VRBox: A Virtual Reality Augmented Sandbox for Immersive Playfulness, Creativity and Exploration

Thomas Fröhlich
Digital Media Lab, TZI
University of Bremen
Bremen, Germany
tfr@uni-bremen.de

Dmitry Alexandrovsky
Digital Media Lab, TZI
University of Bremen
Bremen, Germany
dimidi@uni-bremen.de

Timo Stabbert
University of Bremen
Bremen, Germany
stabbert@uni-bremen.de

Tanja Döring
Digital Media Lab, TZI
University of Bremen
Bremen, Germany
doering@uni-bremen.de

Rainer Malaka
Digital Media Lab, TZI
University of Bremen
Bremen, Germany
malaka@uni-bremen.de

ABSTRACT

Augmented sandboxes have been used as playful and educational tools to create, explore and understand complex models. However, current solutions lack interactive capabilities, missing more immersive experiences such as exploring the sand landscape from a first person perspective. We extend the interaction space of augmented sandboxes into virtual reality (VR) to offer a VR-environment that contains a landscape, which the user designs via interacting with real sand while wearing a virtual reality head-mounted display (HMD). In this paper, we present our current VR-sandbox system consisting of a box with sand, triple Kinect depth sensing, a virtual reality HMD, and hand tracking, as well as an interactive world simulation use case for exploration and evaluation. Our work explores the important and timely topics how to integrate rich haptic interaction with natural materials into VR and how to track and present real physical materials in VR. In a qualitative evaluation with nine experts from computer graphics, game design, and didactics we identified potentials, limitations as well as future application scenarios.

CCS Concepts

•**Human-centered computing** → **Virtual reality; Empirical studies in interaction design;**

Author Keywords

Augmented sandbox; virtual reality; gestural interaction; playful interaction; natural materials for interaction; tangible interaction.

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Figure 1. VRBox from first person perspective. The landscape can be shaped by interacting with real sand.

INTRODUCTION

Playing with sand is something most people relate to from childhood days, where this unstructured play gave room for experimentation, exploration, or cooperation. As children we develop important skills in the sandbox like proprioceptive sensing, body and space awareness, or social skills and can engage in creative behavior and open-ended play [16]. These fond memories last a lifetime and, when given the opportunity, many adults enjoy playing with sand and rediscovering the sensations of this activity.

Interactive and augmented sandboxes offer these kind of experiences but further add an interactive element to the sand, which allows for increased interaction and application possibilities. Here, people can play with the sand, making use of their natural ways of expression while at the same time perceiving interactive visual feedback that is projected onto the sand. Through these visuals, changes of the sand's surface can be immediately experienced and reacted upon to. In the literature, there is a considerable body of research that has explored augmented sandboxes and its tangible affordances (e.g., [26, 24, 2, 8, 25]). In many application scenarios, sandboxes have been applied to offer a better understanding of spatial and geographical phenomena [13, 22], or to experience the terrain

playfully [25, 8, 2]. Most setups use a projector mounted above the sandbox, projecting an image on the surface of the sand and a depth camera for tracking the sand's shape. For example, Reed et. al's project on heat map-like coloring of the sand to indicate different types of landscapes [24].

While setups like these already offer a nice direct interaction with sand as natural material to change the visual output, we move a step further and integrate real sand interaction into virtual environments (VEs) with mid-air gestural interaction. This offers new ways to use and explore the sand landscape, such as by placing virtual objects into the scene or by teleporting oneself into the shaped environment. Moreover, our work explores the important and timely topics how to integrate rich haptic interactions into VR and how to track and present real physical materials in VR.

In this paper, we present *VRBox*, an interactive sandbox for playful and immersive terraforming that combines the approach of augmented sandboxes with modern Virtual Reality technology and mid-air gestures. The system extends the existing approaches with an additional interaction and visualization layer to interact with the sand and virtual objects. Furthermore, in *VRBox* users can switch perspectives from a tabletop mode into a first person mode by teleporting directly into the own creation, allowing for an immersive experience of the landscape in full-size. We provide technical details of the construction as well as releasing all material and source code to the public. Furthermore, we evaluated *VRBox* in a qualitative user study with nine experts from computer graphics, education, and game design. The evaluation focused on questions regarding the user experience, technical aspects, and possible application use cases. In particular, we were interested in exploring research questions such as:

- Is Virtual Reality a suited extension for sandbox interaction?
- Is free hand interaction beneficial considering the discrepancy of visual and tactile experience?
- Can first-person experiences like teleporting into the 3D world increase immersion and user experience?
- How do users rate the playful and creative aspects of *VRBox*?
- Can the sand surface be visually abstracted (e.g. block world) without compromising user experience?

Our results show a very positive attitude towards *VRBox*, highlighting the immersive and creative experience that the system offers due to the novel first person experience and extended interaction capabilities using virtual objects in VR. We contribute application scenarios in productive and entertainment contexts such as gaming and collaboration.

RELATED WORK

In 1997 Ishii and Ullmer envisioned to use the affordances of physical objects and to bring them together with digital technology as part of tangible user interfaces [14]. Since then, natural materials have also been explored as part of interactive systems (c.f. the material probe study on natural elements as

interaction materials by Häkklä et al. [10]). These natural materials are used because they naturally offer rich multimodal feedback, come along with deeper meanings and often provide emotional associations. Moreover, the natural qualities of these materials have the potential to define, guide and constraint the interaction, such as in ephemeral user interfaces [9] that last for a limited time only or change over time, depending on the properties of the materials used for interaction. In our setting, we use sand as natural element that comes along with great properties for sculpting and shaping, affords moving the hands through and often naturally triggers associations of playfulness, creativity, exploration and early childhood.

Real sand or similar material as interaction material has been used in several applications and installations. In 2002, Piper, Ratti, and Ishii presented their *Illuminating Clay* system for the analysis of landscapes in the landscape design process [22]. Their system consists of a clay model that users manipulate, a laser scanner for capturing of depth information, and a projector that closes the feedback loop for visualization of different landscape analysis functions. The authors point out the simplicity and effectiveness of displaying 3D data directly onto the surface of a 3D model. *Sand Garden* [24] is a game, where a digital landscape must be shaped, providing valleys, water, and mountains in order to make the virtual villagers happy. The system uses a projection and a second screen to display the game world. The sand itself is augmented and functions as a controller for the game. An educative use case for augmented sandboxes is presented by Sanchez et al. [26], engaging students to experiment with topographical maps exploring importance of water, erosion, or mountains in the evolution of the landscape. The advantages are the better understanding of abstract concepts, better involvement, and more efficiently experimentation using a sand model. *Inner Garden* by Sol Roo et al. [25] is a tool to support mindfulness practices, which is defined as "the act of playing a deliberate and non-judgmental attention to the present moment" where "positive impact of a person's health and subjective well-being" can be achieved. Users create a miniature world by playing with the sand and the natural elements of the world are connected to physiological measurements like respiration, helping to stay focused on the body. This system also offers a VR mode where users can explore their creation virtually. Another interesting use case has been developed by Audi [1] where users can first form their own racing track in a not augmented sandbox. The resulting race track is then imported into a VR driving simulator, offering direct perception of the user's creation by driving through the digital model. However, no direct interaction with the sand in VR is supported. To the best of our knowledge there is no augmented sandbox setup, in which users can directly interact with physical sand in virtual reality.

Among the rare example works that have explored integrating the interaction with natural materials in VR is a system by Pier and Goldberg [21], in which users can directly interact with water in VR. The authors conclude that water is an extremely immersive medium that fosters curiosity and children-like play. The experience of real sand around the feet while wearing a VR head-mounted display has been recently explored by [11], who created a multi-sensory VR environment in which users

are in a beach scenario. The authors advocate to incorporate non digital sensory experiences in virtual reality, on the one hand expanding the design space of virtual environments and on the other allowing users to adjust the virtual environments at their taste. Nevertheless, they do not use the sand for interaction in VR.

Some other works investigated how to realize interaction with physical objects in VR and how physical or tangible interaction impacts the immersion. For example, Hoffman investigated in a comparative study how users anticipate the physical qualities of objects in VR when subjects can physically touch the objects [12]. The results of the study show that participants could better anticipate the physical properties of the objects in VR and also the sense of presence was enhanced. TurkDeck [6] uses human controlled walls to provide haptic feedback to a subject that navigates through a environment in VR. The authors found out that, when physical walls are present in VR, the enjoyment and the sense of realism is raised.

In our work, we provide a novel approach for the integration and presentation of a physical sand landscape in real time in VR, thus providing novel haptic feedback experiences. Furthermore, we combine this with a teleporting feature in order to allow the exploration of the self-designed landscape from a macro-perspective. For exploring small architectural models at scale in VR, a similar approach has recently been applied by MacroScope [27]. In this system, a wide-angle camera is placed on a tabletop and captures objects that are placed on the table. The camera streams the image directly to a HMD, allowing users to experience the table top setting from the perspective of the camera. Oasis [28] and Kintinuous [15] are systems that use a Google Tango or a Kinect respectively first to record a 3D environment and then to allow users to navigate through it in VR. Sra and colleagues [28] implemented in their system Oasis object tracking and detection of walkable areas. Using these techniques, the system allows for virtual world generation, where the shape and the boundaries of the physical space are remapped to different visual styles.

In our work, we combine real sandboxes with VR interaction and thus provide a novel and original system that explores natural physical materials in VR, gestural interaction and teleporting in a terraforming use case.

PROTOTYPE

Setup

The box has a volume of $140 \times 80 \times 30$ cm. The ground and the inner walls are covered with pond foil and an additional layer of non-reflective cloth. This size provides a good balance for single user as well as for collaborative scenarios in the future. When working with sand (especially with wet sand) there can be occlusions in the surface structure that one single sensor cannot recognize. Therefore, to minimize occlusion of the user we use three Kinect v1 sensors that are mounted on a railing at a height of 120 cm above the sand surface. The tracking volume is captured from three angles of an isosceles triangle reconstructing of a full 3D point cloud of the sand model. For virtual reality, an HTC Vive¹ is used, opening the opportunity

¹<https://www.vive.com/>

Figure 2. The VRBox system. The Box is filled with sand for the interaction (see also Figure 4).

to track additional objects. To enhance the immersion, a Leap Motion² sensor, attached to the HMD, provides information about the hand and arm positions of the users. The application runs on a Windows 10 System with an Intel i7 3,4 GHz and 16 GB of RAM.

Volume Tracking and Calibration

The system is implemented as a client-server architecture. The server application captures the depth images from the Kinect devices at 30fps and sends them, after preprocessing, to the VR application (client) via UDP. Figure 2 shows an overview of the incorporated components.

To fuse the Kinect sensors, the relative orientation of each depth camera was computed using OpenCV [29, 3]. In the next step, the point cloud data is generated using the Kinect Fusion toolkit³. The fused point cloud has a resolution of $512 \times 512 \times 256$ points. The VR environment is implemented in Unity3D⁴. We designed a 3D model of the sandbox as a reference for the calibration between the sandbox and the head mounted display. To match the positions of the real and the virtual sandbox, all components need to be calibrated precisely. We calibrate the position of the sandbox relative to the Vive tracking system by placing a Vive controller on the sandbox, so the virtual representation of the interaction environment matches. To provide a satisfying VR experience, it is crucial, that the application runs at a steady frame rate of 60 fps. Hence, we had to accept some compromises about the level of detail of the terrain. In the VR application the terrain is represented in a blocky Minecraft[18] like style on a 98×59 mesh with 32 height levels. This resolution provides a good compromise between level of detail and latency. To avoid the hands being mapped on to the terrain, we added a threshold at the top rim of the box. Everything above the rim is ignored by the Kinect sensors and the area underneath the

²<https://www.leapmotion.com>

³<https://msdn.microsoft.com/en-us/library/dn188670.aspx>

⁴<https://unity3d.com>

Figure 3. A user performs a pinch gesture for spawning objects.

hands is marked as occluded. To increase performance the terrain is split into chunks of 8 by 8 blocks. Only those blocks, that have been occluded (by the hands) for a duration of at least 6 frames (100 ms) are updated. Since the incoming point cloud stream from the depth sensors is noisy, to avoid jittering, the height of each block is updated gradually at a rate of 10 Hz. When a new height value for a block is provided by the sensors, the block is repositioned to that value, which takes up to 200 ms. The total latency from the moment the sand was formed, until the changes are visualized in VR accounts 1.5 - 2 seconds. On top of the tracked terrain the hands provided by the Leap Motion are rendered.

The Terraforming Use Case

Our use case is a terraforming task where users form a 3D world of their liking with the sand and extend their creation by adding a water level to create rivers and other waters, add different lighting moods and decoration objects like trees, flowers, and castles.

In VR, users see the virtual representation of the tracked sand-box and sand surface and form a terrain with their bare hands. Furthermore, they can interact with virtual menu using their hands. The menu items are placed to the left and right of the user in VR and are represented as bubbles that users can interact with using their hands, see Figure 5. The bubbles serve different functions. First, a set of them can be used to decorate the sand surface with virtual objects like trees, castles, and other assets. These can be used in the sense of a pouring glass, where users grab a bubble using a pinch gesture (see Figure 3) (e.g. containing a tree asset) and "pour" the trees onto the sand surface, see Figure 4. Single objects can also be placed in the same way where we concentrated on a small set of items that can be put onto the sand individually. On the left side of the user, one bubble can be used to manipulate the water level in the form of a vertical slider. Another bubble serves as a teleport item. Users can grab the teleport bubble and put it on the sand surface to mark the location where they would like to be teleported to. Then, users have to perform a "look up" gesture where they have to look up straight in order to perform the teleport. When the head reaches the highest point,

Figure 4. Spawning trees into the 3D world using the pinch gesture.

<i>Id</i>	<i>Field of work</i>	<i>Exp. in VR</i>	<i>Sex</i>
P1	CG researcher / developer	Yes	Male
P2	3D environment artist	Yes	Female
P3	VR researcher / developer	Yes	Male
P4	CG researcher / developer	Yes	Male
P5	CG/VR researcher / developer	Yes	Male
P6	Game designer	Yes	Male
P7	Game designer	Yes	Male
P8	Education/Social worker	No	Male
P9	HCI researcher	Yes	Male

Table 1. Summary of participant backgrounds

the teleport is performed and when looking down, users see from a first person perspective, standing directly in the virtual world. Looking up again teleports back into tabletop mode. Further, a delete bubble and lighting bubbles (create sunset or sunrise) were implemented.

USER STUDY

In order to evaluate *VRBox*, we conducted a qualitative user study with nine experts from computer graphics (4), education (1), game design (3) and HCI (1). We chose these areas to gather feedback from a technical perspective and from two relevant application areas that we envision to profit from such a technology. All participants were between 30 and 50 minutes in VR. On average, the subjects formed terrains for 20 minutes and explored the environment from first person perspective for 10 minutes.

In the following, we introduce our nine participants in more detail. P1 works as a computer graphics (CG) researcher working on collision detection and development with the Unreal engine where he creates virtual testbeds for various research projects in the context of VR. P2 is a 3D environment artist working on in a local game studio where she models various types of 3D assets and environments. P3 works as a researcher developing tools for VR in relation to semantic support in the operating room. P4 is a researcher in CG working on collision detection. P5 is also a researcher with a CG background and game developer working on VR and multi user VR environments and telepresence. P6 is a game designer with a local game studio working on gameplay and the development of game mechanics. P7 is a game designer creating virtual environments and levels for a racing simulation in a local

Figure 5. View on the VR menu. On the left are the decoration objects. On the right, the teleporter, delete, light, and water level controls.

game studio, working on the topic since 2011. P8 is a special needs teacher for mathematics and biology currently working in youth welfare services. Participant 9 is an HCI researcher in the area of educational user interfaces and a hobbyist game developer. Our participants are between 20 and 39 years of age, with eight males and one female subject. The demographics are summarized in Table 1.

Procedure

We tried to keep the humidity and form stability of the sand as constant as possible. Therefore, before each interview day, the sand was watered with 1.5 to 2.0 liter. The sand was then stirred up, so that the sand could soak in the water. We prepared the sand by smoothing the surface in order to provide a "blank canvas" for each participant. After a general introduction, participants were introduced to the system, explaining the overall functions of the system including the use of VR and Leap based hand tracking. We pointed out and demonstrated that for optimal hand tracking the hands should always be in front of the user so that they can be seen by the Leap sensor. After this, we started the tracking systems and again smoothed the surface. We assisted in putting on the VR headset and made sure that hand tracking worked as expected. While wearing the headset, we asked to try to form the sand surface building hills and valleys in order to get a better feeling for the system. After up to five minutes, we introduced the virtual controls next to the sandbox.

Users were now asked to create an environment of their liking, again introducing the different tools and interaction possibilities. The task was to at least create one hill or mountain, one water body and one lowland area. Further, users should add a lighting mood of their choice and place some virtual objects into the scene order to extend their creation.

After the scene had been created, we took various screenshots of the result from the following perspectives: exterior view in VR, exterior view of the *VRBox*, and insight view in VR (could be multiple). In the next step, users filled in the System Usability Scale (SUS) questionnaire [4] and subsequently performed the interview as the last part of the study.

Interview

As we were interested in evaluating technical aspects and the possible application areas learning and design, we structured the interview in three parts: general questions, technical aspects, and application. In the general questions we asked what was especially fun about using the system, and which motivational aspects users anticipate for using the system. Also, we were interested how users perceived the teleporting into their own creation and how they felt about it, if users could think of other ways of placing objects and adjusting the light, what other features they felt missing in order to extend it as a creative platform, and if they thought that *VRBox* supported creativity in a playful way. We also asked which playful aspects of the system were generally appreciated, and if the users thought that using *VRBox* more creative results could be achieved compared to existing software solutions (e.g. Cities Skylines [7], Minecraft [18]).

In relation to the technical aspects, we asked how users evaluated the discrepancy between the direct haptic sensation when working with the sand and the decoupled visual feedback, how users perceived the visual representation and resolution of the block world, and what they thought about the time lag in refreshing the block world. Further, we were interested in the perception of sand as a material for the task and what alternatives users could envision, which kind of tools users were missing analog to sand box toys, and how tangible user interfaces could be integrated and used in *VRBox*. For the latter, we introduced the concept of tangibles in the form of videos and examples based on the research of Ishii and others (c.f. [14]).

Regarding the application scenarios, we asked what application scenarios users could envision for *VRBox*, how *VRBox* could be used as a game element of core game mechanic or another application, which kinds of creative use cases users perceived as possible, and if they could think of using *VRBox* as an educational tool. We were interested if users could think of using *VRBox* in a productive context (e.g. planning tool or design tool for game worlds), how multiple users could interact with the system, and also asked for general feedback of what was especially positive or negative about interacting with *VRBox*.

RESULTS

To analyze the interview results, we first collected the answers and distributed them to the three main categories General Comments, Technical Aspects (e.g., Usability and Tools), and Application Scenarios. Then we summarized similar answers in order to reduce the amount of statements. In the next step, we scanned the answers for emerging topics beside the ones that we defined for the interview. We identified Playfulness, Creativity, and Material as emerging categories. Thus, we distributed the accumulated answers into the categories *General Comments*, *UX and Usability*, *Tools and Useful Extensions*, *Application Scenarios*, *Sand as Material*, *Playfulness* and *Creativity*. In the following, we present the results along these categories.

Figure 6. Two resulting 3D worlds (top row and bottom row) from our user study. On the left are the first-person views and on the right the tabletop views of the respective models.

General Comments

We asked what our participants generally perceived as fun. The answers include exploration (P1), working with the sand (P2, P5, P8), visualization in VR (P2, P3), innovativeness (P3), teleporting (P4), immersion (P4), and decoration (P6, P8). One participant mentioned that through the 3D representation he didn't feel like working with actual sand (P6). P9 noted the advantage of having a sense of scale. Critique was expressed regarding the tracking accuracy, that the deco tools disappear too fast, and that the placement of individual objects was too difficult (P1).

Concerning reasons that motivate people to use *VRBox*, we found creative application (P1, P2), relaxation (P1), self expression (P2), playfulness (P2, P7), ease of use compared to traditional tools (P2, P9), manual crafting (P3, P8), absence of any peripherals (P3), quick prototyping (P4, P9), and the use of the inner perspective (teleporting, P4, P7). Further mentioned were visualization capabilities (P5), the colorful, interactive style and versatile use (P6), the novelty (P7, P8), and sense of scale (P9).

We asked specifically how the participants perceived the teleporting as a core mechanic. The answers highlight the easy to use activation gesture (P1, P3, P5), and found, that the function adds value (P2), is exciting and provides a nice feeling to "being in" the own creation (P3, P5, P8), that it is engaging to be more involved in creating a world (P4, P6, P8), that it worked well and it's a powerful, moving, and thrilling feeling

(P5). P6 commented that it would add value to include more details (P6), that tunnels and walking options would increase the experience. Improvements could be done by overcoming some clipping issues (P7), and one participant felt insecure about the function and had a dim feeling about it, but was still curious (P7). P5 highlighted the higher immersion compared to AR sandboxes.

P9 stated that it is really interesting to create something and then see it from a first-person perspective almost immediately in 3D and that users get a really good understanding of the space (which is the biggest limitation with modeling in 2D). In his opinion, *VRBox* makes 3D modeling a lot easier because with traditional systems, there are a lot more iterations on assessing the 3D scale and how the environment feels when being in there.

VRBox could be an alternative to real models (P2) and one comment highlighted the transient property as beneficial (P6). P3 said that it would be interesting to compare *VRBox* to current terrain generation techniques. The Minecraft [18] like look was appreciated (P1), while the menu too far away (P1), the box was too small (P2), and sound could be added for a stronger sense of immersion (P2). P3 mentioned that *VRBox* is an interesting work with a lot of potential. P4 said the systems is pleasing and intuitive.

UX and Usability

Data regarding UX and usability aspects were gathered with the SUS questionnaire and by open interview questions that

targeted technical aspects, which may negatively affect the immersion and the workflow.

On the SUS scale, the participants rated *VRBox* in the top quartile with $\mu = 78.6$ and $\sigma = 9.45$. Interestingly, P8, who has never tried out VR before is rather an outlier (z -value = 2.23) with a SUS-score of 57.5. The other participants, who are more familiar with game design and computer science rated the setup with an average score of 82.5, with ranging values from 70 up to 85.

All participants perceived the scanning resolution as grainy (P7) allowing to capture "big differences" while small details get lost (P4), and wished for a higher resolution of the terrain. The level of detail was nevertheless well accepted as "part of the rules" (P7) and did not disturb the immersion (P2, P3, P4, P5, P7, P8), some even highlighting the usefulness of the abstraction for improved imagination (P8). P3 said that without the decorations the displacement is negligible but the virtual objects cause a discrepancy, because they cannot be touched. P7 and P9 noticed a discrepancy, but it wasn't an obstacle and that they relied on the visual feedback than on the tactile sensation. Quite often, the subjects noticed glitches or artifacts when the tracking system falsely interprets the user's hands as part of the terrain (P1, P3, P4, P6). The latency of the terrain updates was perceived by P3, P5, and P9 as critical. Particularly P3 felt latency more important than the level of detail. The other subjects found the delay acceptable. P6 and P4 didn't realize much delay or were used to it from other applications (P1). P4 said: "When you are in the process of moving it, it doesn't bother that much." However, P1 pointed out, that when working with the sandbox regularly, the latency can become tedious. P9 noted that the hands were in the way and that he felt a disconnection between the sand and the display, missing a one to one relationship.

Tools and Useful Extensions

Most subjects thought of physical tools to help them shape the sand, such as shovels, rakes, and molds (P1, P3, P5, P6, P7, P8, P9). P1 and P2 imagined virtual tools for water sources or extended UI elements. Options for colors adjustments and adding night scenes, moon, stars, and clouds would be beneficial (P2, P4, P5). Tangible objects could be used as points of interest or in-game objects like spawn points, water sources or physics simulations (P1, P3, P5, P6, P7, P8). Additionally, they can be placed as modifiers to shape the surface of the terrain like spline curves (P2). P1 proposed a control panel at the edge of the sandbox, and P9 imagined a tip-jar metaphor.

Generally, the pouring metaphor for object placement was accepted (P1, P2, P3, P4). Alternatively, objects could be placed with the hands (P3, P4) or with scattering or sprinkling gestures (P1). It was criticized that the placement lacks precision (P2, P3, P4, P5, P6, P7) and that undo/redo or re-placing weren't implemented. Options such as spawn radius adjustment, object scale, color, and different spawn area shapes were proposed. Similarly, subjects P1-P6 and P9 asked for more control over the light settings, including color, direction, and intensity. P3 also suggested a sun object, that can be placed in the scene as a main source of light.

Application Scenarios

All participants suggested either prototyping, landscape modeling, or city planning as main application scenarios. The system could also be used as an installation in museums or festivals (P6). *VRBox* could be integrated in the content creation pipeline in game design (P1), for idea generation, architecture visualization, and presentation in general (P4). P1 states that *VRBox* is not ready for production due to the low accuracy, and P6 saw it more as a toy than a tool.

For games, *VRBox* could be used in simulations and planning games (P5, P6), physics simulations, table tops (P5), exergames (using the weight of the sand, P1), tower defense (P1, P9), or god games (like Black&White [20] P1, P5). Multi user scenarios include co-op and player vs. player games (P1, P2, P3, P4, P5, P6, P8) with synchronous playing using multiple HMDs or distributed playing (external devices). Co-op was suggested with one user modeling and the other acting on the game play (P1, P6, P8) or giving instructions from outside (P7). Here, co-presence visualization would be needed (P5, P6). City planning simulations, landscape shaping (P2, P8), game world and map creation, 3D paintings, and Zen garden games have further been proposed (P1).

Furthermore, participants mentioned general application in education (P4, P6, P7), weather and climate simulation (P1, P2, P9), city transport simulation, agriculture planning (P1, P2), urban and rural infrastructure (P1), terrain modeling (P2), tech and science teaching (P2, P3), and 3D modeling (P3). Also, teaching physical and mechanical principles (P4, P8), creativity support in education (P6), art classes (P6), experiments and creativity (P2), relaxation and mind wandering (P1) were mentioned.

Sand as Material

All participants agreed that for the use case of terraforming sand is an appropriate material, especially because it is well-known from playing with (regular) sandboxes (P1). P2 and P6 found it too dirty. P3 mentioned, that sharp edges were difficult to create with sand, and he recommended using a denser material. P6 suggested to use kinetic sand, as it brings more robustness to the forms. But he also admitted that it is costly. P8 added that clay could be added for models that are impossible to form with sand.

Playfulness

P1 stated a disconnection between tactile and visual resolution and an indirect visual perception which makes *VRBox* not playful. Working with the hands made P2 feel like in childhood days, but the participant also stated that the menu interaction disconnected her from the immersion. Teleporting was playful for P4 while modeling was particularly nice for P5. Object placement was very good to bring the world to life. P6 was unsure about playful characteristics and stated, more detail would be better and more interaction could be added. Decoration and the interactivity using the own body was playful for P7 and creating an own scene was a huge attraction.

Creativity

All nine participants agreed that *VRBox* playfully supports creativity. P1 was ambivalent if a beautified or plain model

supports imagination and thus creativity better. Simultaneous modeling in the physical and virtual medium is a creative factor for P2 and P8 because it provides power and supports playful experimentation. *VRBox* enables art creation by facilitating manual work without peripherals, and VR adds unlimited possibilities to extend creations (P3). The model creation is translated to something more using visuals and applying force increases the liveliness and fun (P4). Similar models could be created in 3D tools but *VRBox* is more interactive, fun, and playful. P5 said that a lot of things can be created and there is no pre-determination of results. Users can decide what world they want to be in as a major factor for creativity. *VRBox* would be useful for kids and younger people as modeling is a form of creative expression (P6). The spatial perception is supported by modeling landscape (P7).

P1 says that *VRBox* offers more creative results than standard applications and that sand interaction is something more than building a landscape in block by block. P2 states an increased freedom using the own hands and no peripherals, a good connection to the task without learning an interface, and the very low learning curve. In line, P8 mentions the direct access to the many parameters of the model, and the benefit of direct connection between action and result. *VRBox* is faster than traditional modeling and useful for non-technical people like artists compared to Blender and the like, enabling 3D content creation for everyone (P3). P4 was unsure if *VRBox* is more fun or if *VRBox* stimulates creativity. P5 was unsure if *VRBox* is more creative because of VR itself, and task dependency. P7 highlights creativity because of immersion and the many possibilities. P9 denied creativity because of the limitations of what can be modeling with sand.

DISCUSSION

In the following subsections, we discuss the accumulated interview data related to our research questions.

VR as an Extension for Sandbox Interaction

The use of VR in combination with a sandbox was well received by our participants and there is supporting evidence that this combination works well and adds benefit to the technology. In this sense, our participants positively emphasized the overall visualization capabilities that VR offers, teleporting and inner perspective, higher immersion, sense of scale and presence, found it engaging to be more involved in the own creation, stressed that VR offers a good understanding of space and location (also objects in relation to each other), and pointed out that VR adds unlimited possibilities to extend the own creations. Based on these finding, we are confident that VR is a beneficial extension to augmented sandboxes, considering our group of participants, being mainly familiar with VR applications.

Free-Hand Interaction and Visual/Tactile Discrepancy

The free hand interaction itself was perceived ambiguously. We noted several comments about the Leap sensor losing the tracking, disorientation issues of the hand model, and the problem of keeping the hands in the field of view while rotating the body. On the positive side, our free hand interaction

metaphors were received well. Participants positively mentioned the pouring-style interaction for object spawning using the bubbles and the absence of peripherals. From this we conclude that free hand interaction is beneficial for interacting in VR with a physical medium like sand. However, technical challenges have to be overcome regarding hand tracking, posture recognition and stability. For other prototypes and systems, more powerful hand tracking systems can be used that do not have these limitations that the Leap sensor and Leap development kit have.

Regarding the discrepancy between the tactile sensation and visual perception, we also received mixed feedback. There are two technical components to this issue. First, the sensing of the sand surface and second the visualization in block style. From the user perspective, we received statements that it "feels right", that there is no big difference, the discrepancy is there but negligible/wasn't in the way, and perceived as part of the rules. On the other hand, users told that it didn't feel like working with actual sand, that tracking accuracy is low, that there are glitches, and that the visualization should look more like sand. Overall, most of the users were mostly satisfied with the experience of seeing virtual objects that resemble a large but not complete part of their tactile sensation. We conclude that this can be improved but was not a problem in our case.

First-Person Experience for Immersive Feeling

Being able to teleport into the own creation and having the sense of "being" there was perceived as one of the most appealing features of *VRBox*. We collected a large variety of supportive statements. According to the participants, the function adds value, is exciting, engaging, powerful, moving, provides immersion, provides a good understanding of the own creation, and is a thrilling experience. One participant felt insecure in the beginning, but then also said that he was still curious about the function. After overcoming some minor technical issues like clipping, this feature adds great value to augmented sandboxes and is very well perceived due to the immersive characteristic.

Playfulness and Creativity

We found different playful aspects in our study. Working with the sand as in childhood days was mentioned several times, the teleporting feature, object placement, bringing the world to life, and that using the own body were perceived playful. For one participant the disconnection between visual and tactile made *VRBox* less playful. As there are mainly positive attributions for playfulness, we assess *VRBox* as a playful environment. Regarding creativity, all participants agreed that *VRBox* supports creative expression. The reasons were different: beautification, modeling of sand, endless possibilities, no predetermination, expressiveness, freedom, and low learning curve. We collected a lot of positive feedback regarding the creative capabilities and assess that with *VRBox*, users feel creative.

Visualization and Visual Abstraction of the Sand Surface

On the positive side, the block world look was generally appreciated, it was perceived as colorful, the level of abstraction was well accepted, "fits well", was pleasant, did not interfere

with the immersion and provided a good abstraction of the sand. It was further stated that a visual approximation of the details can lead to a more free expression compared to very high detail. However, participants also mentioned that a higher resolution would be better. From this we conclude that the overall block style is suitable for this kind of use case and people tend to like it, also because due to Minecraft, they are already used to it. However, more detail could be added by increasing the resolution of the blocks, keeping the overall style while increasing the detail.

Limitations

In general, all participants showed a positive attitude towards *VRBox*. However, the sample size and composition of our participants needs to be considered when interpreting our findings. With only one female participant, there is a high gender bias in our study results, which needs to be considered in future work. Further, most participants are working in computer science related fields and have prior experience with VR, having a natural tendency towards the acceptance of new technology. P8, which is the only non-technical participant with an educational background was more critical about the setup and rated the system much lower on the SUS scale. This is a finding which requires further investigation in future studies, because with *VRBox* we aim to support explorative learning, which should center around providing a positive user experience and usability for novice users in order to support the learning experience. Thus, the selection of participants should focus more on those users and also on users of the respective target groups, depending on the implementation (in our case for example students and teachers for the terraforming use case). One limitation regarding the interaction is a missing locomotion feature. Having the option to move through the virtual environment from a first-person perspective would increase the immersive and explorative capabilities of the system even more and will be integrated for future studies.

CONCLUSIONS AND FUTURE WORK

In this paper we presented the setup and implementation of *VRBox*, an augmented real sandbox that is used in a VR environment and combined with gesture interaction. With this prototype, we explored the integration of rich haptic interaction with natural materials into virtual reality and present a solution for tracking and presenting real physical materials in VR. We evaluated our system in a qualitative expert study with nine participants and found strong support for our assumption that VR increases the immersive and exploratory aspects of augmented sandboxes, leading to high levels of self-perceived creativity and playfulness. We further contribute application scenarios and possible use cases in gaming and 3D modeling. *VRBox* will be made public as an open source project in order to facilitate further development and replication as we see high potential in our system.

We conclude that VR is a very beneficial addition to augmented sandboxes and supports immersion, participation, and control. Using free hand interaction, users can rely on their natural ways of expression without having to interact through hardware. There is a discrepancy between the tactile sensation and the visual appearance, especially because of the blocky

world style. However, as our results show, users are very positive regarding this aspect and can adapt well to a little offset between what they feel and what they see. Further, the creative capabilities of our system have been highly appreciated, making it a useful tool for different kinds of tasks like modeling and gaming.

Future work will include improvements in the tracking quality and visualization detail by adding higher resolution modes, more robust hand tracking, and increased locomotion features where users can move through the virtual world more freely. For example, a flying mode or teleporting features could be implemented as well as other, more immersive locomotion options such as magical or body-centric variants, as presented by [19]. Besides the technical and interaction aspects, we plan to further explore creative and playful application scenarios and research cognitive boundaries of redirected haptics. For application scenarios we build upon our findings as a starting point and plan to develop advanced modes for terrain design and also for sculpting where an interesting area of research could investigate how to restore previously modeled structures by augmenting the visualization with a translucent “ghost” model for fast and easy re-modeling. Regarding the redirection of haptics, which is the “*warped mapping between the real and virtual worlds, such that the relation between the user and the virtual space can be different from the one between the user and the real space*” [5]. With redirected haptics, virtual worlds can be experienced in a different way than the actual real-world model. For example, virtual worlds can be experienced to be much larger than the actual model or the effort of moving the arms across the model could be reduced. This can be achieved by warping the virtual dimensions so that users don’t recognize the differences, which represents an interesting line of research [5, 17, 23].

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