I'm in Control! Transferring Object Ownership Between Remote Users with Haptic Props in Virtual Reality

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Figure 1: Remote VR collaboration can be extended with physical elements such as tables and props (a-b). Physical local objects and virtual remote objects are mixed in the UI (c-d) to seamlessly interact with all the objects.

ABSTRACT

Virtual Reality (VR) remote collaboration is becoming more and more relevant in a wide range of scenarios, such as remote assistance or group work. A way to enhance the user experience is using haptic props that make virtual objects graspable. But physical objects are only present in one location and cannot be manipulated directly by remote users. We explore different strategies to handle ownership of virtual objects enhanced by haptic props. In particular, two strategies of handling object ownership – *SingleOwnership* and *SharedOwnership*. *SingleOwnership* restricts virtual objects to local haptic props, while *SharedOwnership* allows collaborators to take over ownership of virtual objects using local haptic props. We study both strategies for a collaborative puzzle task regarding their influence on performance and user behavior. Our findings show that *SingleOwnership* increases communication and enhanced with virtual instructions, results in higher task completion times. *SharedOwnership* is less reliant on verbal communication and faster, but there is less social interaction between the collaborators.

CCS CONCEPTS

• **Human-centered computing** → **Human computer interaction (HCI)**; **Mixed / augmented reality**; **Virtual reality**; **Collaborative interaction**; **Interaction techniques**.

KEYWORDS

Virtual Reality, Collaboration, Haptic Props, Interaction Techniques

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1 INTRODUCTION

Collaborative work allows to combine knowledge and shape collective solutions that incorporates different perspectives. This can benefit various application areas ranging from problem-solving and content layouting, to architecture and manufacturing tasks [26, 31, 54]. A promising technology to enable collaboration across

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distance is VR. One can imagine a workspace where a user is collaborating at a table. The table and its objects are physical, spatially registered with and visualized in the virtual scene. This provides the advantage of physicality, the intuitive familiarity of working on a table and the tactile sensation of grabbing and manipulating objects. At the same time, the benefits of virtuality can be exploited — one can perceive the remote collaborators' presence and the interaction is synchronized over the network in a unified VR experience.

Lots of future collaborative work can shift to VR. With technical advancements, future VR systems could integrate physical objects and provide them as haptic props that are ubiquitously applicable during collaboration. This could enable remote users to create a collective solution by using physical objects present in their location. Here a fundamental challenge is interaction with remote physical objects. One can manipulate the own local object as well as the virtual representation of a remote object but not manipulate the actual remote physical object.

Yet, collaborators may be of distinct expertise, where an ability to manipulate remote objects directly can become helpful. Related work suggests augmenting objects with motors [12, 44] or using teleoperated robot arms for remote control [15]. Or, to indicate the manipulation virtually, which the partner can then physically recreate in their location [20, 23]. However, as these approaches either require extensive hardware augmentation or user effort, it is desirable to seek alternative ways to tackle this challenge.

We investigate a new approach that engages users more actively and closely preserves the notion of physical manipulation across local and remote spaces. Our idea is to use passive haptic props in each physical location for the interaction with virtual objects. These haptic props have a variable representation in the virtual environment and can be used to control the available virtual objects. We explore this in two ways of ownership of the assigned virtual objects: *SingleOwnership* and *SharedOwnership*. *SingleOwnership* restricts collaborators to manipulate only the virtual objects that are associated with their local haptic props, whereas *SharedOwnership* allows transferring virtual objects between remote locations by taking over ownership with haptic props.

We implemented a distributed multi-user VR system that allows remote collaborators to interact with haptic props to solve a spatial arrangement task. The system incorporates haptic props registered at two locations by optical tracking. The spatial information is shared live across the network. Collaborators experience virtual objects assigned to remotely located haptic props at the correct 3D location and orientation in the virtual room. We conducted a user study to gather insights about the performance, experience, and trade-offs of the collaboration with different ownership strategies. We implemented a puzzle task that required the collaborators to create a certain arrangement of puzzle pieces using haptic props. To fulfill the task, the collaborators had to exchange knowledge with the given ownership techniques.

For *SingleOwnership* we employed two conditions. (1) collaborators could either use haptic props to arrange their own puzzle piece and then rely on verbal communication and gestures to communicate the solution of the task to each other. (2) Collaborators could create virtual instructions that indicate the correct arrangement of puzzle pieces using *blank haptic props* (*Instruct*). Therefore, we provided an additional set of haptic props. These haptic props were 'blank' and could be assigned to a puzzle piece by the user. For *SharedOwnership*, we employed two transfer techniques namely *copy* and *cut*. *Copy* allowed collaborators to use blank haptic props to retrieve a copy of a virtual object that is assigned to a remotely located haptic prop. *Cut* allowed collaborators to reassign virtual objects from remote haptic props to blank local haptic props. In this case, the remote haptic prop turned blank.

By having the ability to transfer remote objects using local haptic props, collaborators perceived that they communicated less using speech or gestures. Our results indicate that which strategy to handle ownership works best – *SingleOwnership* or *SharedOwnership* – is depending on the underlying scenario. We found that collaborators were significantly slower when using virtual instructions compared to verbal communication or transferring ownership via *copy* or *cut*. By having the ability to transfer remote objects using local haptic props, collaborators perceived that they communicated less using voice or gestures. Overall, we found that *SingleOwnership* techniques are more useful if awareness between collaborator's actions is needed (e.g., novice/expert scenario), while *SharedOwnership* techniques provide benefits when collaborators want to use their own expertise to solve a task with fewer dependencies on each other. For example, creating a collaborative solution to which collaborator contributes with their own knowledge to shape the best result.

The contributions of this work are as follows:

1. The design of *SingleOwnership* and *SharedOwnership* collaboration techniques. *SingleOwnership* techniques rely on instructions either verbally or by using haptic props. *SharedOwnership* techniques allow transferring virtual objects between remote locations using haptic props. This allows the collaborators to work more independently.
2. An open-sourced VR system for multi-user remote collaboration with tracked physical objects at both locations.
3. A user study comparing our techniques and revealing insights on the unique trade-offs between spatial task efficiency and communication engagement of the users.

2 RELATED WORK

In the following, we review previous work on video-based remote guidance, 3D-based collaboration, as well as tangibles and haptics with a focus on their use in collaboration.

2.1 Video-based Remote Guidance

As one of the first efforts, Kuzuoka investigated experts collaborating remotely over a screen with a head-mounted device (HMD) user [30]. The user's HMD included a small display that showed the collaborator's finger pointer image to indicate position. The evaluation showed that gestures led to improved task performance, with fewer words needed. Other methods for providing input to the collaborator are annotations through gestural sketching [41], visual hand embodiment, and cursor pointers [16]. The latter describes two fundamental ways to support the collaborator: pointing gestures for reference and representational gestures to convey form and nature of actions. Kirk and Fraser compare unmediated hands, hands and sketch, and digital sketch only, either presented on a monitor or projected into the workspace [28]. No difference was found for output location (monitor or projected), but hand gestures had the highest performance. Others extended screen-based input to communicate rotation and translation of objects [2].

2.2 VR-based Collaboration

Traditional voice or video-based remote guidance confine the collaboration, e.g. from ambiguous language [52] or confusion [24]. Hence, VR-based collaboration approaches that go beyond voice and video-based guidance are promising for co-located [40] and remote collaboration [5]. It is beneficial for the experience when collaboration happens synchronously [19]. However, collaboration can be asymmetric, meaning users can collaborate using different technologies [27, 50]. Moreover, previous work shows that 3D-based collaboration is not limited to two users [22, 46] and allows group-to-group telepresence [4]. Yet, it requires efficient interaction concepts to enable fluid collaboration [55].

An essential part of remote 3D-based collaboration is reconstructing collaborators' bodies [25, 29] and their physical environment [17], allowing scenarios such as *Holoportation* [39]. Awareness cues, such as gaze and head movement, can be added for a more realistic collaboration [42, 45, 51]. Previous work found task performance to benefit from a combination of these awareness cues [21]. Others have explored how hand gestures and sketches can be integrated in collaboration scenarios [18, 49]. Studies found that hands are very intuitive [53] and increase task performance accuracy [49]. Hence, we utilize them for our scenario, empowering collaborators to communicate via pointing and gestures.

2.3 Physical Object Integration

2.3.1 Tangibles. Tangibles allow computer interfaces to be closer to the physical world by providing users with haptic feedback [20]. They can enhance task performance (e.g., allow for more precise input [12]), achieve a higher learning gain, and perceive problem-solving as playful [47]. Tangible interfaces for collaboration were introduced in 1998 [6]. They often require active components to reflect the movement of the tangibles at other physical locations [43]. Prior work explores scenarios, such as playing air-hockey over distance [37] or transmission of shapes [32]. Nonetheless, the active components remain technically challenging, making them less generalizable (c.f., air-hockey scenario [37]).

2.3.2 Haptic Props. Combining tangibles with VR is promising as aspects of the physical object (e.g., visual appearance) can be added in real-time, enabling a more universal usage [23]. These generic physical objects are often referred to as haptic props, designed to give users the sensation of touch (e.g., as passive [33] or active haptic props [23]) without a strict 1:1 mapping between object and function. How to enable more expressive physical sensations in VR has been explored before. For example, people can physically move objects in the background of the virtual session [8, 10], the prop itself can dynamically change weight [56], and can be actuated through robots [35, 58] or quadcopters [1]. It is also possible to use dynamic repurposing of interaction elements, such as the passive haptic [3] or the user's manual input [9, 57] to be able to interact with a more diverse set of props. Complementarily, our research investigates increasing expressiveness of haptic props for remote collaboration where local and remote props are mixed.

2.3.3 Collaborative Haptic Props. For co-located collaboration, these haptic props can be shared by users [23], whereas if remote, each collaborator needs their own set of haptic props [13]. Previous work frequently studied asymmetric collaboration that uses a combination of AR for a novice user on-site and VR for a helping remote expert [7, 14, 38]. Nevertheless, in many scenarios it makes sense to utilize symmetric collaboration between VR users (e.g., problem-solving [31], content creation [11], or training [22]). Different types of active haptic props have been proposed in the literature that can reflect manipulations by remote collaborators [13, 23]. Additionally, the teleoperation of a robotic arm can allow users to manipulate remote objects [15]. However, these systems are more challenging to construct and require additional components such as motors or displays. We extend the prior work by a study of how remote and local users can interact with passive haptic props and utilize them in a synchronous collaboration task.

3 HAPTIC PROPS FOR COLLABORATION

We introduce our approach to collaboration using passive haptic props in an immersive VR environment (see Figure 2). Our approach is split up into two integral parts – *SingleOwnership* and *SharedOwnership*. First, we introduce how we use passive haptic props to interact with virtual objects, and we present how collaborators can help others to solve tasks by creating virtual instructions using these props (*SingleOwnership*). Second, we describe techniques for sharing ownership of virtual objects across remote locations using haptic props. These techniques are inspired by established concepts like *copy* and *cut* known form standard desktop PCs (*SharedOwnership*). Since concepts are well-known and ubiquitously available, we were interested in how they apply to the utilization of haptic props.

3.1 Interacting with Haptic Props

In a remote collaboration scenario, each collaborator possesses a set of haptic props which are mapped to virtual objects (see Figure 2a). The goal is to place the virtual objects in a specific arrangement by using haptic props. As it is not possible for a local collaborator to move remotely located haptic props, we need a mechanism to manipulate virtual objects mapped to remote haptic props using local haptic props. For example, in Figure 2b a remote object is reassigned to the local haptic prop by transferring its virtual representation. This is one example, how haptic props can be used to interact with remote objects. To enable seamless collaboration, haptic props need clear semantics. In the following, we introduce how we accomplished that by giving our haptic props two states.

3.1.1 Assigned Haptic Props and Blank Haptic Props. Our collaboration techniques are based on two different states of haptic props. The haptic props can either be assigned to virtual objects that are part of the collaboration task or can be blank. If the haptic prop is assigned to a virtual object the collaborator that physically possesses the haptic prop is the owner of the virtual object and can move it around in VR. If the haptic prop is blank, it can be used to interact with virtual objects that are assigned to remotely located haptic props (see Figure 2b). These two states form the basis of our collaboration techniques. In the following, we introduce our techniques in greater detail.

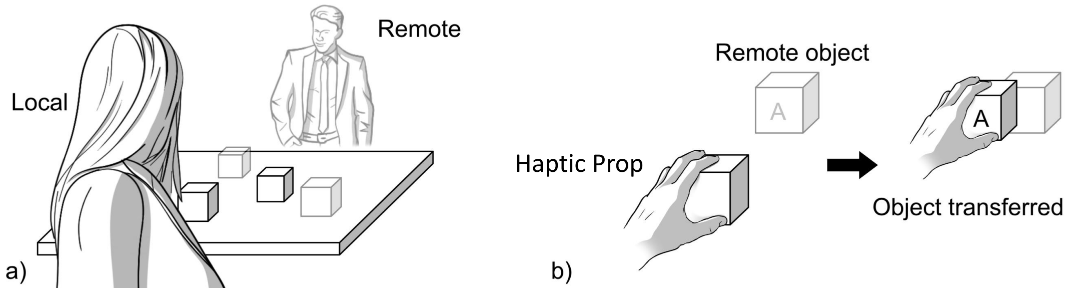


Figure 2: (a) A local and a remote users collaborating using virtual objects which are assigned to haptic props. (b). A remote object is transferred to the local object. This transfer can be triggered when a local object intersects a remote object.

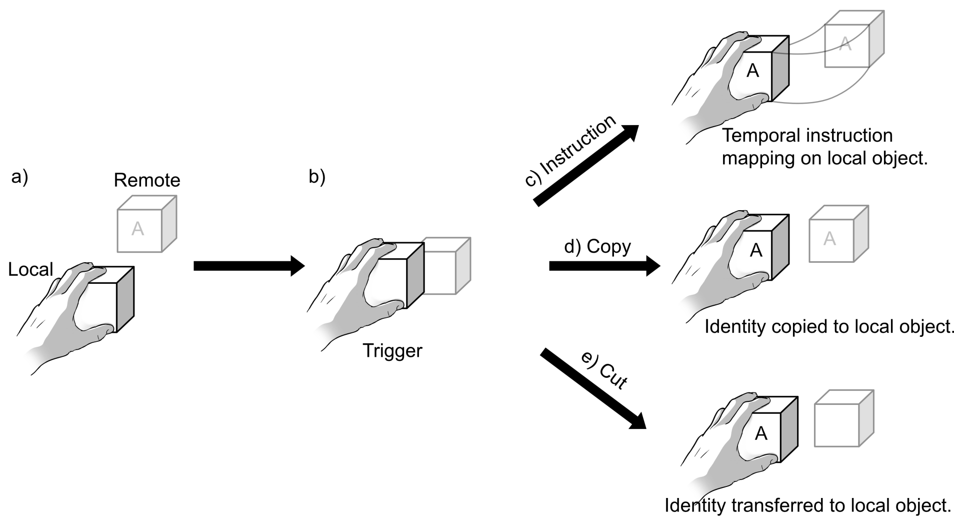


Figure 3: Three ways of handling ownership of the local user to a remote user's object. Initially, intersecting a local object with a remote object starts the interaction (a-b). Then, an Instruction (c) shows a virtual replica useful to indicate what to do to the remote object. Techniques (d) and (e) transfer the ownership from a remote to a local user. Either a copy of the virtual object is created (d) or the identity of the virtual object is assigned to the local haptic prop (e). The remote object then turns into a blank.

3.2 Techniques for Single Ownership

For single ownership collaboration using haptic props, we devised two different techniques.

Baseline. The baseline technique allows each collaborator to arrange virtual objects, using their own local haptic props. In this case, the haptic props can not be used to interact with virtual objects assigned to remotely located haptic props. Hence, collaborators must rely on verbal communication or gestures to collaborate in the VR environment.

Haptic Props for Remote Instructions. This technique allows collaborators to create instructions for each other using blank haptic props similar *Virtual Replicas* introduced by Oda et al. [38]. *Virtual Replicas* are representations of physical objects that are manipulated by a remote collaborator. The virtual replica can be augmented virtually by an expert with annotations to instruct the remote collaborator. This helps in scenarios, in which experts give instructions to trainees or people with different levels of expertise collaborate. We combine remote instructions with haptic props to allow for the natural creation of instructions for remote collaboration. Our technique allows collaborators intersecting a blank haptic prop with a virtual object that is assigned to a remotely located haptic prop (see Figure 3 a-b). This triggers the creation of an instruction that associated the virtual objects with the blank haptic prop (see Figure 3 c). The remote collaborator can now follow the instruction to place the virtual object correctly.

3.3 Techniques for Shared Ownership

In contrast to the single ownership approaches, requiring a remote collaborator to actively place objects with respect to the other collaborator's instructions, we introduce two interaction techniques that allow taking over the ownership of virtual objects that are assigned to haptic props of remote collaborators.

Taking Over Ownership via Copy. One way to retrieve ownership of a virtual object is to copy it (i.e., assigning it from a remote to a local haptic prop). To do so, a collaborator uses a blank haptic prop. To create a copy, a collaborator intersects a blank prop with a virtual object assigned to a remote haptic prop. (see Figure 3 a-b). The virtual object is copied to the blank haptic prop (see Figure 3 d).

Now the copied object can be moved to the correct position without the collaborator's help. The remote collaborator keeps the piece assigned to their haptic prop.

Taking Over Ownership via Cut. Taking over ownership of a virtual object can be accomplished by re-assigning it from a remote haptic prop to a local blank haptic prop. Similar to taking over ownership by copying a virtual object, cut allows a collaborator to use a blank haptic prop to retrieve ownership of a virtual object. To cut a virtual object, a collaborator intersects a blank haptic prop with a virtual object of the remote collaborator (see Figure 3 a-b). Then it is assigned to the blank haptic prop and the remote haptic prop turns blank (see Figure 3 d).

4 IMPLEMENTATION

To evaluate the different collaboration techniques, we developed a distributed synchronized collaborative VR environment in which two collaborators can interact to accomplish their tasks. It is based on using a VR headset and motion-tracking technology at each location. This allows collaborators to be immersed in a virtual environment integrating tracked physical components into the virtual scene. The code of the project is available under MIT license on GitHub[1].

4.1 Architecture

The environment consists of multiple instances of an application running in parallel in two separate locations. Each location uses an *OptiTrack* motion capture system (120*Hz*, latency $\approx$ 8 ms, 0.02 mm precise) to track the collaborator and passive haptic props. In both locations, we calibrated the *OptiTrack* system. Our systems reported a mean 3D error of < 0.5 mm in both our labs. In both locations, we calibrated the HMD systems and aligned them with the *OptiTrack* coordinate system. The arrangement of the cameras did not meet any special requirements except providing sufficient tracking quality in the collaboration area. In our setup, the first location used an *HTC Vive Pro*, and the second location an *Oculus Rift*. The application was created with *Unity3D* and enables users to join a shared virtual environment and interact with the given virtual objects that were assigned to haptic props. To allow interaction between the two locations, local spatial data is synchronized with data from the remote client application, resulting in a seamless, location-spanning VR environment. Therefore, the system utilized a UDP channel to exchange data live and without unnecessary networking overhead.

4.2 Mixing the Virtual Environment with the Real-World

We created a virtual environment consisting of a room with a table in the middle (see Figure 1 c-d). For each location, real-world objects can be integrated into the environment to enable VR-mediated collaboration (see Figure 1 a-b). Static objects such as tables, which have physical representations in both locations, are implemented as shared elements within the virtual environment. Optically tracked haptic props are present on the table at the location of each collaborator. Virtual objects are linked to these haptic props. The motion of each tracked object is then applied to its virtual representations. Virtual objects present at the remote location are rendered transparent to easily indicate which objects are assigned to local haptic props and which to remotely located ones (see Figure 1 c). To give the collaborators a representation of themselves, the system tracks their hands via tracking gloves. We only show the hands of the collaborator, not a full avatar. We did not implement full finger tracking in the current stage of the system. As we had plenty of optically tracked objects, we went for a more simplistic approach. Hence, only a hand with static fingers was shown. Nevertheless, this still enables user-to-user pointing to collaborate. Collaborators were able to interact with the provided haptic props with their hands.

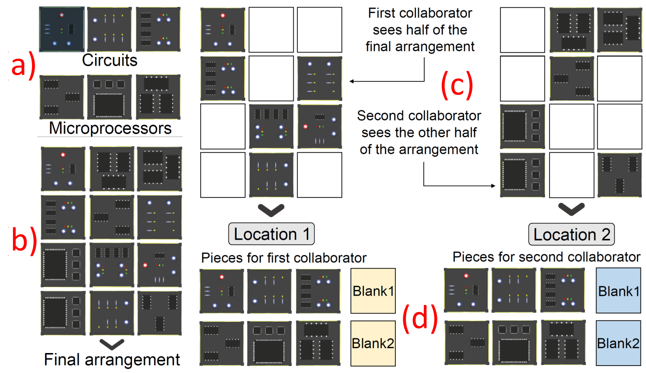


Figure 4: Puzzle Task: (a) The *Circuits* and *Microprocessors* pieces. (b) Plan showing the required arrangement of the pieces. (c) First and second collaborators' individual part of the solution (exclusive knowledge). (d) components available at each location at the start.

5 EVALUATION

We conducted a explorative study using our collaborative environment to connect two collaborators on a virtual table across two physical locations. We explore how *SingleOwnership* and *SharedOwnership* of passive haptic props influences collaboration performance and teamwork quality. In the following, we introduce our details on our virtual environment configuration, the collaborative task, the study conditions, and the procedure and participants. We report results in the following notation; mean values (M), standard deviation (SD), median values (Mdn), and interquartile ranges (IQR).

5.1 Virtual Environment

Our application allowed collaborators of each location to meet at a virtual table in the middle of a virtual room (see Figure 1). The tabletop measured 80cm $\times$ 80cm. Our virtual environment consisted of a simple room with white walls and a wooden floor, clear of any distractions. At the table, the collaborators worked on the collaborative puzzle task. At each physical location, a collaborator sat at a real table in the middle of a tracking space. The virtual and physical tables match exactly in size to prevent any mismatch. The collaborators sat across from each other during the collaborative task.

[1]https://github.com/jonasauda/im_in_control

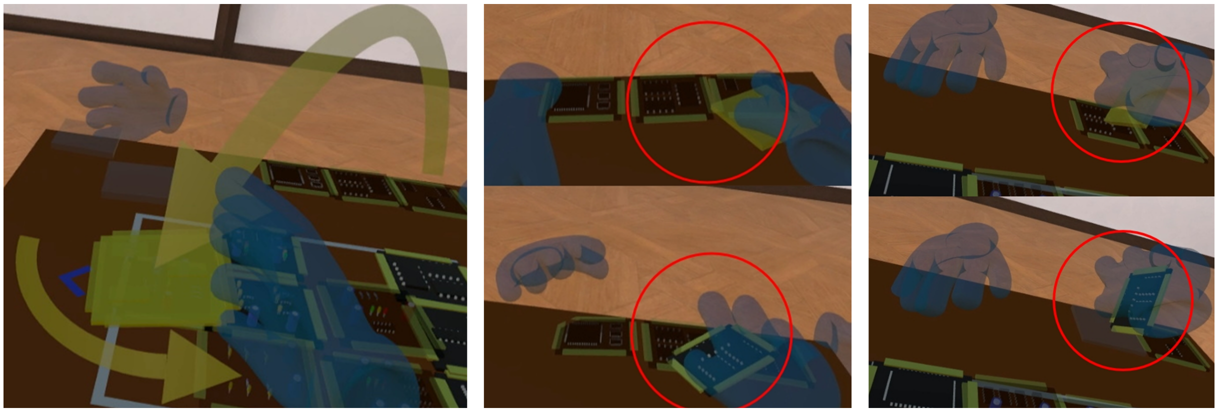


Figure 5: Left: An example of *Instruct*, where arrows indicate the position and orientation of the instructional object. Middle: *Copy* to copy a puzzle piece with a haptic prop, by moving it inside the piece (top), hold for a second, then move out (bottom). Right: Similar procedure, but for *Cut* where a haptic prop retrieves ownership of a puzzle piece (and the original is removed).

5.2 Collaborative Puzzle Task

For the collaboration, we chose a circuit design scenario. The circuit aspect was not important to the evaluation but should give the impression of a meaningful task. The task resembled a puzzle task with circuit elements, we call *puzzle task* from now on. The objective for a pair of collaborators was to assemble a simplified and scaled-up printed circuit board consisting of *Microprocessor* parts and corresponding *Circuit* parts (see Figure 4-a). The required arrangement consisted of 12 square components, represented by 10cm × 10cm wooden pieces that we call haptic props. The task was designed to elicit collaboration: each collaborator had knowledge about half of the complete solution. Hence, to complete the task, the collaborators had to support each other by sharing knowledge. The collaborator in one location was provided with a plan showing the target positions of *Circuit* parts, the other one with the target positions of *Microprocessor* parts (see Figure 4-c). In the beginning, each collaborator had six local parts: three of the type *Microprocessors* and three of type *Circuits* (see Figure 4-d). Hence, the collaborators could only place three of the six initial parts on their own and then had to collaborate to complete the arrangement.

5.3 Study Conditions

We explored *SingleOwnership* using two conditions: using haptic props to collaborate without interacting with remote virtual objects (*Baseline*) and using haptic props to instruct a collaborator (*Instruct*). Also, we explored *SharedOwnership* using two conditions: using haptic props to copy remote virtual objects (*Copy*) and using haptic props to transfer remote virtual objects to local haptic props (*Cut*). The different conditions can be seen in Figure 5 and are described in more detail in Sections 3.2 and 3.3. During *Copy* participants could revert puzzle pieces to blank haptic props by moving them into a dedicated red area in VR.

5.4 Procedure

In the beginning, we welcomed our participants to the study. We introduced the overall procedure and answered open questions. After our participants gave their informed consent we recorded demographic data. Then we situated them at the table and provided the VR-HMD and tracking gloves. We established a communication channel between the two locations using Skype[2]. The two collaborators could briefly introduce themselves. Each group of collaborators consisted of one participant and one confederate. The confederate was instructed to act as a newly instructed participant and had no knowledge of the research questions. The confederate adjusted to the working pace of the participants. Further, the confederates were not instructed to make mistakes intentionally. In total, two different persons acted as a collaborator – one self-identified as male and one as female. We did not tell our participants that they were collaborating with a confederate. After both collaborators were situated at the desk and were provided with a VR-HMD, we introduced them to the collaboration task. Each participant completed the task in four conditions, with each condition involving two trials. To account for learning effects, we only took the second trial into account in the analysis. In the first trial, we made sure that the participants understand how to collaborate using the provided collaboration technique. For each condition, we measured task completion time, the number of actions needed to fulfill the task, and the user experience (UEQ) [48]. For the study, the order of the conditions was counterbalanced. After each condition, the participants also filled out a questionnaire about helpfulness, verbal communication, and quality of collaboration. The study concluded with a brief interview session. Each participant took on average one hour for the study. We used a screen capturing tool to record the virtual setting during the study for later analysis.

5.5 Participants

We recruited 12 participants (6 female, 6 male), aged between 23 and 31 ($M = 26.58, SD = 2.60$). We asked each participant to rate their experience with VR on a 7-Point Likert-scale (1=no expertise, 7=expert). Participants stated they have some VR experience ($M = 3.40, SD = 1.77, Mdn = 3.00, IQR = 3.00$).

[2]Skype (Skype Technologies, Microsoft Corporation, Redmond, Washington, USA) https://www.skype.com, last retrieved September 30, 2021.

5.6 Results

Overall, all participants were able to solve the task correctly with each condition. We compared the different collaboration techniques in terms of task completion time, interaction duration, collaboration behavior, and user feedback. Given the smaller sample size due to one sample per condition and twelve participants in total, we did not assume normal distribution of our data and hence, applied non-parametric tests. Effect sizes are reported as r (>0.1 small, >0.3 medium, and >0.5 large effect).

Task Completion Time. We analyzed the task completion times (TCT) for each condition (see Figure 6a): for *Baseline* we observed an mean TCT of 88.89s ($SD = 21.72s, Mdn = 87.60s, IQR = 33.88s$), for *Instruct* 152.58s ($SD = 73.96s, Mdn = 131.06s, IQR = 111.88s$), for *Copy* 82.15s ($SD = 21.70s, Mdn = 78.20s, IQR = 32.32s$) and for *Cut* 80.89s ($SD = 38.42s, Mdn = 65.71s, IQR = 52.60s$). The Friedman test showed significant differences between the conditions (χ^2(2)=16.90, p=0.001, N=12). A post-hoc test using Wilcoxon Signed-rank with Bonferroni-Holm correction revealed significant differences between *Baseline* and *Instruct* (W=4, Z=-2.746, p=0.021, ϕ=0.56), *Instruct* and *Copy* (W=73, Z=2.67, p=0.029, ϕ=0.54), and *Instruct* and *Cut* (W=78, Z=3.06, p=0.001, r=0.63). Participants were slower in the *Instruct* condition than in *Baseline*, *Copy*, or *Cut*.

Interaction Duration. We compared the interaction duration with the haptic props of each condition. The mean interaction duration was 3.30s ($SD = 0.56s, Mdn = 3.21s, IQR = 0.72s$) for *Baseline*, 3.29s ($SD = 0.77s, Mdn = 3.37s, IQR = 1.14s$) for *Instruct*, 3.13s ($SD = 0.68s, Mdn = 2.90s, IQR = 0.76s$) for *Copy* and 3.52s ($SD = 1.41s, Mdn = 3.18s, IQR = 0.71s$) for *Cut* (see Figure 6b). A Friedman test showed no significant differences between the conditions (χ^2(2)=0.90, p=0.825). We compared the number of interactions with the haptic props (see Figure 6c). For *Baseline*, we observed a mean number of interactions of M=21.75 ($SD = 5.28, Mdn = 20.00, IQR = 7.50$), for *Instruct* we observed M=35.67 ($SD = 13.43, Mdn = 30.50, IQR = 26.50$), for *Copy* M=22.17 ($SD = 5.56, Mdn = 19.50, IQR = 10.00$) and for *Cut* M=20.75 ($SD = 9.56, Mdn = 18.50, IQR = 2.50$). A Friedman test showed significant differences (χ^2(2)=17.07, p<0.001, N=12). A post-hoc test using Wilcoxon Signed-rank with Bonferroni-Holm correction revealed significant differences between *Instruct* to *Baseline* (W=72.5, Z=2.633, p=0.032, r=0.54), *Instruct* to *Copy* (W=63, Z=2.71, p=0.023, r=0.55), and *Instruct* to *Cut* (W=78, Z=3.07, p=0.003, r=0.63). While using *Instruct*, the collaborators had to place two haptic props. First, one collaborator had to place one puzzle piece to create an instruction. Then the other collaborator had to place the corresponding puzzle piece according to the created instruction. Hence, we observe a higher number of interactions. Therefore, this result is dependent on the design of the technique rather than the collaboration performance.

User Experience Questionnaire. Participants were asked to rate basic attributes of their experience after each condition using the *User Experience Questionnaire* (UEQ). We computed the hedonic, pragmatic, and overall quality of each interaction technique (see Figure 7). The overall scores are:*Baseline* M=2.00 ($SD = 1.52, Mdn = 2.00, IQR = 2.16$), *Instruct* M=1.85 ($SD = 0.84, Mdn = 1.81, IQR = 1.34$), *Copy* M=1.63 ($SD = 1.09, Mdn = 1.75, IQR = 1.94$) and *Cut* M=1.89 ($SD = 0.88, Mdn = 1.94, IQR = 1.56$). A Friedman test showed no significant differences between the conditions (χ^2(2)=1.89, p=0.60, N=12).

Verbal Communication. We asked participants to specify the amount of verbal communication needed per condition (7-Point Likert scale; 1=low amount, 7=high amount). Participants stated they verbally communicated a lot for *Baseline* ($M = 6.33, SD = 0.99, Mdn = 7, IQR = 1$), while the need to communicate verbally for *Instruct* ($M = 4.08, SD = 2.31, Mdn = 4, IQR = 3.50$), *Copy* ($M = 4.08, SD = 2.23, Mdn = 4, IQR = 4$) and *Cut* ($M = 3.83, SD = 2.08, Mdn = 3.5, IQR = 2.5$) was lower. A Friedman test showed significant differences (χ^2(2)=15.00, p=0.002, N=12). A post-hoc test using Wilcoxon Signed-rank with Bonferroni-Holm correction revealed significant differences between *Baseline* and *Instruct* (W=36, Z=2.734, p=0.047, r=0.56) and *Baseline* and *Cut* (W=45, Z=2.8617, p=0.023, r=0.58).

User Feedback. The *Baseline* condition was reported to be *"helpful"* [P8] and *"efficient"* [P11]. *"I could immediately point with my hand at the space where a circuit should go. This reduced the need for words and aided the solution-finding process."* [P1]. Comparing it to the other techniques, P12 stated *"It did not really do anything to help me. I needed my partner to talk to me, otherwise, I could not do it at all"*.

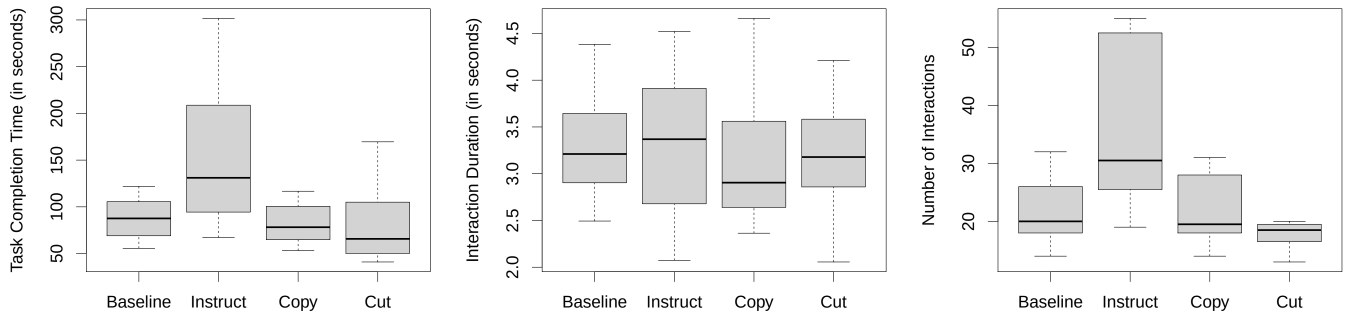
The *Instruct* condition was perceived very positively due to its low mental demand (*"It was intuitive and easy to follow the other person"* [P3], *"You could easily see what to do"* [P12]) and efficiency (*"We could multitask and already show each other where a tile would need to go"* [P1]). P8 stated that this condition brings about *"better collaboration compared to cut or copy where no communication was necessary - here we had to work together to solve the task"*. On the other hand, P8 also noted that it was difficult to show the exact rotation of a component using instruction objects.

Some participants reported a higher cognitive load for *Copy* (*"It was helpful but I had to remember which tile I could delete."* [P3], *"It could be a bit confusing [...]"* [P4], *"[It was] confusing because there was so much going on."* [P12]), while others thought *"everything was systematic and clear"* [P9].

Helpfulness of the *Cut* technique was positively perceived. It was reported to *"require little effort"* [P10] and be *"clear and interesting"* [P9]. Many participants felt this method to be quite efficient (*"I did not have to wait for my partner. I could continue by myself"* [P5], *"I clearly knew which one to take next and didn't need to wait for my partner"* [P12]). However, some participants found it to be disorienting, as *"it was confusing when the other participant cut a piece of mine that I could use as a blank plate"* [P1].

Ranking of Collaboration Techniques. While *Instruct* (4), *Cut* (3) and *Copy* (2) were chosen as the favorite multiple times each. Three participants had no clear favorite. Reasons to prefer the *Instruct* technique included a strong sense of collaboration [P1] and communication [P8], as well as the ease of use [P3, P4]. *Cut* was preferred due to the possibility of working individually [P5, P7]. *Copy* and *Baseline* both were chosen because they require little effort.

Collaboration Strategies. We asked participants about any strategies they had developed over the course of the study. Several participants reported that they always placed those components that they had information about first. Then they turned their attention



(a) Task completion times.

(b) Interaction duration.

(c) Number of interactions.

Figure 6: Results on interactions with haptic props.

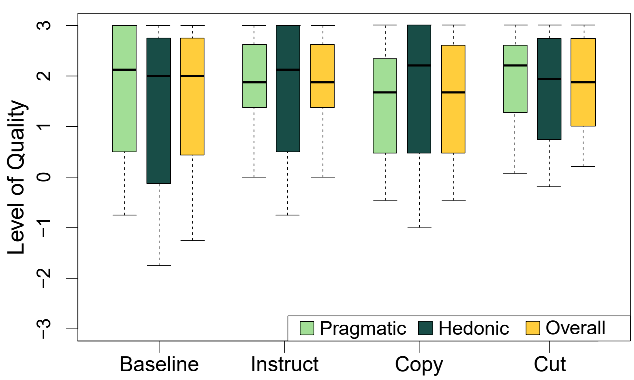


Figure 7: The scores of the User Experience Questionnaire.

to their partner and the remaining components [P3, P7, P8, P12]. P7 considered the difficulty of describing a particular component's target position before deciding where to place components. By placing components on positions that *"would be more complicated to describe"*, P7 avoided a difficult description. As each component exists twice and target positions are interchangeable, there is an alternative target position for each component.

6 DISCUSSION

We explored remote collaboration in VR with a focus on the interplay of virtual objects and passive haptic props, leading to the following insights.

Instructions Take More Time. The addition of instructive props will, as expected, take more time than the baseline, albeit being useful to precisely guide the partner. We note that the instructions affect the communication behavior; users stated to communicate less. This is in line with prior work on remote and immersive collaboration, such as Kuzuoka's Spatial Workspace Collaboration [30]. Less communication can be disadvantageous when engagement with peers is required but can be beneficial as well, e.g., using communication resources for other purposes. Furthermore, instructions can be created by one collaborator who can then move on to the next object for an asymmetric way of interaction.

Baseline without instructions was perceived positively by the participants. They appreciated that they could use pointing to indicate the correct position of puzzle pieces. Another interesting aspect is how instructions might influence *learning* compared to a spoken description. Prior work showed that visual instructions generally lead to higher recall and rule transfer gains [34]. As a result, instructions might be particularly useful in application areas that include a learning process.

On the one hand, collaborators appreciated that they could multitask while using instructions. 5 of 12 participants gave instructions in parallel while working on the task in the *Instruct* condition. On the other hand, some collaborators appreciated the ability to work linearly. Here, a participant started with instructing and the other followed. Then they switched, making it a more planned activity.

Taking Over Ownership. *Copy* and *Cut* allow users to take initiative. These techniques are more suited for tasks with equal roles. For *Cut*, the number of blank props remained the same as one prop was always assigned to one object. For *Copy*, participants had more redundant use of props, leading to search for unneeded pieces to turn them into blank props to continue placing new puzzle pieces (as we had a limit of props in the study). At times this was perceived as slightly more mentally demanding. Further, participants reported that they continued solving the puzzle task decoupled from each other. Here, they had not to wait for the other collaborator's actions.

User Experience. Overall, for all conditions, participants rated their user experience as high. The *Baseline* was rated highest and *Cut* was rated lowest, with a small difference of 0.11. Here, a trend towards the higher end of the scale could be observed (see Figure 7) and we think a ceiling effect was present here. Thus, we did not observe any significant differences between the conditions.

Limitations. We investigate haptic props with a particular form factor and made of a particular material (wood). This was appropriate for our use case since all haptic and virtual objects were similar in shape and size. A takeover in ownership via *Cut* and *Copy* may be perceived differently when the size of haptic props and virtual objects differ. Moreover, we used optical tracking to link haptic props to their counterparts that are shown to the collaborators. While collaborating, the collaborators had to make sure the optical markers of the props were not accidentally covered by their hands. It was possible to interact with the haptic props without covering the markers. Yet, this might have influenced collaboration. To have more control and reduce recruiting efforts, we used confederates. We created different levels of 'expertise' through training. However, this was not known to the participants. We instructed the confederates to not take over the collaboration, and act as if newly introduced to the task. The confederate adjusted to the working pace of the participant but did not intentionally make mistakes. To our knowledge, no participant recognized that they were interacting with our confederates. Furthermore, participants completed each condition twice. We only evaluated the second attempt. Thus, we could instruct confederates to help the participants in the first attempt to ensure familiarity with the corresponding collaboration process. Nevertheless, using confederates with a certain knowledge on the task might bias the results by affecting the collaboration behavior. Pairs of novice collaborators might collaborate at different speeds or might communicate more frequently to exchange knowledge on how to use the different collaboration methods. Collaborators might have different levels of expertise [7, 14, 38] which also can influence collaboration performance. For example, a novice collaborator can adapt to the behavior of a collaborator who has a certain expertise. Finally, our smaller sample size increases the likelihood for Type II errors. To confirm our results further investigations with larger sample sizes are required.

Future Work. We envision haptic props as a scenario-specific tool that, for instance, could be ordered with the desired shapes for a domain-specific task, such as virtual meetings, media production, or interior design, where the number of shapes is foreseeable. For leisure activities such as gaming, a generic set of haptic props may be sufficient. Such a set does not necessarily match all the potential shapes of virtual objects within a VR game. However, this might still be acceptable if efficiency and accuracy are not the primary objectives. Future investigations could focus on enabling more generic forms that make use of dynamically fabricated or even shape-changing objects [36].

7 CONCLUSION

We explored different ways to use haptic props in VR for remote collaboration. The collaboration was centered around a puzzle task. Each collaborator had half of the knowledge about the solution. We explored how collaborators can use haptic props to share knowledge if they cannot take over ownership of virtual objects. Therefore, we introduced instructions that can be created using haptic props in virtual environments and help to communicate how a virtual object should be used. We found that instructions reduced verbal communication and were easy to follow. Further, we explored how taking over ownership of virtual objects can influence collaboration. We introduced two techniques known from standard desktop environments (i.e., *Copy* and *Cut*). Through these methods, collaborators felt more decoupled from each other but each collaborator could work individually and did not have to wait for the other collaborator, resulting in lower task completion times.

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