28], this is only one application, meaning that other use cases might similarly examine how to situate and prioritize the physicality of interaction.

Alternative domains: Beginning the design process with the physical is also a reminder that other physical-digital interactions could be applicable in VR. For example, in Ishii and Ullmer's influential Tangible Bits paper [18], the ambientROOM [19] was used as an example of how sensors and other technology could be embedded in physical settings. Today, this might be accomplished with microcontrollers or RFID tags; yet, the *effect* of these systems, with physical objects and environments seemingly producing a digital output is quite similar to what a VR headset already provides. Move to a specific location in either the ambientROOM or in our proofs of concept and the player will hear birds and rain. VR changes where and how the interaction takes place, but does not need to change the physicality of the interaction. A consideration for the physicality of spaces is also a prompt to consider the varied social characteristics of spaces. For Hornecker and Buur [15], embodied interactions include an examination of how spaces afford physicality and/or interactions with others, whether in co-located or remote settings. Consider the shared familial experience in work presented by Brereton et al. [4], with the ambient communication of light to show a kettle being turned on in an elderly parent's home; or, similarly, a device that allows families to synchronously share music in homes across borders [48]. Drawing on our participants' comments about the shared sounds of home, we can envision a system that offers players a way to create, personalize, and import ambient sound, and that allows players to share these virtual worlds for both synchronous and asynchronous listening depending on personalized contexts. Our preliminary results suggest several possibilities for personalized enjoyment, ranging from exploratory to meditative engagement, based on the physical, social, and sensory qualities of the experience.

Themes for future work: The variety of physical interactions within our relatively simple installation suggest that there is a need for more analytical work to examine differences of physicality across VR design. Lab-based work could include further examinations of gesture, movement, touch (see e.g., [53]), and ethnographic studies could examine the social, physical, and everyday aspects of play (see [34], for an example of morning routines and screen use). Given the various forms of physicality in installation-based VR outside academia, there may be a need for new modes of classification, evaluation, and analysis in order to respond to recent VR experiences that are said to be "increasingly complex and participatory" [24]. Our participants' hesitations, expectations, and surprise indicate that there is an opportunity to ask what particular actions tell us about current VR design, as well as how repeated actions and experiences might come to define how VR is understood. Reflecting particularly on the themes of *expectations* and *physicality* in our user test, although Marshall and Tennent [28] primarily focus on how current conceptualizations constrain designers, it is also important to highlight how some conceptualizations can also constrain users. In their discussion of how limited and limiting computational experiences are compared to human practices that involve the body, Klemmer, Hartmann, and Takayama argue that conventional interaction design with a keyboard and mouse "homogenizes" the user into someone who looks at a screen, clicks a mouse, and types on a keyboard [26]. Comparing the novice participant in our study who saw VR as a sensory experience to the more experienced participant who saw VR as mediated by controllers, we could ask, how does current design understand (and/or how does it limit or constrain) the human body when creating physical-digital interactions in VR? Moreover, if the input mechanisms for VR become increasingly homogenous, in what ways is the user also homogenized? Such questions may help to examine the impact and implications of current conceptualizations of VR, XR, or MR. What is at stake as we develop these conceptual tools is not just how the medium is defined, but also how the user is defined by the medium.

5 CONCLUSION

In order to contribute to the development of design that engages with the body in VR, we offer two sound-based proofs of concept for narrative VR. We demonstrate linear and open-ended sound-based interactions that focus on the actions the player is asked to perform (e.g., touch, stand, kneel, grasp, walk, listen, reach, dance), demonstrating how we might conceptualize VR as a physical, embodied medium rather than rely primarily on its visual potential. The decades of sound-based interactive work that we draw on is also a call to examine how work outside VR research might be applied to VR. Doing so may provide a way for other domains to contribute to current trends in VR research and design, presenting design principles from otherwise disparate work that engages the body and incorporates physical environments.

ACKNOWLEDGMENTS

This research was undertaken, in part, thanks to funding from the Canada Research Chairs program, Canadian Foundation for Innovation, Social Sciences and Humanities Research Council, and the Ontario Ministry of Research and Innovation. We thank Alexander Verni, Jay Goldman, Roni Cantor, and Syed Gilani for their collaboration, and the students and researchers in the Synaesthetic Media Lab and the Responsive Ecologies Lab at Ryerson University for their valuable feedback.

REFERENCES

[1] Bruno 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. DOI: https://doi.org/10.1145/2839462.2839484.

[2] Peter Arnold, Rohit Ashok Khot, and Florian 'Floyd' Mueller. 2018. "You Better Eat to Survive": Exploring Cooperative Eating in Virtual Reality Games. In *Proceedings of the Twelfth International Conference on Tangible, Embedded, and Embodied Interaction* (TEI '18). ACM, New York, NY, USA, 398-408. DOI: https://doi.org/10.1145/3173225.3173238.

[3] Jeffrey Bardzell, Shaowen Bardzell, and Lone Koefoed Hansen. 2015. Immodest Proposals: Research Through Design and Knowledge. In *Proceedings of the 33rd Annual ACM Conference on Human Factors in Computing Systems* (CHI '15). Association for Computing Machinery, New York, NY, USA, 2093–2102. DOI: https://doi.org/10.1145/2702123.2702400.

[4] Margot Brereton, Alessandro Soro, Kate Vaisutis, and Paul Roe. 2015. The Messaging Kettle: Prototyping Connection over a Distance between Adult Children and Older Parents. In *Proceedings of the 33rd Annual ACM Conference on Human Factors in Computing Systems* (CHI '15). ACM, New York, NY, USA, 713-716. DOI: https://doi.org/10.1145/2702123.2702462.

[5] 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.

[6] Ella Dagan. 2018. The Cloakroom: Documentary Narratives in Embodied Installation. In *Proceedings of the Twelfth International Conference on Tangible, Embedded, and Embodied Interaction* (TEI '18). ACM, New York, NY, USA, 498-505. DOI: https://doi.org/10.1145/3173225.3173297.

[7] William Gaver. 2012. What should we expect from research through design? In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems* (CHI '12). ACM, New York, NY, USA, 937-946. DOI: https://doi.org/10.1145/2207676.2208538.

[8] Jan Gugenheimer, Evgeny Stemasov, Julian Frommel, and Enrico Rukzio. 2017. ShareVR: Enabling Co-Located Experiences for Virtual Reality between HMD and Non-HMD Users. In *Proceedings of the 2017 CHI Conference on Human Factors in Computing Systems* (CHI '17). Association for Computing Machinery, New York, NY, USA, 4021–4033. DOI: https://doi.org/10.1145/3025453.3025683.

[9] Saumya Gupta, Joshua G. Tanenbaum, and Karen Tanenbaum. 2019. Shiva's Rangoli: Tangible Storytelling through Diegetic Interfaces in Ambient Environments. In *Proceedings of the Thirteenth International Conference on Tangible, Embedded, and Embodied Interaction* (TEI '19). ACM, New York, NY, USA, 65-75. DOI: https://doi.org/10.1145/3294109.3295635.

[10] 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: https://doi.org/10.1145/2839462. 2839471.

[11] Daniel Harley, Aneesh P. Tarun, Sara Elsharawy, Alexander Verni, Tudor Tibu, Marko Bilic, Alexander Bakogeorge, and Ali Mazalek. 2019. Mobile Realities: Designing for the Medium of Smartphone-VR. In *Proceedings of the 2019 on Designing Interactive Systems Conference* (DIS '19). Association for Computing Machinery, New York, NY, USA, 1131–1144. DOI: https://doi.org/10.1145/3322276.3322341

[12] 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.

[13] Daniel Harley, Alexander Verni, Mackenzie Willis, Ashley Ng, Lucas Bozzo, and Ali Mazalek. 2018. Sensory VR: Smelling, Touching, and Eating Virtual Reality. In *Proceedings of the Twelfth International Conference on Tangible, Embedded, and Embodied Interaction* (TEI '18). ACM, New York, NY, USA, 386-397. DOI: https://doi.org/10.1145/3173225.3173241.

[14] Kristina Höök, Jeffrey Bardzell, Simon Bowen, Peter Dalsgaard, Stuart Reeves, and Annika Waern. 2015. Framing IxD knowledge. *Interactions 22*, 6 (November - December 2015), 32–36. DOI: https://doi.org/10.1145/2824892.

[15] Eva Hornecker and Jacob Buur. 2006. Getting a grip on tangible interaction: a framework on physical space and social interaction. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems* (CHI '06), Rebecca Grinter, Thomas Rodden, Paul Aoki, Ed Cutrell, Robin Jeffries, and Gary Olson (Eds.). ACM, New York, NY, USA, 437-446. DOI: http://dx.doi.org/10.1145/1124772.1124838.

[16] Mark Hauenstein and Tom Jenkins. 2004. Audio shaker. Retrieved July 30, 2019, from http://nurons.net/audioshaker/about.htm.

[17] Hiroshi Ishii, Ali Mazalek, and Jay Lee. 2001. Bottles as a minimal interface to access digital information. In CHI '01 Extended Abstracts on Human Factors in Computing Systems (CHI EA '01). ACM, New York, NY, USA, 187-188. DOI: https://doi.org/10.1145/634067.634180.

[18] Hiroshi Ishii and Brygg Ullmer. 1997. Tangible bits: towards seamless interfaces between people, bits and atoms. In *Proceedings of the ACM SIGCHI Conference on Human factors in computing systems* (CHI '97). ACM, New York, NY, USA, 234-241. DOI: http://dx.doi.org/10.1145/258549.258715.

[19] Hiroshi Ishii, Craig Wisneski, Scott Brave, Andrew Dahley, Matt Gorbet, Brygg Ullmer, and Paul Yarin. 1998. ambientROOM: integrating ambient media with architectural space. In CHI 98 Conference Summary on Human Factors in Computing Systems (CHI '98). ACM, New York, NY, USA, 173-174. DOI: http://dx.doi.org/10.1145/286498.286652.

[20] Sergi Jordà, Günter Geiger, Marcos Alonso, and Martin Kaltenbrunner. 2007. The reacTable: exploring the synergy between live music performance and tabletop tangible interfaces. In *Proceedings of the 1st international conference on Tangible and embedded interaction* (TEI '07). ACM, New York, NY, USA, 139-146. DOI: http://dx.doi.org/10.1145/1226969.1226998.

[21] Sergi Jordà, Martin Kaltenbrunner, Günter Geiger, and Marcos Alonso. 2006. The reacTable: a tangible tabletop musical instrument and collaborative workbench. In ACM SIGGRAPH 2006 Sketches (SIGGRAPH '06). ACM, New York, NY, USA, Article 91. DOI: https://doi.org/10.1145/ 1179849.1179963.

[22] Sungchul Jung, Gerd Bruder, Pamela J. Wisniewski, Christian Sandor, and Charles E. Hughes. 2018. Over My Hand: Using a Personalized Hand in VR to Improve Object Size Estimation, Body Ownership, and Presence. In *Proceedings of the Symposium on Spatial User Interaction* (SUI '18). ACM, New York, NY, USA, 60-68. DOI: https://doi.org/10.1145/3267782.3267920.

[23] Martin Kaltenbrunner. 2006. Tangible Musical Interfaces. Retrieved July 25, 2020 from https://modin.yuri.at/tangibles/.

[24] Helen Kennedy and Sarah Atkinson. 2018. Virtual Humanity: empathy, embodiment and disorientation in humanitarian VR experience design. *In Refractory: A Journal of Entertainment Media.* 30, 2 (July 2018). Retrieved July 25, 2020 from https://refractory-journal.com/30-kennedy-atkinson/

[25] Kickstarter. 2012. Oculus Rift: Step into the Game. Retrieved July 25, 2020 from https://www.kickstarter.com/projects/1523379957/oculus-rift-step-into-the-game.

[26] Scott R. Klemmer, Björn Hartmann, and Leila Takayama. 2006. How bodies matter: five themes for interaction design. In Proceedings of the 6th conference on Designing Interactive systems (DIS '06). ACM, New York, NY, USA, 140-149. DOI: https://doi.org/10.1145/1142405.1142429.

[27] Joe Marshall, Steve Benford, Richard Byrne, and Paul Tennent. 2019. Sensory Alignment in Immersive Entertainment. In *Proceedings of the 2019 CHI Conference on Human Factors in Computing Systems* (CHI '19). Association for Computing Machinery, New York, NY, USA, Paper 700, 1–13. DOI: https://doi.org/10.1145/3290605.3300930.

[28] Joe Marshall and Paul Tennent. 2019. The Limitations of Reality. In *Proceedings of the Halfway to the Future Symposium 2019* (HTTF 2019). Association

for Computing Machinery, New York, NY, USA, Article 31, 1–4. DOI: https://doi.org/10.1145/3363384.3363475

[29] Heather McKinnon and Marcus Foth. 2017. The work of making: reflections on the process, form and function of two sets of design research artefacts. In *Proceedings of the 29th Australian Conference on Computer-Human Interaction* (OZCHI '17). Association for Computing Machinery, New York, NY, USA, 191–200. DOI: https://doi.org/10.1145/3152771.3152792.

[30] David Merrill, Hayes Raffle, and Roberto Aimi. 2008. The sound of touch: physical manipulation of digital sound. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems* (CHI '08). ACM, New York, NY, USA, 739-742. DOI: https://doi.org/10.1145/1357054.1357171.

[31] Paul Milgram and Fumio Kishino, 1994. A taxonomy of mixed reality visual displays, IEICE TRANSACTIONS on Information and Systems 77, 12 (1994), 1321 – 1329.

[32] Matti Niinimaki. 2009. Beat Blender. Retrieved July 25, 2020 from https://mansteri.com/works/beat-blender/.

[33] Joseph A. Paradiso, Kai-yuh Hsiao, and Ari Benbasat. 2001. Tangible music interfaces using passive magnetic tags. In *Proceedings of the 2001 conference on New interfaces for musical expression* (NIME '01). National University of Singapore, Singapore, 1-4.

[34] Sarah Pink, Camille Santiago Caminha, Angelica Porto C. de Souza, Renata Zilse, and Alex Sandro Gomes. 2017. Design Ethnography for Screenless Interaction Style: hands-on and no-hands in early morning routines. In *Proceedings of the XVI Brazilian Symposium on Human Factors in Computing Systems (IHC 2017)*. Association for Computing Machinery, New York, NY, USA, Article 20, 1–10. DOI: https://doi.org/10.1145/3160504.3160524.

[35] Mirjana Prpa, Kıvanç Tatar, Jules Françoise, Bernhard Riecke, Thecla Schiphorst, and Philippe Pasquier. 2018. Attending to Breath: Exploring How the Cues in a Virtual Environment Guide the Attention to Breath and Shape the Quality of Experience to Support Mindfulness. In *Proceedings of the 2018 Designing Interactive Systems Conference* (DIS '18). ACM, New York, NY, USA, 71-84. DOI: https://doi.org/10.1145/3196709.3196765.

[36] Jens Reinhardt, Eike Lewandowski, and Katrin Wolf. 2019. Build your Own!: Open-Source VR Shoes for Unity3D. In *Proceedings of the 10th Augmented Human International Conference 2019* (AH2019). ACM, New York, NY, USA, Article 45, 2 pages. DOI: https://doi.org/10.1145/3311823.3311852.

[37] Pejman Sajjadi, Edgar Omar Cebolledo Gutierrez, Sandra Trullemans, and Olga De Troyer. 2014. Maze commander: a collaborative asynchronous game using the oculus rift & the sifteo cubes. *In Proceedings of the first ACM SIGCHI annual symposium on Computer-human interaction in play* (CHI PLAY '14). Association for Computing Machinery, New York, NY, USA, 227–236. DOI: https://doi.org/10.1145/2658537.2658690.

[38] Bert Schiettecatte and Jean Vanderdonckt. 2008. AudioCubes: a distributed cube tangible interface based on interaction range for sound design. In *Proceedings of the 2nd international conference on Tangible and embedded interaction* (TEI '08). ACM, New York, NY, USA, 3-10. DOI: http://dx.doi.org/10.1145/1347390.1347394.

[39] Stefania Serfain, Cumhur Erkut, Juraj Kojs, Niels C. Nilsson, and Rolf Nordhal, 2016. Virtual Reality Musical Instruments: State of the Art, Design Principles, and Future Directions. Computer Music Journal, 40, 3, 22-40.

[40] Orit Shaer and Eva Hornecker. 2010. Tangible User Interfaces. Now Publishers Inc., Hanover, MA, USA.

[41] Anselm Strauss and Juliet Corbin. 1990. Basics of qualitative research: Grounded theory procedures and techniques. Thousand Oaks, CA: Sage.

[42] Ivan E. Sutherland. 1965. The ultimate display. In *Proceedings of the Congress of the International Federation of Information Processing* (IFIP), 506–508. http://doi.org/10.1109/MC.2005.274.

[43] Ivan E. Sutherland. 1968. A head-mounted three dimensional display. In *Proceedings of the December 9-11, 1968, fall joint computer conference, part I* (AFIPS '68 (Fall, part I)). ACM, New York, NY, USA, 757-764. DOI: https://doi.org/10.1145/1476589.1476686.

[44] Karen Tanenbaum, Joshua Tanenbaum, Alissa N. Antle, Jim Bizzocchi, Magy Seif el-Nasr, and Marek Hatala. 2010. Experiencing the reading glove. In *Proceedings of the fifth international conference on Tangible, embedded, and embodied interaction* (TEI '11). ACM, New York, NY, USA, 137-144. DOI: http://dx.doi.org/10.1145/1935701.1935728.

[45] Paul Tennent, Joe Marshall, Patrick Brundell, Brendan Walker, and Steve Benford. 2019. Abstract Machines: Overlaying Virtual Worlds on Physical Rides. In *Proceedings of the 2019 CHI Conference on Human Factors in Computing Systems* (CHI '19). ACM, New York, NY, USA, Paper 581, 12 pages. DOI: https://doi.org/10.1145/3290605.3300811.

[46] 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.

[47] Paul Tennent, Joe Marshall, Vasiliki Tsaknaki, Charles Windlin, Kristina Höök, and Miquel Alfaras. 2020. Soma Design and Sensory Misalignment. In *Proceedings of the 2020 CHI Conference on Human Factors in Computing Systems* (CHI '20). Association for Computing Machinery, New York, NY, USA, 1–12. DOI: https://doi.org/10.1145/3313831.3376812.

[48] Javier Tibau, Michael Stewart, Steve Harrison, and Deborah Tatar. 2019. FamilySong: Designing to Enable Music for Connection and Culture in Internationally Distributed Families. In *Proceedings of the 2019 on Designing Interactive Systems Conference* (DIS '19). ACM, New York, NY, USA, 785-798. DOI: https://doi.org/10.1145/3322276.3322279.

[49] Tanh Quang Tran, HyunJu Shin, Wolfgang Stuerzlinger, and JungHyun Han. 2017. Effects of virtual arm representations on interaction in virtual environments. In *Proceedings of the 23rd ACM Symposium on Virtual Reality Software and Technology* (VRST '17). ACM, New York, NY, USA, Article 40, 9 pages. DOI: https://doi.org/10.1145/3139131.3139149.

[50] Eric Whitmire, Hrvoje Benko, Christian Holz, Eyal Ofek, and Mike Sinclair. 2018. Haptic Revolver: Touch, Shear, Texture, and Shape Rendering on a Reconfigurable Virtual Reality Controller. In *Proceedings of the 2018 CHI Conference on Human Factors in Computing Systems* (CHI '18). ACM, New York, NY, USA, Paper 86, 12 pages. DOI: https://doi.org/10.1145/3173574.3173660.

[51] Shunki Yamashita, Ryota Ishida, Arihide Takahashi, Hsueh-Han Wu, Hironori Mitake, and Shoichi Hasegawa. 2018. Gum-Gum Shooting: Inducing a Sense of Arm Elongation via Forearm Skin-stretch and the Change in the Center of Gravity. In *Proceedings of the Virtual Reality International Conference - Laval Virtual* (VRIC '18). ACM, New York, NY, USA, Article 21, 3 pages. DOI: https://doi.org/10.1145/3234253.3234310.

[52] Yaying Zhang, Bernhard E. Riecke, Thecla Schiphorst, and Carman Neustaedter. 2019. Perch to Fly: Embodied Virtual Reality Flying Locomotion with a Flexible Perching Stance. In *Proceedings of the 2019 on Designing Interactive Systems Conference* (DIS '19). ACM, New York, NY, USA, 253-264. DOI: https://doi.org/10.1145/3322276.3322357.

[53] Zhuoming Zhou, Elena Márquez Segura, Jared Duval, Michael John, and Katherine Isbister. 2019. Astaire: A Collaborative Mixed Reality Dance Game for Collocated Players. In *Proceedings of the Annual Symposium on Computer-Human Interaction in Play* (CHI PLAY '19). Association for Computing Machinery, New York, NY, USA, 5–18. DOI: https://doi.org/10.1145/3311350.3347152.

[54] Thomas G. Zimmerman, Jaron Lanier, Chuck Blanchard, Steve Bryson, and Young Harvill. 1986. A hand gesture interface device. In *Proceedings of the SIGCHI/GI Conference on Human Factors in Computing Systems and Graphics Interface* (CHI '87), John M. Carroll and Peter P. Tanner (Eds.). ACM, New York, NY, USA, 189-192. DOI: https://doi.org/10.1145/29933.275628.