Does It Feel Real? Using Tangibles with Different Fidelities to Build and Explore Scenes in Virtual Reality

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ABSTRACT

Professionals in domains like film, theater, or architecture often rely on physical models to visualize spaces. With virtual reality (VR) new tools are available providing immersive experiences with correct perceptions of depth and scale. However, these lack the tangibility of physical models. Using tangible objects in VR can close this gap but creates the challenges of producing suitable objects and interacting with them with only the virtual objects visible. This work addresses these challenges by evaluating tangibles with three haptic fidelities: equal disc-shaped tangibles for all virtual objects, Lego-built tangibles, and 3D-printed tangibles resembling the virtual shapes. We present results from a comparative study on immersion, performance, and intuitive interaction and interviews with domain experts. The results show that 3D-printed objects perform best, but Lego offers a good trade-off between fast creation of tangibles and sufficient fidelity. The experts rate our approach as useful and would use all three versions.

CCS CONCEPTS

• **Human-centered computing → Virtual reality**; **Haptic devices**; *User studies*;

KEYWORDS

tangibles; virtual reality; user study; expert interview; visual tracking; animation; previsualization

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Figure 1: Illustration of the system: getting a realistic tactile impression while exploring and building virtual scenes.

1 INTRODUCTION

Many visual design disciplines such as film, animation, theater, architecture, urban planning, product and interior design use a profound planning phase for the visual outcome of a product to creatively explore ideas, plan technical solutions, and communicate a shared vision. This planning phase is usually referred to as previsualization (previs) [31]. The previs process can vary between the different disciplines but always aims at producing an early impression of how the media, product or space will look before starting the production.

Previs gains increasing popularity through the steady advancement of technology and most of today's previs work is done digitally. Digital previs brings the advantage of precise planning, producing high-quality visual output and the ability to use the results of the previs phase in the production process. However, the use of complex 3D tools requires skilled technical users excluding creative, non-technical users such as artists, designers, directors from the previs production process. Therefore, many iterations of designs and communication between creative personnel and technical staff is required [26]. Virtual Reality (VR) creates an immense advantage for the previs process by being able to perceive detailed digital content in an immersive way with correct depth and scale. From early VR systems [40] to recent work [12, 45], VR has shown to be useful for visualizing layouts and spaces. Especially non-technical persons can benefit from VR as they are able to naturally explore spaces by looking around and do not have to struggle with complex controls [26].

For decades, previs has been used in the form miniature models for set and stage designs, buildings, interior designs and urban spaces. These forms of previs are mainly produced by the creative persons, e.g., artists, designers, directors, and rely on their natural expression in form of tangible, haptic models which can easily be spatially arranged and repositioned. In this paper, we bring together the immersive experience of VR with the intuitive control of tangibles and realistic touch of miniature models. We aim at providing creative persons without much technical knowledge with the ability to create digital previs themselves by utilizing their natural forms of interaction for creation and exploration of 3D scenes. However, combining VR with tangible interaction for miniature models creates the problem that the user can not see the tangible object as he/she is wearing a head mounted display (HMD). The user can only see the virtual object that is represented by the tangible.

3D-printing can produce tangible objects that accurately resemble the virtual object but can be time consuming and costly to produce [25]. Using uniform shaped objects which do not represent the shape of the virtual object on the other hand can be implemented easily but may be difficult to grasp correctly. Construction toolkits like Lego present a trade-off for fast, easy and cost-effective prototyping of functional objects with a rough but related shape (as for example integrated in a combined Lego and 3D-printing approach in [25]). Each of the three approaches - uniform objects, construction toolkits, and 3D-printing - produces tangibles with different haptic fidelities and with different advantages and drawbacks. To evaluate the impact of these different fidelity approaches on the user's immersion, performance and intuitive control we implement a VR system for tangible interaction.

The contribution of this paper is twofold: First, we present the first empirical study comparing different fidelities of model-scale tangible objects in VR shedding light on the trade-off between high-fidelity and easy-to-implement tangibles (to the best of our knowledge). Second, we present interviews with experts from the film, animation and theater domain highlighting the benefits of model-scale tangible objects in VR and discussing the ability to integrate the approach into the professional workflow. The results show that 3D-printed tangibles would be the first choice of most users. However, Lego tangibles do not differ significantly to 3D-printed tangibles in perceived grasping accuracy, perceived performance and haptic impression. This indicates that Lego offers a good trade-off between easy manufacturing of tangibles and sufficient fidelity. Experts rated the system as highly beneficial and see a great potential for non-technical persons. They envision the system as a good extension of the traditional workflow and even tough they identify potential for the uniform and 3D-printed versions in specific application scenarios, they see high potential in Lego tangibles for the integration.

2 RELATED WORK

This work draws from and builds on research in the domains of previs, tangibles user interfaces and haptics in virtual environments.

PreVis

Previsualization as a visual planning phase is an established process widely used in film [46] and animation productions around the world [31]. In recent years research has focused on bringing real time game technologies to the field of previs [28, 29] to make the process easier and more efficient. But also other domains like architecture and construction benefit from the advancements in technology and use digital previs [12, 45] for their planning phase. As previs often involves complex planning phases like the layout of urban spaces, tangible user interfaces have been used (c.f. [30, 42]) as intuitive interaction for this process.

Tangible User Interfaces

Tangible user interfaces (TUIs) - also called tangibles - have emerged as an interface type that interlinks the digital and physical worlds [19, 37]. They build on the users' knowledge and skills of interaction with the real non-digital world and therefore are often associated with reality-based interaction [20]. In particular, TUIs take advantage of natural physical affordances to achieve a heightened legibility and seamlessness of interaction between people and digital information [19]. In their tangible interaction framework, Hornecker and Buur [17] identified a number of dominating tangible interaction concepts such as *inhabited space*, *embodied constraints* or *externalization*, which are all highly relevant for visualization and planning tasks, as also discussed by

Shaer and Hornecker [37]. Especially for 3D manipulation tasks, tangible interaction has shown to be faster and more intuitive than mouse or touch interaction [4] and benefits from the natural spatial memory of humans [7], as for example already explored with passive real-world props in early 3D user interfaces for neurosurgical visualization [16].

However, it also has to be taken into account that the design and implementation of tangibles is often challenging. To address these challenges, Shaer et. al. presented a specification paradigm for the design and implementation of tangible user interfaces [38]. A major design decision when designing tangible user interfaces is related to the physical representation that is linked to a digital counterpart - this can vary from abstract representations, e.g. in the form of spheres or cuboids (c.f. [9]), to small-scale models of real objects, e.g. of specific buildings as in [27, 41], up to the real physical objects. In our work, we investigate the effect of different physical representations of virtual objects to provide passive haptic feedback in virtual environments.

Haptics in Virtual Environments

A number of studies have shown that haptic feedback fosters embodied interaction, presence and immersion in virtual environments (e.g. [2, 5, 14, 34, 35]). Generally, this feedback is provided either by active or passive haptics. Typical approaches for active haptics include robotic-actuated props [43] or special virtual reality controllers [3] that can, for example, render surface textures in a yet relatively low resolution. Further approaches have explored electrical muscle stimulation [23] or ultrasonic-based mid-air haptics [22] to provide haptic feedback in VR. However, active haptics approaches generally require complex hardware while still providing only a limited range of haptic experiences.

Passive props often provide a more feasible approach with natural feedback qualities. They have been applied in virtual reality in different fidelities. Insko [18], for example, found that already low-fidelity physical models constructed from cheap materials such as styrofoam or plywood support increasing the participants' sense of presence. In a VR training scenario, Arteaga Martin and colleagues [24] found that tangible props can have a positive effect on the experience, especially if they closely resemble the form of the actual objects, but do not necessarily result in better performance. Reinhardt and Hurtienne [33] examined the effect of different tangible props for an (in this case non-VR) Kinect-based sports game and found the tendency that users felt less competent with incomplete tangibles. The authors followed that the benefits of tangibles with low fidelity might primarily be domain-dependent. Games such as Metaspace II [39] or Real Virtuality [6] integrated real physical objects, such as a box and a rod, in order to enhance the realism in a virtual environment. Harley and colleagues [13] provided a system to integrate real objects into virtual reality and presented an actuated stuffed animal as interaction object for "Tangible VR", thus combining active and passive haptics. The VR sandbox [11] even provides a box filled with real sand that can be used in VR to design the surface structure of the virtual environment.

Supposing that it is not always possible to have physical objects for each virtual object, Azmandian et al. [1] used haptic retargeting to generate the illusion of multiple haptic objects in the scene via warping the visual space while only one real object was present. Zhao and Follmer [47] extended the approach of haptic retargeting to complex, arbitrary shapes, allowing a continuous mapping across all points on the boundaries of different physical and virtual shapes and reducing user-perceived differences between the objects. While this approach yields potential, it is quite complex and needs further development in order to work for numerous objects with different shapes placed in varying spatial distances to the user.

In our work, we systematically explore the use of passive physical props for virtual environments further. While physical models of different fidelities have been explored in VR in dedicated cases, to our knowledge, a systematic comparison of different fidelity levels of passive physical props has not been conducted. This work contributes to this body of work by exploring different fidelity levels of tangibles in a VR setting for previsualization.

3 SYSTEM

To investigate the impact of different fidelities for tangibles in VR and possible application scenarios, we implemented a VR prototype with tangible interaction. The prototype consists of an OptiTrack Motion Capture[1] system with six OptiTrack Prime 13 cameras and the Motive 2.0.2[2] motion tracking software. The setup is a table with three OptiTrack cameras on the left and right side in a height of 1.8 m, oriented towards the surface of the table (see Figure 2). The users sit in front of the table and can interact with the tangibles on the table. For VR, we incorporated the Medion Erazer X1000 VR headset[3]. The VR headset, tangibles, table and fingers of the user are tracked by the OptiTrack system using retroreflective markers. The internal tracking of the headset was disabled and replaced by the OptiTrack tracking with seven markers attached around the headset. The table was also equipped with eight markers to be able to present it to the user in VR at the correct position. The headset, table, and tangibles were defined as rigid body objects in the Motive software. On the software side, the prototype is built on the Unity

[1] http://optitrack.com
[2] http://optitrack.com/products/motive
[3] https://www.microsoft.com/de-de/windows/windows-mixed-reality

Figure 2: System setup with three Optitrack cameras on each side of the table and HMD and tangibles on the table.

2018.2[4] game engine. The OptiTrack NetNat SDK[5] was used for streaming the tracking data from the Motive software to Unity in real time.

The prototype software receives tracking data for all defined objects and places the corresponding virtual object at the received position and orientation. A static virtual environment (VE) is the basis for the layout on top of the virtual table. The user can place the tangible objects on the table to layout the virtual scene, which is presented to him/her in VR. When wearing the VR headset, the user is neither able to see the real tangible object nor his/her hands and fingers. The tangibles are represented by virtual objects which are positioned at the exact position of the real tangible object. As the user has correct perception of depth trough the VR headset he/she is able to anticipate where to grasp the object. But in order to move the hand to the corresponding position and correctly grasp the tangible object it is also necessary for the user to see his/her fingers. As the OptiTrack software does not support finger tracking by default, we used individual retroreflective markers at the tip of the thumb and index finger of the user. The positions of the fingertips are presented to the user as abstract spheres in the VE like it is done in other work [21]. These give the user a sense for the position of their fingers and enable them to precisely move their fingers to the position of the virtual object.

[4]https://unity3d.com

[5]http://optitrack.com/products/natnet-sdk

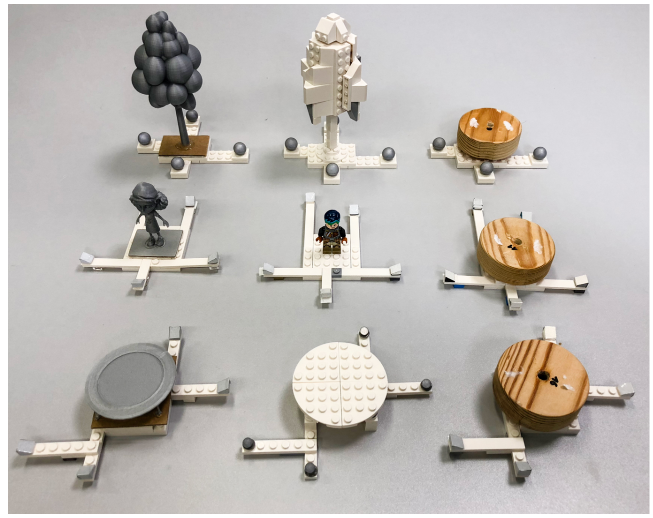

Figure 3: Tangibles with different fidelities: 3D-printed, Lego-built, uniform shaped objects from left to right. The tangibles represent a tree, a girl and a trampoline from top to bottom.

Tangibles

For the purpose of this study and the example scenario, tangibles are created to represent seven different virtual objects. Independent of their fidelity, all tangibles need an option to attach the OptiTrack markers, and therefore all of them have a base structure built with Lego (see Figure 3). The base plates are approximately 10 cm in diameter. If more tangibles are needed, around 30 different marker configurations would be feasible with this size of base plates. The marker structures are unique for each of the seven represented objects, but the same object in different fidelities has the same marker structure to allow for an easy exchange. As mentioned before, the tangibles were created in three different fidelities: uniform shaped, solely Lego, and 3D-printed objects (comp. Figure 3). The uniform shaped objects have a diameter of 6 cm, are about 1.5 cm thick and can be equally grabbed from all sides. The Lego tangibles were constructed to represent the possible spectrum of possible objects that can be built from Lego, ranging from simple objects like a Lego figure up to more complex structures like a custom built tree. The average build times for the Lego tangibles are 5-20 min based on the complexity of the model. For the 3D-printed objects, their virtual counterparts were transformed into a printable 3D model, which then was printed using PLA material on an Ultimaker 3 Extended[6]. The print times varied between 6-8 hours based on the complexity of the 3D-printed tangible.

[6]https://ultimaker.com/en/products/ultimaker-3

4 STUDY

We performed two evaluations to investigate the impact of different fidelities for tangibles used in a virtual reality application for scene creation and the applicability of this approach into professional previs scenarios in the film, animation, and theater domain: A user study with 24 participants and expert interviews with eight professionals from the animation, film, and theater field.

Apparatus

The apparatus for the study consists of a real world and a virtual setup. In the real world, the user sits in front of a table with the dimensions of 1.4 m × 0.9 m. The tangible objects are placed on the table and can be moved and positioned anywhere on the table. The virtual setup consists of a virtual version of the table with the same dimensions which is tracked by the OptiTrack and therefore positioned at the exact position as the real table. On top of the virtual table a static virtual scene is added as the basis for the layout. Seven virtual objects are present in the scene and can be moved by the user through the corresponding tangible object in the real world. The 3D models for the scene and the virtual objects are high quality models from a real production of a forthcoming animated tv series. The scene represents a small townhouse with a backyard garden and some trees, see Figure 1 and Figure 4. The virtual objects that can be placed in the scene are: A girl, an elderly woman, a trampoline, a ball, a garden gnome, a tree, and a spider, see Figure 4.

The experiment ran on a Windows PC with an Intel i7-6700, 16GB RAM, and a Nvidia GTX1080. The target frame rate was set to 90 frames per second (FPS) to match the refresh rate of the Medion Erazer X1000 VR headset. The OptiTrack system was set to a frame rate of 240 FPS for smooth tracking of the headset and tangibles.

User Study

The user study aimed to find the impact of different fidelities for tangibles in VR on immersion, performance, and intuitive interaction. Therefore, we conducted a comparative user study with a within-subjects-design with three conditions. The three conditions compare interaction with (1) uniform shaped tangible objects, (2) Lego built tangible objects and (3) 3D-printed tangible objects.

Participants. 24 participants (6 females and 18 males) between 22 to 56 years old with a mean age of 31 years (SD = 8.72) took part in the user study. From this group of participants two are left-handed. Two participants did not report on their current occupation, 17 participants were either students or researchers at the university, while five were employed outside of the university. Three participants are domain experts from film and theater and were part of both studies. Except one, all participants reported to be free of any restrictions regarding their 3D vision. 23 out of 24 had previous experience with VR and assessed their ability visual thinking as good. All participants reported being interested in new technologies.

Procedure. After giving informed consent, participants were assigned to one of the three conditions (uniform shaped, solely Lego, and 3D-printed objects) to start with. The order of conditions was pseudo-randomized across participants using a latin-square scheme to counterbalance for potential biasing effects of the tangibles' fidelity. The participants performed all three conditions and filled out a questionnaire about their experience after each condition. Each condition consisted of two tasks: First, the participants should touch and reposition each of the seven tangibles objects in order to get a feeling for them. Second, they were instructed to place the objects at specific positions in the scene according to a predefined script. The study took about 30 minutes. At the start of each condition the objects were placed in the (virtual) field of view of the participants after they had put on the VR headset. This was necessary to let the participants grasp the objects without any prior visual information of the tangibles. The tangibles were removed from the table after each condition before the participants put off the headset. After finishing all three conditions the participants were free to examine all tangibles in detail. The questionnaire consisted of the presence questionnaire by Witmer and Singer [44] as it has been used in a large number of studies and includes items that address involvement and sensory factors. We used the revised version by the UQO Cyberpsychology Lab (2004)[7]. Additionally, we asked for perceived grasping accuracy, comparison between the real and virtual object and intuitive control with the following three questions on a 7-point Likert-scale:

- How did you perceive the accuracy for grasping the objects? *not precise – very precise*
- How did you perceive the representation of the virtual objects compared to the physical objects? *not similar at all – very similar*
- How did you perceive the interaction with the objects in the scene? *complex – intuitive*

In the end, the participants answered a summarizing questionnaire asking for a ranking of the tangibles and if a realistic physical model aids the interaction. Additionally, we collected basic demographic information as their age, profession, dominant hand, ability to see 3D and to perform visual thinking and experience with VR.

[7]The revised version of the presence questionnaire has an overall score, but this excludes the haptic score, as this is an optional scale. Therefore, we will report the overall score without the haptic subscale. The haptic subscale be reported only separately.

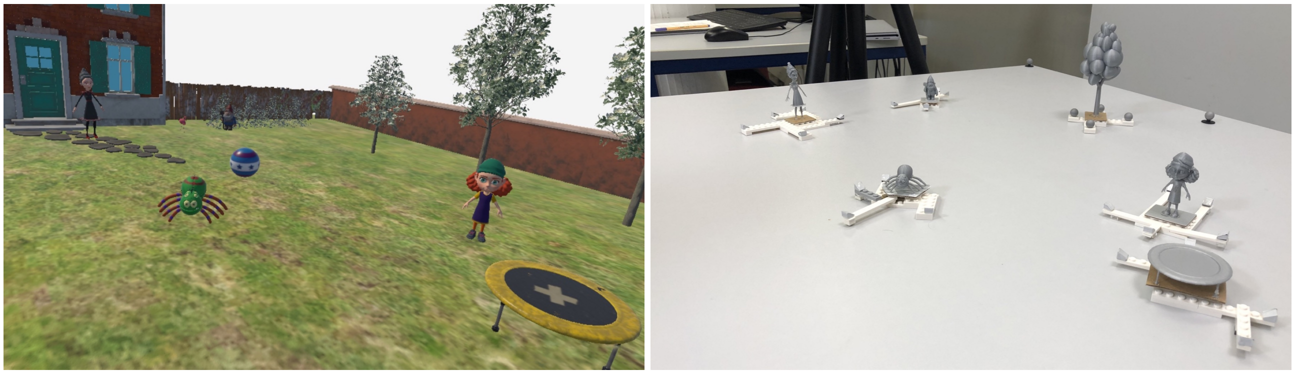

Figure 4: *Left* the virtual environment and *right* the real setting with tangibles.

Data Processing. For each participant and condition, we collected the answers to three self-defined questions and the responses to the revised presence questionnaire. The data was analyzed in R [32]. We conducted a Shapiro-Wilk-Test to check for violations of the normal distribution. For all samples the normal distribution assumption did not hold. Therefore, we conducted a non-parametric Friedman-test for the ranking and Bonferroni-corrected Wilcoxon tests for dependent groups for pairwise post-hoc comparisons.

Expert Interviews

In order to find out if tangible scene planning in VR is suited to be used by creative professionals in the previs domain and and if it can be integrated into the workflow we conducted interviews with experts.

Participants. Eight professionals from the application areas of film, animation series and theater production took part in the expert interviews. **P1** is a cameraman and **P2** is a 3D artist, both from a film studio for commercials and image films. From an animation studio producing animated TV series, **P3** is a CG supervisor and **P4** is a technical director. Four experts from the theater domain took part in the study. **P5** is a costume and set designer, **P6** is a technical director, **P7** is a light director and **P8** is a production director, all working for a major Austrian state theater.

Procedure. Each expert was introduced to the system with detailed information of the setup and the tangibles. After the introduction each participant used the system for 15 minutes (5 min for each tangible condition). For each condition, the experts followed the same tasks as in the user study. They could place the objects to their liking for the first few minutes and then were given a specific placement task according to the same predefined script of the user study. After using the system we conducted an interview with the following questions:

- Do you see the system as a possible way to quickly and easily plan scenes in your domain?
- What could be the advantages and disadvantages of such a system compared to your standard workflow?
- Can you imagine integrating such a system into the workflow? Which tangible version could be suited?
- Can you image to use such a tool yourself or that a set designer / director (creative, non-technical person) would use it to plan scenes?
- How do you consider the effort and time necessary to work with such a system to plan scene compared to your standard workflow?

5 RESULTS

In the following, we present the results of our user study and the expert interviews.

User Study

The results from the self-designed questions are graphically represented in Figure 5, while the χ^2 and p values can be found together with the results from the revised presence questionnaire in Table 1. Figure 5 illustrates that with increasing tangible fidelity (left to right the order is always uniform shaped objects, Lego, 3D-printed objects) the Likert score increases as well - higher always means better. The Friedman-test showed a significant effect within each group (*accuracy*: $\chi^2 = 22.24$, $p < .01^{**}$; *comparison*: $\chi^2 = 38.75$, $p < .01^{**}$; *intuitive*: $\chi^2 = 29.56$, $p < .01^{**}$).

The post-hoc pairwise comparison revealed that for grasping accuracy there is no significant effect between 3D-printed objects and the Lego. However, between the other two pairings, a significant effect was found (see Table 2, *accuracy*). This means the grasping accuracy for Lego and 3D objects was significantly higher compared to the uniform shaped objects, whereas between Lego and 3D objects no significant difference could be observed. The answers regarding how the participants perceived the virtual vs. the tangible object all

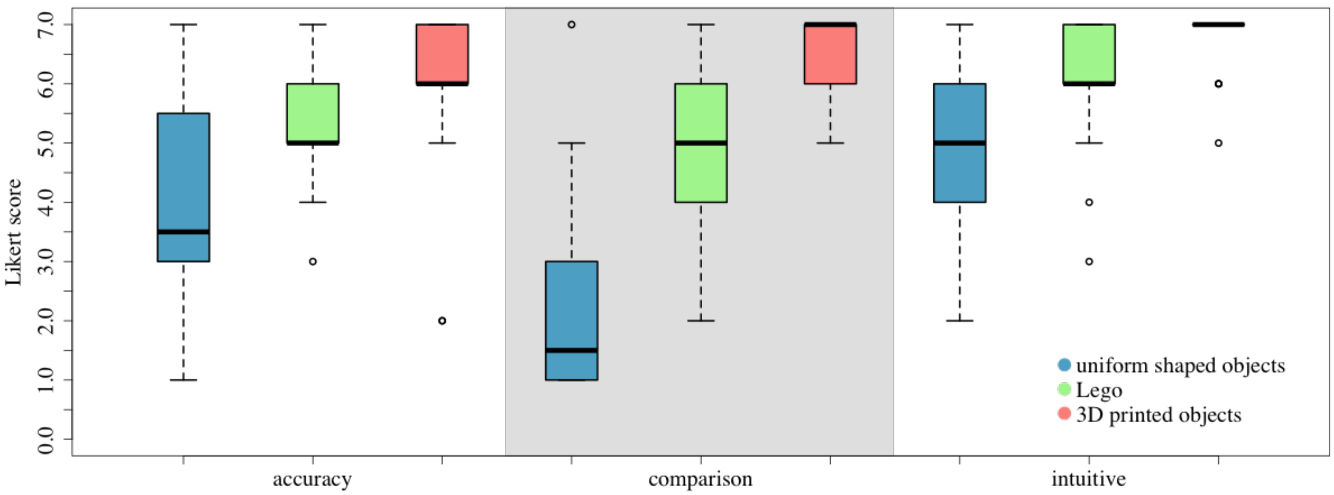

Figure 5: Boxplots with medians showing the results (the higher the better) of the self-design questions (see section 4).

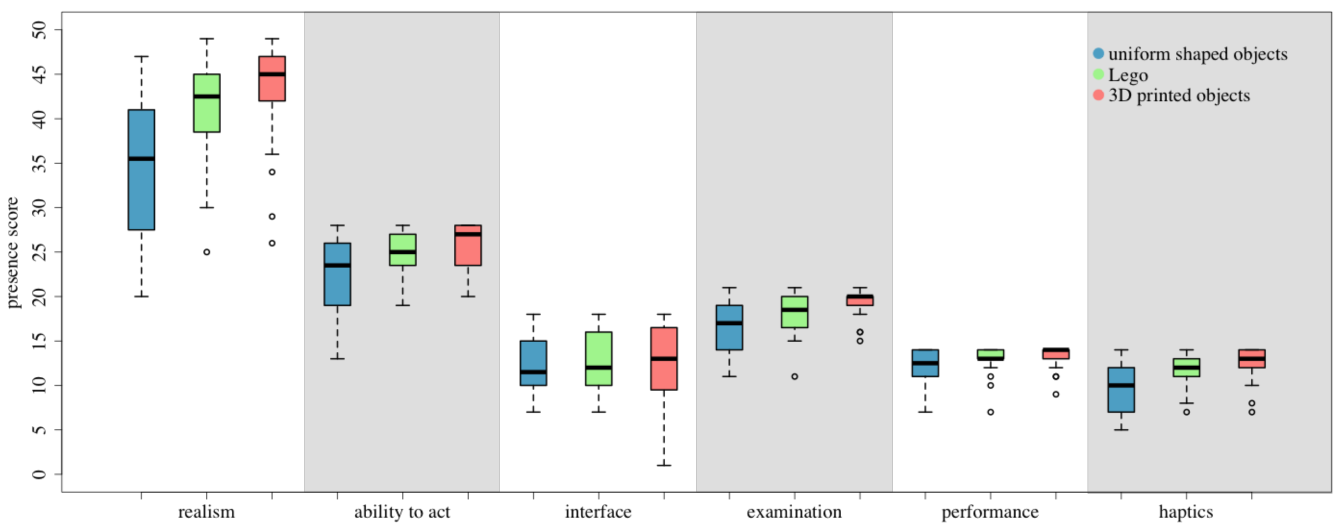

Figure 6: Boxplots with medians showing the results (the higher the better) of the presence questionnaire subscales [min,max]: realism [0;49], ability to act [0;28], interface [0;18], examination [0;21], performance [0;14], and haptics [0;14].

pairwise comparison showed a significant effect (see Table 2, *comparison*) as well as the scores for how the interaction with the tangibles was perceived (see Table 2, *intuitive*). This means, the higher the fidelity the more similar the objects were perceived and the more intuitive the interaction was for the participants.

The results from the subscales of the revised presence questionnaire are shown in Figure 6. Due to different maxima of each subscale, which are described in the caption of the figure, this figure is just comparable within each subscale. The same effect of increasing scores towards higher fidelities as in Figure 6 can be observed. Besides the interface subscale, the Friedman-test reached significance in all subscales, including the overall scale (see Table 1). The overall score excludes the haptic score (see Figure 7), as mentioned before. The post-hoc pairwise comparisons of the significant groups are significant between all three pairs, besides for 3D-printed objects vs. Lego regarding the self-evaluated performance and haptic (see Table 2). This means there was no significant difference for the participants regarding the haptic aspects

Table 1: χ^2 values and p value of the Friedman-test for all three self-designed questions, all subscales of the presence questionnaire and the overall score without the optional haptic score.

	Accuracy	Comparison	Intuitive	Realism	Ability to act	Interface	Examination	Performance	Haptic	Overall (w/o haptic)
χ^2 *value*	22.24	38.75	29.56	30.68	16.12	1.013	23.273	11.16	18.694	32.28
p value	$< .01^{**}$	$< .01^{**}$	$< .01^{**}$	$< .01^{**}$	$< .01^{**}$	> 0.05	$< .01^{**}$	$< .01^{**}$	$< .01^{**}$	$< .01^{**}$

Table 2: Pairwise post-hoc comparisons using a Bonferroni-corrected Wilcoxon test between 3D-printed object and Lego, 3D-printed object and uniform shaped object, and Lego and uniform shaped object.

	Accuracy	Comparison	Intuitive	Realism	Ability to act	Interface	Examination	Performance	Haptic	Overall (- haptic)
3D vs. Lego	$p > .05$	$p < .05^{*}$	$p < .05^{*}$	$p < .05^{*}$	$p < .05^{*}$	$p > .05$	$p < .05^{*}$	$p > .05$	$p > .05$	$p < .05^{*}$
3D vs. uni. obj.	$p < .05^{*}$	$p < .05^{*}$	$p < .05^{*}$	$p < .05^{*}$	$p < .05^{*}$	$p > .05$	$p < .05^{*}$	$p < .05^{*}$	$p < .05^{*}$	$p < .05^{*}$
Lego vs. uni. obj.	$p < .05^{*}$	$p < .05^{*}$	$p < .05^{*}$	$p < .05^{*}$	$p < .05^{*}$	$p > .05$	$p < .05^{*}$	$p < .05^{*}$	$p < .05^{*}$	$p < .05^{*}$

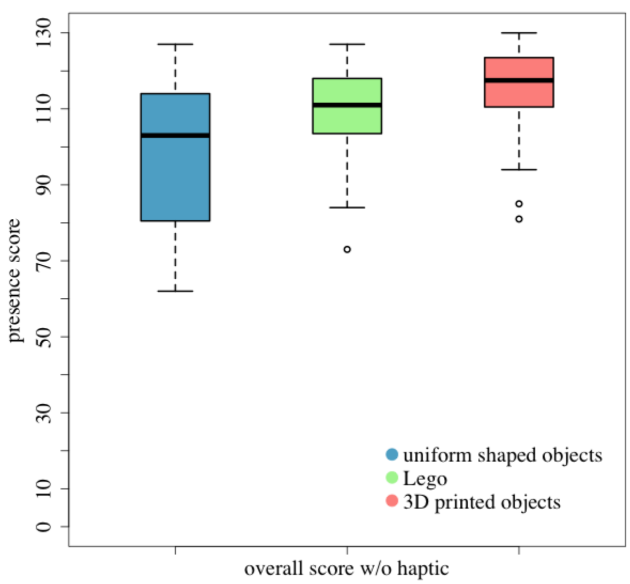

Figure 7: Boxplots with medians showing the overall score of the presence questionnaire without the optional haptic score [0;130] (the higher the better).

of the 3D-printed objects and the Lego built ones and in their perceived performances.

As the participants were asked for a ranking of the tangibles they just experienced, 22 out of 24 chose the 3D-printed object as their favorite one, while two preferred the Lego one. 18 out of 24 selected Lego as second place, five chose the uniform shaped objects and one selected the 3D-printed objects. On third place 19 of the participants place the uniform shaped objects, while four like Lego the least and one put the 3D-printed object last in their ranking.

Expert Interviews

We performed a thematic analysis on the answers from the eight domain experts. The interview answers were coded and an initial set of themes was developed. An iterative review process resulted in the following four final themes: *creative process*, *ease of use*, *time saving* and *practicality*.

Creative process: This theme covers the participants' answers regarding the impact of tangible scene design on the creative process of their work. It is the main theme as most of the answers related to it. All participants mentioned a possible positive impact on creativity and could imagine integrating the system into their professional (creative) workflow. Benefits of the system as described by several participants are more creative freedom, the opportunity to test different possibilities and easier imagination the final outcome. Two participants (P3, P8) mentioned that the creative process is mostly collaborative and the tool is well suited to present and communicate ideas to others. P5 highlighted that trying out different designs is a standard procedure in the theater domain, but simple digital tools like SketchUp[8] would not be as effective as a tangible system as it relies on the natural interaction with the hands and the result is directly visible

[8] https://www.sketchup.com/

in 3D. Additionally, P3 mentioned that in animation some directors use stop-motion film sequences with clay-figures or other deformable materials to visualize their ideas. This process often takes a long time and could be made much easier and faster. Using miniature models in the creative process to try out ideas and visualize designs was mentioned several times. P7 mentioned that a director of a production wanted to have mini figures to plan the scenes before and he could imagine that others would like to use such a system too. P8 mentioned that stage designers usually build stage models of wood or cardboard or even 3D-print their stage designs. Integrating a digital tool, similar to the one presented in this work, into their process could help stage designers to easily try out different design or quickly change parts that would be much more effort to change in an already built stage model. All participants agreed that a system as it is presented here is more flexible than solely analog planning making it possible to work on the ideas. The immersive presentation in VR was valued for the possibility to correctly plan perspectives and look into the model and recognize details even on small models. Despite the positive answers to the creative process, it was also mentioned that a digital tool may not be suitable for every creative person as they rely on their own practices for their creative work.

Ease of use: This theme captures participants answers regarding the ease of use and intuitiveness of the interaction with the system. All participants mentioned that the tool is very easy to use and some stated that no learning is required in contrast to other digital tools. Overall, all participants could imagine that they or creative persons without technical knowledge would use the tool. P3 said that after a phase of familiarization he could imagine even a wide audience would use it. P8 stated that it has the potential to convince colleagues who are in general skeptical of digital previs and to completely change the way they work. P5 highlighted that the system is so easy that he can also imagine older persons to use the system. In contrast, four participants (P1, P2, P4, P6) said that potential users would be either primarily younger or open-minded about new technologies.

Time-saving: This theme combines all answers regarding the time-saving aspect of tangible scene design. All participants were in agreement that the tool would allow for a very quick and easy planning phase. They mentioned that it was much faster to adapt and change things in the scene, which is a frequent action, and therefore save a significant amount of time (P2, P5, P6). Therefore, the planning phase would be much faster than in the traditional workflow with other digital tools, as these actions are often more complicated in other digital tools. Two participants (P3, P7) mentioned that the time saved could be used for more iterations, which could lead to higher quality results in the end. It was also highlighted that the result was directly digital and no rebuilding of a physical model in a digital tool was required, which is another potentially time-saving aspect.

Practicality: This theme encapsulates the answers regarding the practicality of the different fidelities of the tangibles and the overall system. 3D-printed and Lego tangibles were considered the best for interaction by all participants, but different aspects of the professional workflow influenced the consideration for the practical application. While 3D-printed tangibles were too expensive and time-consuming to produce for the majority, two participants (P3, P4) from animation series assess 3D-printed tangibles as suitable for their field. Each episode contains mostly the same objects, which can be reused for planning. Four participants (P1, P2, P5, P7) see a high potential for Lego as a method for tangible creation in their field since it can be easily created and customized in a short time. In the theater domain, Lego and uniform tangibles are suitable as they already heavily rely on placeholder items which will be replaced by the final object incrementally over the production (P6, P8). The overall system was described as very useful by all participants for their professional work but it was mentioned that it might not be suitable for every situation (e.g., for placing objects in the air). In addition, some of the participants saw the complex setup and expensive equipment as a drawback of the system.

6 DISCUSSION

The results from the questionnaires and the ranking show a clear preferences for interacting with 3D-printed tangibles in the virtual environment. Nevertheless, the long and expensive manufacturing process is only suitable for a limited set of scenarios. Because of that, the experts preferred the Lego tangibles. However, for certain scenarios with reoccurring objects, e.g., in series, they could use 3D-printed objects as well.

In the user study both design experts and novices took part. This could have had an impact on the result of the study but the expert participants performed similar compared to the other participants and the significant results do not change when excluding experts. No significant effects were observed comparing 3D-printed tangibles and Lego tangibles regarding their grasping accuracy, their haptic aspects and the users' perceived performance. As these aspects are probably the most important ones when interacting with tangibles in VR, this indicates that Lego and 3D-printed tangibles are both valid choices for the interaction in VR. This claim is also supported by the significantly worse performance of the uniform shaped objects regarding all aspects (besides interface, as the VR environment was exactly the same for all three conditions). These results indicate that there is a threshold for the required haptic fidelity to enable accurate interaction with good performance. Lego tangibles, which roughly resemble the shape of the virtual object, seem to be above the threshold and offer the best trade-off between sufficient fidelity and fast production of tangibles.

We expected significant differences regarding the questions of comparing the virtual to the physical object (*Comparison*) and how intuitive the interaction was perceived (*Intuitive*), as an object which closely resembles the shape of the virtual object can be grabbed more intuitively and the haptic impression is closer to the visual appearance. As the questions for the *Realism* subscale focused on similar aspects as the questions for the *Intuitive* subscale, the same results could be expected.

The significant differences in the pairwise comparison for the *Ability to act* and *Examination* subscales (see Table 2) might be due to the increased immersion effect of the more realistic representations by the higher fidelity tangibles. Research has shown that haptics has an influence on how we perceive objects [8] and matching haptic and visual impressions leads to higher integration [15] making the experience more compelling. This indicates that even though a certain fidelity might be sufficient for interaction with tangibles, the immersion might still be higher with more closely matching objects. This is supported by the overall score of the presence questionnaire, which increases significantly with each fidelity raise (compare Figure 7 and Table 2).

All experts were enthusiastic about integrating tangibles in combination with VR into their professional workflow and saw the opportunity to change the way they are working. Two experts saw also potential in using the uniform shaped objects, since their unique characteristic is that they do not have to be built and are directly usable. As their scores are also above average on all scales, they would qualify where an ad hoc solution is needed. The thematic analysis revealed a particular positive impact on the creative process of the professionals. Multiple participants described the system to be highly useful for exploring different designs and options, which indicates that the system encourages epistemic actions [10] well. In general the interview results indicate a huge potential for a combined system of self-constructed tangibles and VR for professional use. The self-constructed tangibles do not necessarily need to be built with Lego, any other construction toolkit allowing for easy and fast assembling are feasible.

The results with respect to grasping accuracy, haptic aspects and performance of Lego tangibles and the expert feedback indicate that Lego is the preferred option and that VR previs with tangibles is a promising solution. It can be seen as the best from the traditional world: the physical models - but a bit easier to build - combined with the detailed and immersive VR, allowing for a more natural creation and exploration of 3D scenes without the use of complex 3D tools.

We see the following limitations for our study: We explored fidelity just under the aspect of shape and omitted further factors such as material, weight, or texture, which could be a focus of future work. As all tangibles had a Lego base construct to attach the markers (see Figure 3), these bases sometimes interfered with each other when trying to place objects closely together. Also the hand tracking could block the attached markers which then led to inaccurate tracking. The hand tracking did not include the whole hand, which was involved in handling the tangible, just the tip of the index finger and thumb were tracked and shown in VR. This could have an influence on the immersion and presence. However, as Schwind et al. [36] showed, decreasing the number of fingers on an abstract hand does not significantly lower the levels of presences, whereas realistic hands with less fingers do. An additional limitation, which was already mentioned by the experts, is that the setup is quite expensive and complex and therefore is not yet applicable to a professional workflow in film, theater or animation without technical support.

7 CONCLUSION

This work evaluates the effect of tangibles with different haptic fidelities on immersion, performance, and intuitive interaction for 3D scene creation in VR. We compare tangibles with different production processes (uniform shaped objects with no similarity to the virtual object, Lego-build, and 3D-printed tangibles, which resemble the virtual object) in a user study with 24 participants and an expert interview with eight previs experts. The interviews focused on the applicability of the system in the previs domain and integration of the tangible production processes into the previs workflow. The results from the study and the interviews show that Lego offers the best trade-off between sufficient fidelity and fast production. There are no significant differences with respect to grasping accuracy, haptic aspects, and the users' perceived performance when compared to 3D-printed tangibles. One of the main benefits of the system the experts mentioned is saving time in the previs process by being able to digitally plan and adapt the scenes. While all three fidelities are suitable for specific scenarios, the long and expensive manufacturing process of 3D-printed tangibles have to be considered. For future iterations, we will investigate further tracking options, e.g., by placing flat markers directly on the tangibles or using cheaper tracking solutions.

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