TactileVR: Integrating Physical Toys into Learn and Play Virtual Reality Experiences

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Figure 1: In TactileVR the user puts on a virtual reality headset, and interacts with virtual objects and toys, proxies of physical objects. The objects serve as the building blocks of the VR experience as well as means of interacting with it.

Abstract

We present TactileVR, a proof-of-concept virtual reality system in which a user is free to move around and interact with physical objects and toys, which are represented in the virtual world. By integrating tracking information from the head, hands and feet of the user, as well as the objects, we infer complex gestures and interactions such as shaking a toy, rotating a steering wheel, or clapping your hands. We create educational and recreational experiences for kids, which promote exploration and discovery, while feeling intuitive and safe. In each experience objects have a unique appearance and behavior e.g. in an *electric circuits lab* toy blocks serve as switches, batteries and light bulbs.

We conducted a user study with children ages $5-11$, who experienced TactileVR and interacted with virtual proxies of physical objects. Children took instantly to the TactileVR environment, intuitively discovered a variety of interactions, and completed tasks faster than with non-tactile virtual objects. Moreover, the presence of physical toys created the opportunity for collaborative play, even when only some of the kids were using a VR headset.

Index Terms: H.5.1 [Multimedia Information Systems]: Artificial, augmented and virtual realities—; H.5.2 [User Interfaces]: Interaction Style—; I.3.7 [3-D Graphics]: Virtual Reality—

1 Introduction

Virtual Reality is an immersive experience which simulates physical presence in a real or imagined place, by definition a sensory experience which may encompass any or all of our senses. *Sight* comes first, with solutions ranging from large stereoscopic displays to head mounted displays (HMD). *Sound* is added via speakers or a headset, often manipulated and virtually placed in 3-dimensional space.

Touch is often depicted as the sense which cannot be deceived [4], it is how we convince ourselves a thing is real. As Margaret Atwood writes in 'The Blind Assassin': "Touch comes before sight, before speech. It is the first language and the last, and it always tells the truth". Touch is also how we separate ourselves from the world, "where touch begins, we are". Moreover, holding an implement extends our sense of self, encompassing the tool. As we physically wield it our perception of reality changes and we see tool-dependent affordances everywhere (e.g. hammer and nails proverbial quote).

From birth, the sense of touch is fostered in infants. Tactile toys are used to teach toddlers about different materials and textures, and how to interact with common objects (e.g. zippers, buttons, knobs). In school tactile implements are used to study subjects such as math and physics.

We found children a tough audience for VR: they have little patience for technical difficulties, they don't like wearing uncomfortable accessories, and they want to run around and engage with the world and with other children. Current solutions for haptics, the field of recreating the sense of touch, have their limitations: gloves, tactile surfaces, hand gestures and ultrasonic blasts of air (see related work) are often too abstract in feel or too cumbersome for children, who prefer unmediated interaction with the objects around them.

TactileVR creates an immersive intuitive VR experience for kids. In a TactileVR scenario a child is able to walk around freely in a virtual world (limited by room size), see his virtual hands and feet and other participants, and can interact with the virtual world by touching and playing with simple and familiar, everyday objects (figure 1). The real and physical nature of the system means that everyone can join in, both kids with a VR headset and those without.

We built a prototype by equipping a large room with a motion tracking system. For each participant, we tracked the position and orientation of her head-mounted VR device, as well as her hands and feet using a small set of reflective markers. A large set of soft colorful blocks, toy cars and other simple objects are also tracked. We created a set of recreational and educational scenarios for children to experience. All scenarios can be explored and interacted with by moving, shaking, throwing, kicking, rotating, and tapping

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the tactile objects.

We conducted a pilot study, followed by an extensive (and very noisy) user study with 11 kids ages $5-11$. The kids were introduced to VR in a classic setting (seated with a controller), and were then shown the TactileVR lab. Each of them performed a set of tasks, both with tactile objects and virtual ones. The children also experienced the scenarios, discovering for themselves the different interactions possible. We measured the kids performance on the tasks, and conducted extensive interviews with them.

Our contributions are: (1) An easy to implement and relatively low-cost, haptic feedback system (2) A novel way of using natural interactions with simple objects to drive complex VR simulations (3) A study of how children interact with virtual worlds, and the importance of self-locomotion and haptic feedback to their sense of comfort and confidence.

The paper is organized as follows: We first discuss research in haptics, as well as virtual and augmented reality research, especially as it pertains to child education. We then discuss the technical details of our system, its physical components, and its software stack. Following is a detailed account of our pilot study, user study and their analysis. Finally we discuss our contributions and plans for future work.

2 Related Work

Our work is informed by theories about the sense of touch and its role in sense of self, memory and education. A good overview of the sense of touch, its physiological and neurological basis can be found in [4]. They cover in detail topics such as tactile perceptual organization, tactile attention, the social aspects of touch and technologies of touch (including virtual reality). Embodied cognition offers us new ways to think about bodies, mind and technology [9]. When a person holds a tool his sense of self extends to absorb the end-point of the tool [10].

Minogue et al [12] explore the advantages of "hands on" education, and ask whether one can know something more completely by touching it. They present a user study with young children who were asked to feel different objects, and then attempt to reconstruct which objects they handled. Children had distinctly better success with familiar objects and shapes. Zacharia et al [21] study how physicality (actual and active touch of concrete material) is a necessity for science experimentation level at the kindergarten level. Hamze-Lip et al [5] discuss how the current generation of children are immersed and fluent in technology and benefit from integrating more advanced forms of education.

There are many approaches for haptics in virtual and augmented reality. [11] describes ultrasonic and electrostatic surface haptic devices which can create tactile perceptions of surface features or textures. A similar approach was implemented on friction-based touch displays in [8]. Aireal [18] is a haptic technology which delivers tactile sensations in free air, without requiring the user to wear a physical device. Early and ongoing efforts have focused on creating haptic gloves [2] which react when the user reaches for a virtual object.

In 1996, MIT Media lab demo'd KidsRoom [1], vision-based tracking, and projection were used to create an educational interactive and collaborative experience for children. Roussos et al [15] presented NICE, a CAVE like environment where kids used wands to participate in an interactive simulation of a garden. Interaction was intuitive, such that to water a plant, one would drag a cloud over. A precursor to our approach, a study by Hoffman [6], divided users into two groups: one picked up virtual objects using a wand controller, while the other group handled physical objects, tracked and recreated in the virtual world. The study demonstrated the effectiveness of tactile augmentation as a technique for adding texture and force feedback cues to virtual objects. Along those veins, an experimental game by Spina-Caza [19] used simple wooden shapes to interact with a video game, where the shapes were recreated. Simeone et al [17] present a study on modeling virtual environments based on real ones. They focus on the mismatch between virtual and physical objects, and how it affects user experience. Our approach to haptics does not require the user to wear any physical device, it is able to employ various tracking system (e.g. vision-based or marker-based as used in this paper), and thus allows easy integration of nearly any object into the virtual world. Moreover, we use the physical objects, not only for haptic feedback, but as controllers, and to drive interaction with VR.

RoomAlive [7] is a projection-mapped experience which takes into account room geometry to create interactive games. The user can interact with virtual objects and creatures physically e.g. stepping on a virtual bug. However, they do not integrate physical objects, but use gestures and controllers to interact. A recent demo [3] shows a crafted VR experience in which users explore an ancient tomb, holding a torch (which exists in the virtual world). Our work differs by offering dynamic experiences which change with the presence of different tactile objects in the room, and offer a variety of interaction modalities with each object.

3 Design and Implementation

The TactileVR prototype was constructed in a $40'$ by $20'$ room, equipped with a twelve camera OptiTrack Prime 13 system [14]. The OptiTrack is able to detect multiple rigid bodies with high precision and high frame rate ($240 fps$). We equipped several Oculus Rift DK2 headsets [13]) with reflective spheres placed on a fixed rod structure. Each headset is defined as a unique rigid body in OptiTrack, for positional and orientation (6DOF) tracking. Additional sphere markers (in a fixed configuration) were attached to wearable bands (to be worn on hands and legs). Finally, reflective spheres were glued and sewn onto large soft playing blocks (and other toys), identifying each one as a unique rigid body. The different components of the system are shown in figure 2.

OptiTrack collects the signals from all cameras, and calculates the position and orientation of each rigid body in a global coordinate system. We calibrate the system to align the geometry of the room to the global coordinate system. The TactileVR framework receives this data and updates the position and orientation of each object's virtual proxy. We also experimented with reflective tape and stickers on the blocks (instead of spheres) to better maintain their overall shape. However, as children handle the blocks quite aggressively, they tend to occlude them from most of the OptiTrack cameras. The spheres, protruding from the edges of the blocks, are more visible (for multiple cameras) and therefore provide more reliable tracking. Each block required a unique configuration of reflective spheres, so as to avoid confusing between them. We found that $5-7$ spheres were the minimum required for each block. The headsets in particular require accurate tracking and a high frame rate to avoid motion sickness. To achieve this goal, we combined the rotation data from the IMU and the XYZ position from the OptiTrack system. Moreover, we adjust the internal drifting of the IMU every 60 frames with the rotation data provided by the HMD. Users of our system experienced no nausea, even after using it for 40 minutes or more.

Each object and its virtual proxy are identified by a unique ID assigned by OptiTrack. The appearance of the proxy in the virtual world changes from a replica of the object's original appearance, to scenario-driven models and behaviors (figure 3). The hands and feet of the user are represented by cartoon-like hands and feet, or by a complete humanoid model whose position is calculated using inverse kinematics.

3.1 Detecting Gestures and Object Interactions

The TactileVR framework keeps track of multiple users and objects co-located in a single room as **entities**. The users are repre-

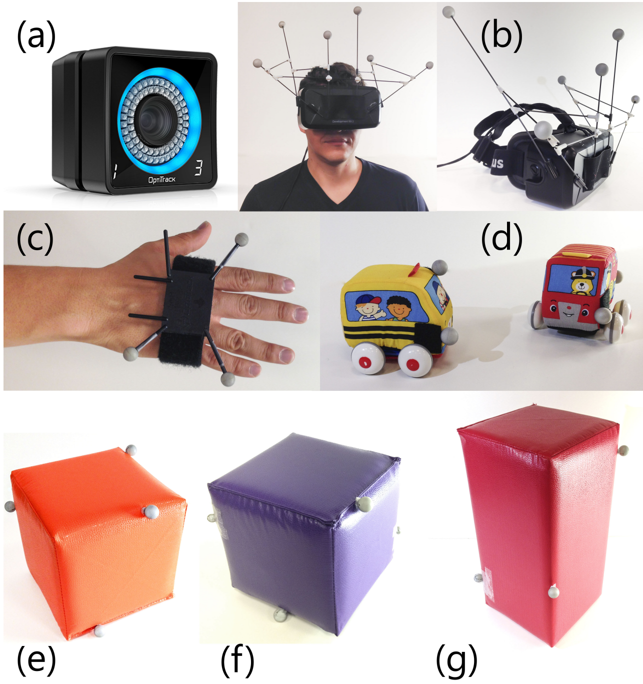

Figure 2: TactileVR Setup: (a) An array of twelve OptiTrack Prime 13 cameras track (b) A head mounted VR display (c) Hand and feet trackers (d-g) A set of colorful blocks and other toys.

sented as $u_1,..u_n$. The hands and feet of user u_i are represented as $u_i^{lh}, u_i^{rh}, u_i^{lf}, u_i^{rf}$ (left and right, hands and feet respectively). The physical objects (toys) are represented as $o_1,...o_m$. Each entity contains two properties derived from OptiTrack: position (as a 3-dimensional vector) and rotation (as a quaternion).

We define derivative properties based on each entity's base properties and its relation to other entities. For example *o.hfloor* is the height of object *o* above the calibrated floor of the room. *o.dlhand* is the distance of the object's center to the user's left hand. *o.velocity* is a 3-dimensional vector defined by the change in the object's position over time (the magnitude of the vector is the object's current speed).

The TactileVR framework was implemented in Unity [20], whose terminology we use to describe our system. Each object in the game is a *GameObject* and is updated each *frame* (whose frequency depends on the host device). In each frame the game is rendered to the output device (screen or HMD). Each object contains base properties (such as those described above) and has basic behavior, and is often customized and extended using scripts. We customize TactileVR objects by attaching interaction modalities (IM) to them, these behaviors become a persistent aspect of an object, with access to its properties over time. Each IM can add properties to an object, and trigger events in the scenario.

For example the **shake** IM triggers an event whenever user u_i picks up the object and shakes it vigorously. It maintains a queue of the object's position, where during the update of each frame we add a value to the queue (with a maximal queue size). Each frame we apply principal component analysis to the values in the queue. If the first component is significantly larger than the other two (motion was mostly along one axis), and multiple zero-crossings occurred (i.e. a user was moving the object back and forth) we trigger an event $held(u_i, o_j, lhand, rhand)$. The **tap** IM triggers an event when a user touches an object o_j with some force. It monitors the velocity of the hands of user u_i when they are in close proximity to o_j. At the moment of presumed contact a $tap(u_i, o_j)$ is triggered.

Figure 3: Each physical object is tracked and represented as a proxy in the virtual world, The proxy's appearance and functionality can change depending on the scenario. As shown here (from top left and in clockwise direction): A block can be pair of binoculars, a house in a quiet village, an exact replica of the real block or the component of an electrical circuit.

The **held** IM checks the distance to a user's hands, and dependent on the physical size of the object determines whether the user is currently holding the object, and whether it is with one hand or both. Similarly, the **binoculars** IM checks whether a user is holding the object in both hands and has it in front of the HMD. The **portal** IM tests whether a user is holding the object in both hands at which time it triggers a *portal:opened* event which causes a virtual opening to appear in the scene, close to the user. Once the user steps through the portal a *portal:crossed* event is triggered. The **stacked** IM maintains for each object to which it is attached, a list of other TactileVR objects which are currently stacked on top or below it.

Each scenario designed for TactileVR assigns one or more IM's to each object which is actively used in that scenario. Interaction modalities can be attached at design time or added dynamically as the scenario progresses and objects are added and removed from the room. The properties and flags raised by each object trigger changes and game-play events.

3.2 Game Design and Scenarios

To demonstrate the efficacy of our system and explore different interaction modalities we implemented different scenarios. Each scenario uses a different combination of tactile objects, with different IM's and has a different theme.

3.2.1 Virtual Toy Room

The initial scenario of TactileVR is a virtual toy room (figure 4), whose dimensions match the physical room. In this scenario the physical blocks are used as a game selection menu. Blocks are rendered as a glowing transparent block within which exists a miniature world, similar to the scenario to which it leads. Picking up the block the child can peek within, and by shaking it, be transported into the selected game. This scenario serves as an introduction to TactileVR, where users can move freely about the environment and interact with the virtual proxies of the toys and other physical objects.

3.2.2 Mushroom Land

An exploration scenario, in Mushroom Land (figure 5) the child is a giant placed over a tiny village. The houses in the village are proxies of real blocks, and change (e.g. from farm house to town house)

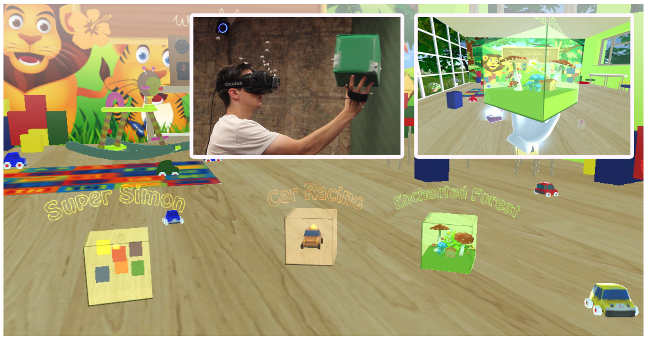

Figure 4: In the virtual toy room scenario, blocks serve as gateways to different games and applications. A user can pick up a block, and shake it to start a new experience.

when shaken (**shake** IM). As the houses are placed on the ground life springs around them in the form of trees, street signs and small people who live in them. When stacking (**stacked** IM) houses together, larger multi-storied apartments form. Other blocks appear as tools which the child uses to affect the virtual environment. Some affect the weather (shake to make it snow or rain), one is a bomb (which when thrown and hits the ground, blows up its virtual surroundings). Within one transparent block, a pair of binoculars float. When the child holds them up to his eyes, the view changes and he can see the stars[1]. Another box is full of seeds which the child can plant. Mechanical toys, such as wind-up cars were also incorporated into this experience, fitting with the village motif.

3.2.3 Electric Circuits

In this scenario, the center of the room is dominated by a virtual carpet with a diagram of an electric circuit (figure 6), with missing components. Several of the physical blocks appear as transparent cubes with the missing components floating within. The children learn about the basics of electricity, the conventions of electrical circuit diagrams, and must place the missing components in the right places. Each component is attached the **target** behavior, which raises a *matched* boolean flag when the object touches its target. As the correct physical components are put in place the circuit closes and begins to work, e.g. a light bulb lights up, an engine starts running.

3.2.4 Race Car

In this scenario (figure 7) the child builds a race track and drives a virtual car on it. Several of the blocks serve as **keypoints** (control points of a closed spline), through which a race track is dynamically created. As the child moves the blocks around, the race track is altered dynamically. One block appears as a steering wheel, floating in a transparent cube. This object has the **rotation** IM attached to it, and as the user picks it up and rotates it, a virtual car starts up, controlled by the user.

4 User Study

In this section we describe our pilot study and the comprehensive user study we designed to validate the following research questions with focus on the first two:

1. Do children prefer interacting with physical objects
2. Does handling physical objects improve accuracy and speed

[1]Note that when holding the binoculars, the environment is occluded. We employ a proximity based renderer which superimposes a wireframe model of obstacles near the user in this mode, similar to the Valve chaperone system.

(a)
(b)
(c)
(d)
(e)

Figure 5: (a) Mushroom land is an exploratory scenario with many different interactions, you can: (b) shake a house to change its appearance or stack it (c) plant seeds from a box and grow new trees (d) shake a weather cube to make it snow (e) raise binoculars to your eyes and see the galaxy.

3. How engaged and curious are children within virtual reality scenarios

Since the study deals with young kids, we wanted to make sure that they felt safe and did not experience any type of discomfort [16]. Moreover we wanted to have their parents involved, and in control. Prior to conducting the study we consulted with the legal and ethics body (in our organization) dealing with user studies. Every participant in the study was accompanied by his parents at all times. The parents signed a consent form and were encouraged to try VR and TactileVR for themselves. The children were given time to familiarize themselves with the system, and were asked every couple of minutes whether they wanted to take the headset off, rest for a few minutes, and whether they were feeling ok. It should be noted that none of the participants experienced discomfort while using TactileVR. Note that the reflective spheres used in the current

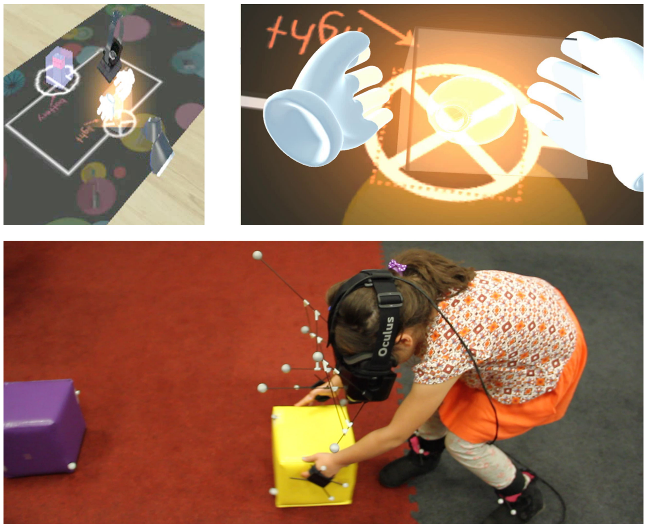

Figure 6: In **Electric Circuits** the child must place missing electrical components on a virtual circuit board. In this simple example the light bulb and battery were missing.

version of the system are attached to the HMD via rigid plastic rods which pose a slight safety risk, and are to be eliminated in future versions of the system. In the meanwhile each child was assigned an adult chaperone.

4.1 Pilot Study

We invited a group of kids to visit our lab on different occasions. The pilot group consisted of a 7 year old female who visited three times over two weeks. A 5 year old female (two times) and an 8 year old male (one time). We monitored and recorded their behaviors, task performance, comments and enjoyment using the system. After trying out the system, we asked the children about their experience and thoughts. We also asked about possible improvements of the overall experience and asked about future scenarios they would like to interact with.

During the pilot study we observed technical issues which were due to the physical size of the kids. Having short arms, they were holding the objects much closer to the HMD than adults which required adjusting the near plane in the rendering pipeline, and modifying the behavior scripts to account for their shorter arms. Due to their slight frame we also needed to adjust the reflective spheres setup on the HMD.

Each child in the pilot study engaged in the following VR setups and scenarios

Figure 7: In the race car scenario, blocks act as keypoints between which a dynamic race track is created. The user holds a block, acting as a steering wheel, and drives a car along the tracks.

- Wearing a VR headset, seated, with a game controller, experiencing one of several off the shelf VR experiences.
- Wearing a VR headset, tracked in the TactileVR lab, experiencing our scenarios (mainly **Mushroom Land**).
- As above but wearing hand and feet trackers.

We observed each child, and conducted interviews with them about their impressions, their comfort using the system, and how they would improve it. Based on the answers we got in the pilot study we made improvements and designed the formal user study.

4.2 Formal Study Design

Eleven children ages $5-11$ with a mean of 8.5 participated in the study. Six of them were boys and five were girls. We observed their behaviors, activities, play types, attention, and engagement. We monitored sessions and recorded videos to code behaviors and summarize activities after the study. Each child's session was $45-60$ minutes. In addition, we gave each child a five minute introduction to virtual reality and the equipment they were about to use. During the session, the children engaged in the following tasks (not all children experienced **Task 0**):

- **Task 0**: Wearing a VR headset, seated, with a game controller, experiencing a *non tactile* version of **Mushroom Land**. Movement is controlled by the left joystick, the child can look around, and can "'shake"' houses by looking at them and pressing the 'x' button.
- **Task 1**: In this task and all the following, the child wore a tracked VR headset, and hand and feet trackers in the TactileVR lab. The child had to interact with four virtual blocks (no physical counterparts), and transfer them (by virtually grasping them) to designated targets on the floor. When the child closed his hands (virtually) around a block, the virtual block was attached to a point p between his hands, moving with the child. When the child separated his hands to the extent of $3cm$ from the block, it detached from his hands, and was again subject to the virtual world's physics system. Note that the designated targets on the floor were marked in different colors (matching the cubes) and contained a dotted white square signifying the center of the target. Identical targets were used in task 2. See figure 8(a)
- **Task 2**: The child interacted with four physical blocks (and their virtual proxies), transferring them to designated targets on the floor. Each physical block was tracked and its virtual proxy (of the same size, shape and color) was fixed to its position and orientation. See figure 8(b)
- **Task 3**: The child interacted with four physical blocks, building a stable tower. See figure 8(c)
- **Task 4**: Free exploration, each child had 20 minutes to play in the different scenarios including Mushroom Land, Race Track, Electric Circuit and Darts.

4.3 Results

Eight of the children engaged in **Task 0**, a "classic" VR setup. Six of these had no prior experience with VR. We interviewed the children about their impressions of VR and how they felt. Five of the eight children felt nauseous after a few minutes with the headset claiming "I'm car sick" and "I feel a little queasy". Overall the children enjoyed looking around virtual world but said that "I wish I could get closer to the houses" and "It's hard to point at the houses".

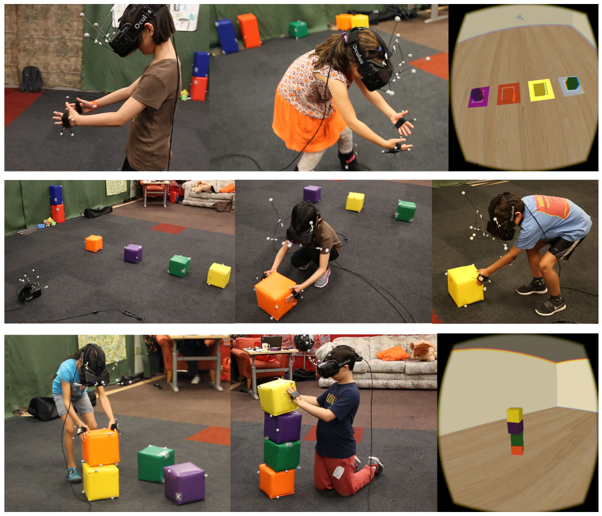

Figure 8: (a) **Task 1:** Children must grasp virtual blocks and arrange them on targets (shown on right). (b) **Task 2:** Children arrange tactile blocks on targets. (c) **Task 3:** Children stack tactile blocks (virtual results shown on right).

Before each task, each child was given time to experiment and interact with the objects .For tasks 1 and 2 we timed the children, and measured the accuracy they achieved when placing the blocks (tactile or virtual) within the targets. Accuracy was measured as percentage of each block's intersection with the dotted white square in each target (figure 8(a) right). The average accuracy for task 1 (non-tactile) was 25% with average of 61 seconds to complete. The average accuracy for task 2 (tactile) was 72% with average of 32 seconds to complete. The results are plotted as accuracy vs. total time in figure 9. Note that we applied a counterbalancing technique with tasks 1 and 2, where the order of these tasks was switched for half of the kids.

All children did well in task 3, and managed to stack at least four blocks in a stable manner in under 40 seconds. Most of the children spontaneously grabbed more blocks and added them to the tower.

In task 4 the children experimented with the various scenarios. We designed the scenarios to engage kids in the VR experience so we could analyze their behavior, and test different interaction techniques with different motivations (e.g. exploration, learning, control). We monitored the interaction modalities the participants experimented with. We offered advice if asked, but mostly sat back and observed. In the **Mushroom Land** scenario each child engaged (on average) in 4.5 interactions out of possible 7 (binoculars, change the weather, plant Seeds, saw trees, exploding bomb, shake houses to switch them and stacking houses).

We interviewed the children, after each of the tasks $1-3$, and after the exploration part (task 4). When asked about task 1 children said "Its like holding air", "When it was the real cubes it was easy to play, but when I couldn't feel them it was... so-so". Regarding task 2 they said "...its more simple because you can feel it now". Children did not express fatigue and said "I didn't feel tired at all, can I play again?". We also asked what worlds they would make up if they could turn the objects into anything. We got highly excited responses and interesting ideas on how to proceed such as "I loved moving the houses around, I wish I could touch the people", "Can you do a Candyland world?", "Maybe a science world? where you can do experiments and be scientists". Children especially enjoyed the **Electric Circuits** and **Mushroom Land** where they could most affect the environment. We asked each child to score each of the following aspects of the TactileVR environment from 1 to 10: how

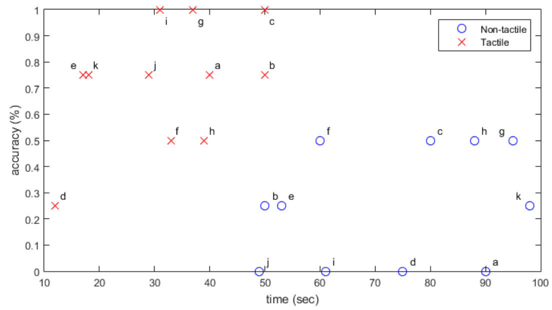

Figure 9: In tasks 1 and 2 we measured time and accuracy as the children were asked to take blocks (virtual and later tactile) and place them on targets in the virtual world. In the figure accuracy is plotted vs. time required, where o's mark non-tactile (virtual) blocks and x's are tactile blocks. The label next to each data point signifies the child ID in the user study.

engaging is the tactile interaction, how easy was it to learn how to play with the system, how fatigued did the child feel after playing, and overall how they enjoyed themselves. Starting out we asked the children for these scores after every task, but they found it hard to differentiate and so we had a conversation with them after each task, and collected scores for all tasks together.

The mean satisfaction with the system was $8.7/10$. We summarized the mean responses (and std-dev) of the children for the four questions in figure 10. Please refer to the user study video submitted as supplementary material to this paper, as it contains reactions and behaviors which were hard to translate to text.

4.4 Discussion

Based on our observations and interviews we noted some fundamental insights:

- Children with no prior experience in VR (almost all of them) dived right into it with no hesitation and within a few moments were running around and stretching the limits (of the system and of the physical cable). Their confidence seems to be related to both the ability to physically touch the various elements in the virtual world, as well as being able to walk around the environment.

- The children seemed to have a much lower bar (than adults) for accepting and embracing new forms of interaction. In fact the carefree and even rough way children handled the TactileVR objects surprised us. Children threw the toys around, stomped on them and squeezed the life out of them. It became clear that any controls integrated into a VR simulation intended for kids need to be highly child-proof. On the other hand, adults who have tried our system, took a much longer adjustment period before starting to walk around and reach out for the physical objects, to trust the system.

- The combination of accurate tracking, free motion and physical feedback from the environment and the tactile objects contributed to a mostly nausea free experience for all kids, including those who tend to get car sick.

- When children play, often everyday objects become something else in their imagination: A pillow case becomes a cape, a milk carton becomes a spaceship. TactileVR creates a physical manifestation for this creative process. We saw this most evidently in the spontaneous multiplayer behavior which emerged. Even when only one child had a VR headset on, the

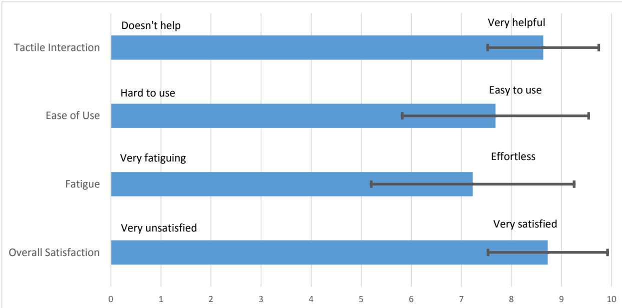

Figure 10: The chart shows user feedback on a scale of $1-10$ (standard-deviation shown in bars) where 10 indicates a good score e.g easy to use, fun to use. Overall we found that all children were satisfied with the experience, all wanted to keep playing (and were not fatigued), and all found tactile interaction to be fun and useful.

other kids still enjoyed playing with the toys, helping build stacks etc. The children called out to each other, invented small games, and built their own fantasy world.

- TactileVR inspired the children, and prompted new ideas and options for play they haven't considered before. As can be seen and heard in the accompanying user study video, the kids had fascinating ideas on the games they could create. An interesting future direction for TactileVR would be the ability to integrate new physical objects, and new virtual manifestations, and allow the child to mix and match, creating his own fantastic world.

5 Conclusion and Future Work

We presented **TactileVR**, a novel way to add immersive presence and tactile feedback into virtual reality. Our system is especially suited for children, an often neglected audience of VR (although early adopters by nature). We have shown how by tracking and integrating toys and other everyday objects into VR, we are able to create educational and recreational experiences for children, an environment in which they can play and learn. Our brand of haptics relies solely on simple position and orientation tracking, which allows using a wide variety of toys and other objects, and recognizing a large variety of interaction modalities.

Our study showed that kids took very quickly to the physical existence of the virtual objects around them. Moreover, they complained about objects which had no tactile feedback. When free to explore the kids discovered how to interact with each scenario, ran around, and played collaboratively with each other.

In the future we would like to replace the current tracking method (with OptiTrack) to a vision-based method which uses a head mounted camera or a few fixed cameras around the room. This will increase accessibility and could also be used to dynamically add new objects into TactileVR. We could then scan physical objects the user holds out, and add a virtual proxy for them. Potentially we could also semantically identify the object, as well as its affordances, and assign meaningful interaction modalities to it. Such a system can also be streamlined, eliminating the need for reflective spherical markers (and the rods by which they are attached to the HMD). Needless to say any improvement in tracking and HMD technology will lead to a more immersive and comfortable VR experience.

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