Enabling Reusable Haptic Props for Virtual Reality by Hand Displacement

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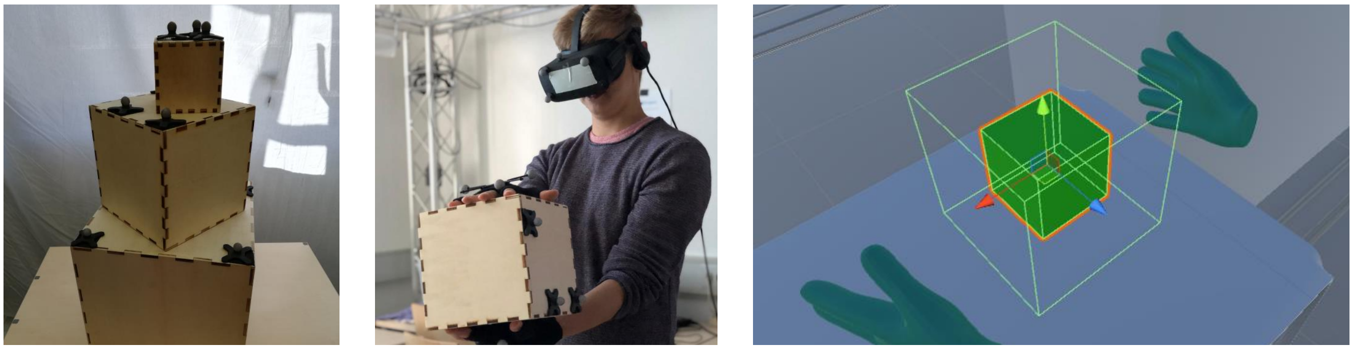

Figure 1: Left: We track haptic props to enhance the virtual experience. Middle: A VR user investigating a virtual box while holding a prop. Right: The virtual view. The haptic prop is rendered transparent (outer green box). To the user, only the solid green box was visible in virtual reality.

ABSTRACT

Virtual Reality (VR) enables compelling visual experiences. However, providing haptic feedback is still challenging. Previous work suggests utilizing haptic props to overcome such limitations and presents evidence that props could function as a single haptic proxy for several virtual objects. In this work, we displace users' hands to account for virtual objects that are smaller or larger. Hence, the used haptic prop can represent several differently-sized virtual objects. We conducted a user study ($N = 12$) and presented our participants with two tasks during which we continuously handed them the same haptic prop but they saw in VR differently-sized virtual objects. In the first task, we used a linear hand displacement and increased the size of the virtual object to understand when participants perceive a mismatch. In the second task, we compare the linear displacement to logarithmic and exponential displacements. We found that participants, on average, do not perceive the size mismatch for virtual objects up to 50% larger than the physical prop. However, we did not find any differences between the explored different displacement. We conclude our work with future research directions.

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CCS CONCEPTS

• **Human-centered computing** → **Haptic devices**.

KEYWORDS

Virtual Reality, Haptics, Illusions, Perception, Retargeting

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1 INTRODUCTION

Virtual Reality (VR) environments are designed to mimic the real world. While visual and auditory channels already provide rich VR experiences, addressing haptics is still challenging [24]. Controllers of current VR systems mainly rely on vibration to provide users with haptic feedback. Controllers cannot replicate different surfaces or textures. When users grasp objects, they fail to provide physical boundaries. Hence, the user's hands pass through impenetrable objects, which negatively impacts immersion. The hands are a vital tool for humans to do haptic explorations to build representations of haptic objects in memory [19]. Further, it was shown that haptics can enhance virtual environments [16] and corresponding UI manipulation [21]. To provide users with believable haptic sensations, previous work proposed different approaches, ranging from body-worn devices such as gloves [7, 11, 12] or suits [18, 20] to haptic props [2, 5, 8, 9, 15, 17, 28, 29] that function as a physical proxy to objects presented in VR. The latter has the advantage that they can be shared by co-located users, are easy to create (e.g., with 3D printing), and can be used without the need for electronic components. However, providing matching haptic props that resemble arbitrary

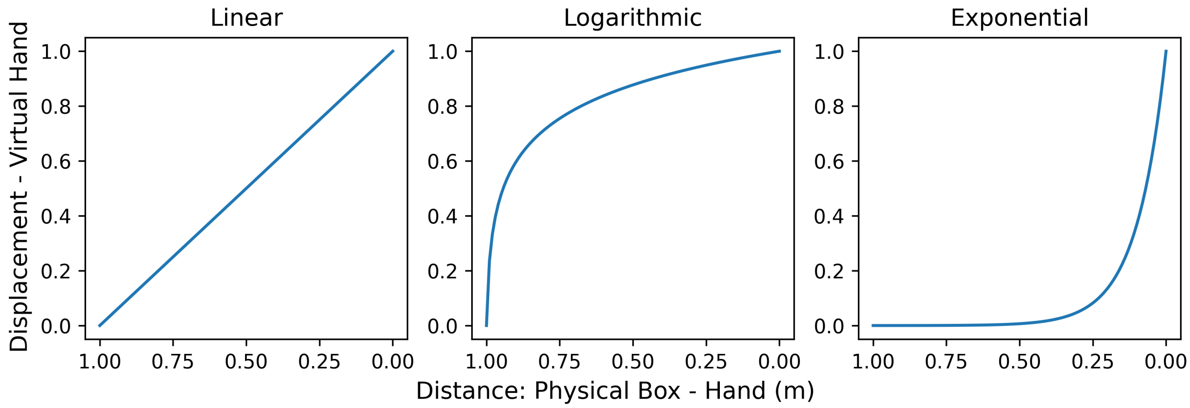

Figure 2: The three functions we used to displace the virtual hand position - f_1 (left), f_2 (middle), f_3 (right). The x-axis describes how far away the physical hand is from the closest point of the physical box. The y-axis describes the amount the offset that is added to the virtual hand dependent on the distance. Here, 0 means no offset is added to the hand, and 1 means that the full offset is added to the hand i.e. the full distance between the physical touching point and the virtual touching point.

virtual objects is often not feasible. Even if objects have the same shape or size, it makes sense to reduce the number of haptic props [1, 9]. Thus, researchers suggested reusing haptic props to represent virtual objects [1, 3, 9, 34]. Nonetheless, it remains unclear to what degree visual illusions conceal size differences between haptic props and their virtual counterparts.

In this work, we explore to what degree one can manipulate the size of virtual objects when using only one physical prop. To create the illusion of differently sized objects in VR, we displaced the position of the user's hands in VR during the interaction with virtual objects. When users reach out to an object in VR, their virtual hand positions are displaced by adding an offset to the virtual hand, ensuring that users touch the virtual object at the same moment they make contact with the physical prop. We conducted a user study with twelve participants. In a first task, we used a linear displacement function and incrementally increased the size of the virtual object to understand at which point participants perceive the mismatch. In a second task, we compared three displacement functions (linearly, exponentially, or logarithmic) and increased and decreased the size of the virtual object to see which function works best.

Our results show that the size of a virtual object, in our case a box, could be increased on average by 50% of its original size through the displacement of the virtual hand without the user noticing. We conclude our work with three research directions inspired by our approach, ranging from multi-user VR to investigating other body parts than the hands, to safety-critical scenarios.

2 RELATED WORK

Previous research has investigated different approaches to address haptics in VR. Body-worn haptic devices such as gloves [7, 11, 12], suits [18, 20], or handheld devices [14] were developed to address the sensation of touch at different parts of the human body. Also, directly manipulating the body via Electrical Muscle Stimulation (EMS) could provide haptics to VR elements e.g. heavy virtual boxes or static objects like virtual walls [22, 23]. In the following, we introduce research related to haptic props which we use in our approach.

Haptic Retargeting. To mimic haptics for multiple virtual objects, Azmandian et al. investigated how one haptic prop can be re-purposed through haptic retargeting [1]. The idea is to re-use one physical object to resemble the haptics of various virtual objects. When users reach out to different virtual objects their physical movement is manipulated by visual illusions e.g. displacing the virtual arm. Through this manipulation, the users reach out in the direction of physically present objects without noticing. Other approaches show that such props could also change their shape before being picked up to match the expectations of a VR user [25]. Cheng et al. redirect the user's hand while reaching out to a virtual object to a specific physical proxy that matches the expected haptics of the virtual object [9]. They found that participants accepted a redirection up to 40°. Zenner and Krüger showed that users were unable to detect a hand displacement of approx. 4.5° in horizontal and vertical direction [33]. Further, they showed that users were not able to detect that the virtual hand was displaced up to 13.75% farther or up to 6.18% less far away from them. Zhao et al. extend haptic retargeting to complex shapes by applying a continuous mapping between physical and virtual objects [34]. Physical objects with similar topology were used to resemble the haptics of virtual objects. Yang et al. apply haptic retargeting to a controller creating a haptic illusion while grabbing a virtual object with chopsticks [30]. In this case, the haptic retargeting was not applied to the user but to the controller i.e. the chopsticks opening angle. Bergström et al. showed how different virtual objects could be represented by one physical object by resizing the user's grasp [6]. The results show that virtual objects could be up to 50% larger than the physical haptic counterpart. Further, researchers published toolkits that provide techniques for retargeting to easy their application in VR [32].

In our work, we re-target the hands of the users to the surfaces of differently sized virtual objects when the users touch a physical prop with a fixed size. Similar to previous research that investigated re-purposing of physical props [6]. We could show that virtual objects could be up to 50% larger than their physical counterpart.

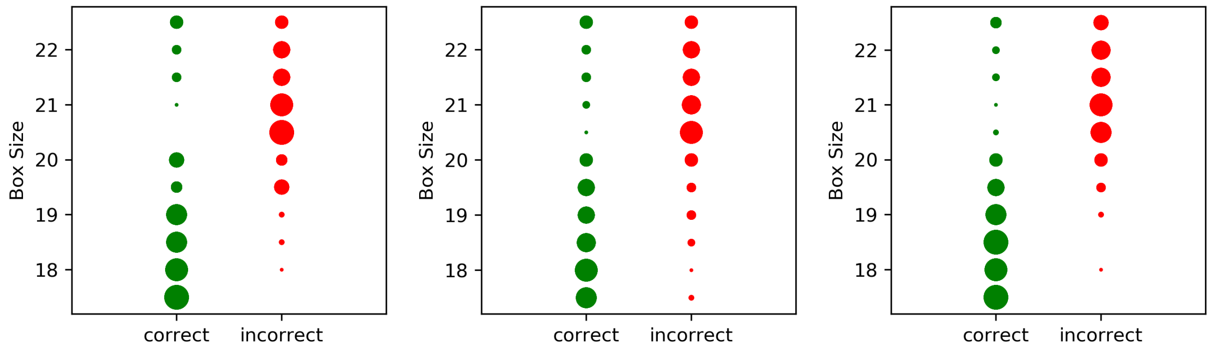

Figure 3: Aggregated estimation of the box size when using the linear displacement function (f_1, left), the logarithmic displacement function (f_2, middle), and the exponential displacement function (f_3, right).

3 HAND DISPLACEMENT

To re-target the hands of VR users, we displace their virtual hands while they are interacting with virtual objects and in reality with a physical prop. We developed three functions that displace the position of the virtual hand of the VR user. These functions add an offset to the position of the virtual hand dependent on the distance between the user's real hands and the surface of the physical prop. The functions are designed to align the virtual hand with the surface of the virtual object when the user touches the physical prop. This works also for virtual objects that are smaller than the physical prop. On the right-hand side of Figure 1, an exemplary scenario is shown. Here, the surface of the physical prop is rendered transparently. The user could only see the green boxes in VR. We developed three functions that determine the offset in a linear, logarithmic, and exponential fashion (f_1, f_2, f_3, see Figure 2).

$$f_1(x) = x, \qquad f_2(x) = \frac{log(100xe + 1)}{log(1 + 100e)}, \qquad f_3(x) = \frac{e^{10x} - 1}{e^{10} - 1}$$

We added an offset to the virtual hand when the distance from the real hand to the center of the physical prop is less than one meter. Adding this offset instantly when the user comes near the physical object would lead to a sudden leap of the virtual hand which may be perceived by the user. Therefore, we designed the three displacement functions that determine the amount of offset that is added to the virtual hand position dependent on the distance of the real hand to the physical prop (see Figure 2). The linear function was designed to add the displacement offset continuously while the hand of the user approaches the surface of the physical prop. The logarithmic function was designed to add the largest amount of the displacement offset while the hand is still far away from the surface of the physical object while the exponential function adds the majority of the offset when the hand is close to the surface of the physical prop. We designed these three different functions to investigate if the participants perceive the virtual hand displacement differently when it is applied either linearly, logarithmically, or exponentially.

4 EVALUATION

We evaluated our approach through a user study. Therefore, we invited 12 participants to our lab (11 male, 1 female, 0 other) aged between 19 and 32 years ($M = 25.67, SD = 4.40$). All participants except two used VR before. The first goal of the study was to understand to what degree we could apply our displacement functions until the manipulation is noticed using a linear displacement. The second goal was to investigate if the user perceives the displacement differently when we use different displacement functions (i.e. linear, logarithmic, or exponential functions). We concluded the study with semi-structured interviews.

Setup. We built three differently sized wooden boxes (cf., Figure 1, left) which served as physical props. One small box (10cm), one medium-sized box (20cm), and a large box (30cm). We attached markers to every box to track their position and orientation using an *OptiTrack 13W* system. Further, we built a VR environment (see Figure 1, right). The environment consisted of a large room with a table in the middle. We aligned the virtual environment with the study environment which also contained a table in the middle. Both, the virtual and the physical table were equal in size. In the VR environment, the participants could see virtual representations of their hands. These hands were fixed in size. The virtual hand length was 18cm which is around the average human hand length (average female and male hand length: $16.9cm \pm 0.9$ and $18.3cm \pm 0.9$ respectively [13]). The physical boxes were placed in the back of the study room. As we positioned a wall in the physical and in the virtual scene, the participants could neither see the physical nor the virtual boxes at the beginning of the study. Only when the participant arrived in the lab, the three differently sized physical boxes were visible to them. We deliberately let the participants know that there is more than one box and that they are different in size.

First Task. In the first task, the experimenter took a physical box and handed it over the table to the participant. The movement of the physical box was mapped to a virtual box which the participants could see in VR. The experimenter always handed the same medium-sized physical box (20cm) to the participant. Only the size of the virtual box was different in VR. We used the linear function (f_1) in this task to displace the virtual hands. The participant then had to determine if the box they see in VR matches the size of the box they were physically holding and then hand it back to the experimenter. During investigating the box bi-manually the participants could rotate, squeeze and re-grasp it as desired. This process was repeated up to 20 times increasing the virtual box size each time by five percent (1cm) of its original size (20cm). By the time the participants realized that they were handed the same box

Table 1: Number of boxes shown to the participants until they recognized that there is a mismatch in size between the virtual and the physical box. Also, the corresponding virtual box sizes are shown. A star (*) indicates that the participant did not notice the manipulation after investigating 20 boxes (i.e. twice the size of the physical box). After 20 boxes the trial was stopped.

Manipulation Noticed					
Participant	*Number of Box*	*Virtual Box Size (cm)*	*Participant*	*Number of Box*	*Virtual Box Size (cm)*
P1	5	25	P7	20 *	40
P2	20 *	40	P8	20 *	40
P3	3	23	P9	3	23
P4	9	29	P10	16	36
P5	3	23	P11	2	22
P6	17	37	P12	20 *	40
Overall	M = 11.5, SD = 7.61	31.5 cm			

all the time, we stopped and continued with the second task. When the participants did not notice the manipulation, we also stopped handing further boxes after they have investigated 20 boxes which was twice the size of the haptic prop. We confirmed that these participants have not noticed the manipulation through a semi-structured interview at the end of the study. The results for each participant are shown in Table 1. On average the manipulation was uncovered after 11.5 boxes. This results in a cube with a side length of $31.5cm$ on average which is around 50% larger than the physical prop. However, there is a large standard deviation ($SD = 7.61$).

Second Task. In the second task, we were interested if there is a difference in perceiving the mismatch between virtual objects and the physical prop when we use different displacement functions. We handed the participant the $20cm$ sized physical prop 11 times but each time the virtual box was scaled by a different factor in a range of 0.875 to 1.125 in steps of 0.025. The scaling was applied in a Latin-squared order. The participants had to investigate the box and state if it is smaller, bigger or has the same size as the haptic prop they were holding. Similar to the first task, the participants could investigate the boxes bi-manually by rotating, squeezing, and re-grasping them as desired. After the participants gave us an answer, they gave back the prop to the experimenter. This process was repeated 2 times i.e. 3 times in total; once for each displacement function (i.e. linear, logarithmic, or exponential).

In Figure 3, we aggregated the answers of all participants estimating if the physical box was smaller or larger or equal in size than the virtual box while the position of their hands was manipulated with the different displacement functions. On the y-axis, the size of the virtual boxes is shown. The x-axis shows if the estimation was correct or incorrect. The size of the green or red dots indicates how many participants guessed either correct or incorrect. When using the linear displacement function participants estimated the size of the given boxes on average 5.83 ($SD = 1.6$) times correctly. Also, 5.83 ($SD = 1.46$) boxes were estimated correctly while using the logarithmic function. Using the exponential function the box size was estimated 6.08 ($SD = 1.61$) times correctly. Our results indicate that the participant's estimation is not strongly affected by the displacement functions. We observed similar patterns for each of the displacement functions.

Participants Feedback. To better understand the effects of the displacement functions, we gathered qualitative feedback from our 12 participants through a semi-structured interview. The participants were asked to rate the correctness of their estimation of the box sizes on a scale from 1 (least accurate) to 7 (most accurate). On average they answered $M = 3.79, SD = 1.28$. Next, the participants were asked to rate how well the visual representation matched the physical sensation on a scale from 1 (not at all) to 7 (completely). They rated on average $M = 4.5, SD = 1.24$. We asked the participants if they noticed that we were handing them always the same physical prop. Five participants said they immediately realized the deception (P3, P5, P9, P10, P11). P2 stated *"the boxes all felt like they were of the same size"*. Two participants did not realize the illusion at the beginning, but later on (P4, P12). P12 stated *"[...] I would have assumed that I got both, the medium and the large box"*. Another three participants did suspect something was not right but they were not sure about it (P2, P6, P8). P6 said *"Sometimes the boxes felt the same but I was not sure if they all were the same"*. Last, two participants said that they have not recognized anything (P1, P7) throughout the study. None of the participants noticed a difference in the movement of the virtual hand while they reached for the boxes, even when we applied different displacement functions.

Limitations. Our sample size of 12 participants which is a rather small sample size. Also, we had an imbalanced gender distribution (11 male, 1 female, 0 other). Future studies could aim for a larger, more balanced sample size. Also, we had a fixed hand size in VR i.e. the average human hand size of females and males. This might lead to differences in estimation [4]. Future work could adjust the hand individually to the participants to make their estimation more precise.

5 DISCUSSION & FUTURE RESEARCH DIRECTIONS

The evaluation of the displacement functions showed that the participants can hardly estimate if the size of a virtual box matches the physical one they were holding if the manipulation of the hand position does not exceed a certain threshold. In the study, on average, the participants noticed the manipulation after the virtual box was 50% larger than the physical prop ($20cm$ side length). Due to a rather high standard deviation (SD = 7.61), this threshold might need further investigation. The qualitative results point out that more than half of the participants were not sure if they received the same physical prop. These participants thought we were handing them differently sized props. This underpins the 50% threshold and is in line with previous approaches that used smaller haptic props [6].

Further, the results of the second task showed that when estimating the difference between a virtual and a physical object both different in size, the users estimate size more correctly when the virtual object is smaller than its physical counterpart. When the size of the virtual object is larger than the physical prop, users tend to think they are either of the same size or smaller than their virtual counterparts. However, the change in the size of the virtual box, in general, was rather small (2.5% of the original size). Thus the estimation of the box size was rather difficult because the boxes only differed by $0.5cm$ to $2.5cm$. We see a tendency that a virtual size illusion remains more likely uncovered when the virtual object size is larger than the physical size of a prop. But further investigations are needed to derive definitive thresholds. Further, such thresholds might depend on the underlying scenario. Thresholds might differ when bringing such illusions to VR games as the user might be distracted by certain game events. However, VR games contain a variety of different virtual objects making it challenging to design a one-size-fits-it-all prop that provides corresponding haptic feedback. Therefore, haptic props could be a promising enhancement for the VR experience.

Inspired by our findings, we want to outline future research directions ranging from multi-user VR to more suitable body locations and safety-critical scenarios.

Conflicts in Multi-User VR Environments. Manipulating the virtual hand position results in a mismatch between the virtual and physical environment. This can introduce conflicts in co-located multi-user VR scenarios. For example, if two users want to shake hands but their virtual hand position differs from the real hand position they can not touch each other. Future research might investigate how severe these conflicts affect VR experiences and how they can be resolved if hand displacement is applied. We propose to investigate if the different displacement functions (i.e. linear, logarithmic, exponential) are suited to resolve conflicts in multi-user VR environments by dynamically applying an offset to reuse haptic props while preserving physical interaction between users. Similar to approaches that redirect VR users to meet again after their walking path was altered [26].

Other Body Locations. Future VR systems might be able to track the whole body of a user making it possible to interact with knees, feet, or elbows. To the best of our knowledge, there is no research neither on how these body parts can be manipulated in a way to reuse haptic props with different virtual representations. Interacting with feet for example could be useful for exergaming [31] or training simulations that make use of different haptic props. Future research could investigate the effects of manipulating the offset of other virtual body parts to widen the interaction space.

Safety Critical Scenarios. Manipulating the virtual position of physical props might induce safety issues. For example, a climbing simulation in VR might benefit from reusing haptic props to enhance realism [27]. Manipulating the hand or feet position improperly might lead to severe issues or injuries. A climber might fall off a climbing wall when the virtual environment suggests physical props at the wrong position or a climber reaches out too quickly for a haptic prop and reaches into empty space because of the mismatch between the virtual and the physical world.

6 CONCLUSION

We developed three displacement functions that manipulate the virtual hand position of a user in physical-prop-enriched VR. This manipulation can be used to make users believe that virtual objects are differently sized than their physical counterparts. Our study showed that with a physical box of $20cm$ side length the manipulation was uncovered after the virtual box was 50% bigger than the physical one when we used a linear displacement function. This is in line with previous approaches that used smaller haptic props [6]. Further, we explored if the three displacement functions (i.e. linear, logarithmic, and exponential functions) affect the size estimation of our participants. Preliminary results for all three displacement functions pointed towards being perceived similarity by the participants but further investigation is needed. We suggest investigating stronger manipulations. This could uncover thresholds that might help designers of haptic VR environments to create more convincing touch interactions with physical props. In the future, VR environments could be experienced in arbitrary real-world settings [10]. The physical and virtual worlds could be combined to create a more immersive experience [15, 28]. Here, displacement functions could be investigated if they are suitable to enhance the degree of freedom for the VR narrative, i.e. manipulating the shape and size of virtual objects while exploiting haptic features of real-world objects that serve as haptic props.

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