VRception: Rapid Prototyping of Cross-Reality Systems in Virtual Reality

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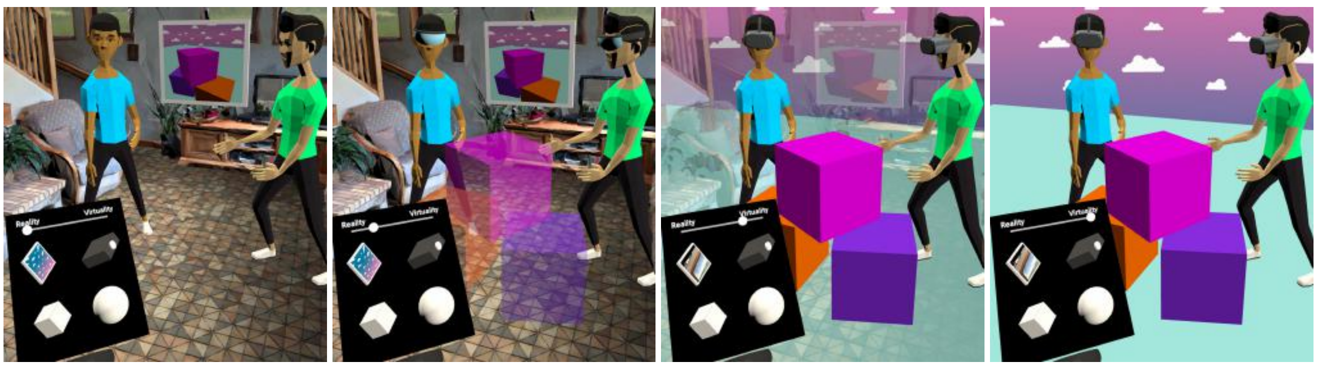

(a) Simulated Reality. **(b) Simulated AR.** **(c) Simulated AV.** **(d) (Simulated) Virtuality.**

Figure 1: The *VRception Toolkit* allows users to transition on the reality-virtuality continuum [41], simulating different manifestations of the continuum, such as Augmented Reality (AR) or Augmented Virtuality (AV), inside of Virtual Reality. The figures (a-d) demonstrate the alpha-blending function to transition between concrete manifestations, however, other transition functions are possible as well.

ABSTRACT

Cross-reality systems empower users to transition along the reality-virtuality continuum or collaborate with others experiencing different manifestations of it. However, prototyping these systems is challenging, as it requires sophisticated technical skills, time, and often expensive hardware. We present *VRception*, a concept and toolkit for quick and easy prototyping of cross-reality systems. By simulating all levels of the reality-virtuality continuum entirely in Virtual Reality, our concept overcomes the asynchronicity of realities, eliminating technical obstacles. Our *VRception Toolkit* leverages this concept to allow rapid prototyping of cross-reality systems and easy remixing of elements from all continuum levels. We replicated six cross-reality papers using our toolkit and presented them to their authors. Interviews with them revealed that our toolkit sufficiently replicates their core functionalities and allows quick iterations. Additionally, remote participants used our toolkit in pairs to collaboratively implement prototypes in about eight minutes that they would have otherwise expected to take days.

CCS CONCEPTS

• **Human-centered computing → Mixed / augmented reality**; **Virtual reality**; *Collaborative interaction.*

KEYWORDS

Prototyping, Cross-Reality Systems, Virtual Reality, Augmented Reality, Transitional Interfaces

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1 INTRODUCTION

Immersive technologies such as Augmented Reality (AR) and Virtual Reality (VR) allow users to engage in alternate digital realities using Head-Mounted Displays (HMD). However, problems that these technologies create are the isolation of users (i.e., HMD users) and the exclusion of bystanders (i.e., non-HMD users) [8, 22]. These issues recently sparked a new research direction – cross-reality systems [58] – which aims to enable interactions across multiple technologies; for example, it allows HMD users in VR to interact with bystanders in the real world. Simeone et al. define them as systems that "envision (i) a smooth transition between systems using different degrees of virtuality or (ii) collaboration between users using different systems with different degrees of virtuality" [58].

Developing prototypes to enable immersive cross-reality systems is often time-consuming and requires both software and hardware prototyping expertise as well as the hardware itself. In particular, cross-reality hardware prototypes (e.g., [13, 21, 22, 40]) have a high entry barrier as they require technology (e.g., displays, projectors, sensors), engineering (e.g., electrical engineering, software development), and design expertise (e.g., rapid prototyping). Enabling rapid, low effort prototyping of cross-reality systems would support researchers and practitioners (i.e., developers and designers) in quickly iterating these systems and make the research area as a whole more inclusive to people who lack resources or do not have the required prototype-building expertise.

To this end, we present *VRception*: the concept of simulating cross-reality systems entirely in VR and allowing researchers and practitioners to rapidly prototype these systems. By simulating all levels of the reality-virtuality continuum, our concept overcomes the asynchronicity of realities. In particular, our concept creates a close coupling of both worlds and simulates a co-located asymmetric environment. This allows researchers and practitioners to instantly remix and blend the simulated real and virtual worlds. Moreover, it reduces the need for strong engineering skills, as it is a software-only approach, allowing to prototype cross-reality systems that typically require hardware setups.

Based on our concept, we developed the *VRception Toolkit*, a multi-user toolkit for quickly and easily prototyping cross-reality systems without the need for hardware prototyping. The goal of our toolkit is to provide an early implementation of our concept that enables researchers to study its' usefulness, which in combination with the open-source nature of our toolkit, allows the community to add features if needed. Our toolkit supports two different prototyping environments: 1) VR with a WYSIWYG (what you see is what you get) editor and 2) Unity. In VR, users are immersed in a simulation of the reality-virtuality continuum (see Figure 1), in which they can combine and configure predefined objects to prototype cross-reality systems. In Unity, users can customize the functionalities of the toolkit, for example, by adding new objects or new transitions between realities. By providing both environments, we can lower the barrier to entry with a simple-to-use VR editor, while not loosing the ability for more advanced customization.

To evaluate the concept of *VRception*, we re-implemented six cross-reality papers published in the last five years [13, 21, 31, 36, 40, 68]. Next, we presented the original authors with our implementation and conducted semi-structured interviews to ask the authors if our implementation could simulate their system's core functionalities and to collect feedback about the implementation of our *VRception Toolkit*. Our expert interviewees highlighted that our toolkit allows rapid and easy prototyping that is otherwise challenging and agreed that we successfully replicated the original systems. To further evaluate how much effort and time it takes to prototype cross-reality systems using the *VRception Toolkit*, we conducted a workshop with eight participants. We asked participants to implement cross-reality systems that allow one to include real-world content in VR and enable bystanders to see the VR experience. Participants with prior knowledge in VR/AR development were able to create different cross-reality systems in an average time of about eight minutes. This further shows that the *VRception Toolkit* is easy to learn and allows users to quickly and easily prototype cross-reality systems leveraging the concept of *VRception*.

The main contributions of our work are:

(1) The concept of *VRception* and its evaluation with six experts who developed and published prior cross-reality systems.
(2) The implementation of the *VRception Toolkit* as a WYSIWYG application inside a VR headset, enabling novice users to collaboratively and rapidly prototype cross-reality systems without coding or hardware building expertise.
(3) Insights from a follow-up evaluation through a workshop, where participants (n=8) were able to quickly (in ~8 minutes) create cross-reality systems using the *VRception Toolkit*.

2 RELATED WORK

In 1994, Slater et al. [60] presented the idea of nested virtual realities and investigated their influence on presence. In this work, we exploit this idea as nested realities inside of VR. We propose to apply the idea to the domain of cross-reality systems, which we will review first. We will then review literature proposing VR as a research and prototyping tool.

2.1 Cross-Reality Interaction and Systems

Several researchers have pointed out the disconnect between the real world and the digital world [18, 56, 70]. This disconnect is particularly present when the user engaging with the digital world is not alone [37] and when collaboration between users is important [8]. Thus, a number of researchers envisioned systems that would enable users to engage with the digital world without totally disconnecting from the real world by using technology to merge the two worlds (e.g., [40, 68]). These systems are referred to as cross-reality systems and they either involve users that can transition on the reality-virtuality continuum to experience different levels of virtuality or they enable users that experience different levels of virtuality to collaborate and bridge realities [58]. Today, there are different research prototypes that focus on users transition on the continuum, such as by transitioning into VR [63, 65] or back into the real world [33]. Moreover, there is a great number of prototypes that aim to bridge different realities, such as by using a smartphone as a "window" into VR [2], projecting VR into the real world [16, 21, 29, 30], or attaching projectors [26, 31, 68] and displays [22] to users and the HMD they wear. However, these prototypes' unique characteristics, such as their form factor (i.e., weight, size), can affect the user's experience. For example, Wang et al. [68] used a taut strap to distribute the weight of the device and Jansen et al. [31] outlined that one of their future aims is to reduce their prototype's weight. As we re-implement six cross-reality systems with our *VRception Toolkit* in this paper, we provide a more systematic overview of these systems in Section 5.1 and Table 1.

2.2 Virtual Reality as a Research Platform

The use of VR for prototyping and studying real-world artifacts is not new. In fact, VR has already been used as a participatory design methodology [42], for the evaluation of user behavior in front of public displays [38], as a test bed for the evaluation of real-world security systems [39], and as an implementation and evaluation method of situated visualization [69], among other uses. Rebelo et al. [53] even argued that VR enables one to develop realistic virtual environments that come with greater control of the experimental conditions compared to a lab setting and that user experience (UX) research may benefit from such a VR-based research methodology. In a similar vein, Antonya et al. [5] argued that VR can support the evaluation and modification of mechanical systems and offer engineers more realistic real-time representations of their systems during the design process. Furthermore, it has also been argued that the use of VR enables researchers to evaluate systems in different contexts [3] and that such controlled virtual environments can provide users with rich contextual experiences [28]. Other works have shown that advances in VR technology present new opportunities for human-centered research. This includes expensive or even dangerous areas to study in the real world, such as pedestrian safety research [14, 55] or using VR as a training platform for underground coal miners [19]. All the works above highlight the potential of VR as a research platform for human-centered research.

As VR is nowadays also used as a research platform, researchers also set out to understand the differences and implications when using VR as a research tool [34, 50]. Here, it is crucial to note that recent investigations into systematically studying the impact of different environments (e.g., laboratory, VR, in-situ) on prototypes have been inconclusive, as effects could not always be replicated in VR [66, 69]. The final component for using VR as an effective research platform is to enable remote studies. Rivu et al. [51], for example, present a framework for remote VR studies and guidelines for best practices of such studies. Saffo et al. [54] went one step further and conducted remote collaborative VR studies and presented their findings. However, Ratcliffe et al. [52] found that safety and hardware variability issues have to be overcome in order to run remote studies effectively.

2.3 Virtual Reality Prototyping Tools

To be able to implement current AR and VR systems, designers and developers have to use time-consuming expert tools that enable software as well as hardware prototyping [10]. Expert tools allow one to design and implement every little detail to create high-fidelity prototypes and products. Frequently used tools for prototyping AR and VR experiences are 3D programming environments such as the Unity 3D or Unreal engine. For these environments, toolkits and programming interfaces exist that help practitioners to implement typical user interactions (e.g., Mixed Reality Toolkit[1]) or integrate the real-world environment (e.g., Oculus Passthrough API[2]). However, technical barriers such as programming skills and a steep learning curve make it difficult for non-experts to quickly build cross-reality prototypes [7, 43, 47]. Therefore, researchers have started to explore new tools that allow non-experts to quickly prototype AR [17, 46, 62] and VR [43, 45] applications without the need for programming or 3D modeling. Nebeling et al. presented 360proto [45], a toolkit that allows designers to create complex 3D environments using sketches on a piece of paper. They then presented ProtoAR [46], a tookit focused on optimizing the workflow in augmented reality. Leveraging physical props in the environment and the camera of the smartphone, the authors optimized the AR development pipeline by removing the need for programming and 3D modeling. While the *VRception Toolkit* has a similar goal, it faces different challenges. When designing cross-reality systems, the designer has to focus on at least two participants in two parallel and synchronized environments (e.g., real-virtual, virtual-virtual). Additionally, the created scenes must be experienced in an appropriate setting. These are both aspects that are at the core of the *VRception Toolkit*. To the best of our knowledge, *VRception Toolkit* is the first multi-user and multi-environment rapid-prototyping toolkit that allows non-experts to build and experience cross-reality systems without the need for hardware prototyping and programming.

3 *VRCEPTION* - CONCEPT

We propose *VRception*, a concept to simulate different realities in Virtual Reality (VR). Thereby, we enable users to rapidly prototype experiences across different realities. Simulated realities can be physical realities but also digital realities, such as AR, AV, or VR. By bringing different realities into VR, users can easily switch between them and remix their elements. With this, we also overcome the limitations of the physical world and reduce the effort necessary to prototype novel cross-reality systems. In the following, we highlight major characteristics that any implementation of our *VRception* concept should consider.

Characteristic 1: Enabling Multiple Realities. In theory, an infinite number of realities could be simulated in VR. For example, more than two realities are relevant when two co-located VR users experience different virtualities [67]. Moreover, when users collaborate remotely, they share the virtuality, but two realities exist in the sense that each has their own physical space [49]. In general, multiple realities can be arranged in two ways: 1) in parallel, which means they exist on the same level, or 2) nested, which means they exist within each other to allow stacking depth [60].

Characteristic 2: Enabling Transition between Realities. Supporting multiple realities requires a mechanism to switch between these

[1]Mixed Reality Toolkit. https://github.com/microsoft/MixedRealityToolkit-Unity
[2]Oculus Passthrough API. https://developer.oculus.com/blog/mixed-reality-with-passthrough, last retrieved March 14, 2022.

realities. Here, we see two competing approaches: a) the designer (or storyteller) moves the user on the continuum, or b) the user is in control of which reality is visible to them. Furthermore, in many cases, it is crucial to not just render one reality, but to blend or remix these realities. For example, AR requires reality to be fully visible and virtuality to be an overlay (see Figure 1b). In general, we expect different types of transitions to be possible, as shown in previous work [65]. Transitions can either be abrupt (i.e., an instantaneous jump from one reality to the other) or happen gradually (i.e., they morph from one reality to the other). Moreover, transitions can affect all objects of a reality simultaneously (increasing transparency on all objects to fade out a reality) or sequentially (more objects disappear as the transition continues).

Characteristic 3: Enabling Rapid Prototyping. An essential characteristic of *VRception* is that any implementation of the concept should enable users to rapidly prototype. Apart from the HMD worn by the user, every part of the simulated realities are software-based and do not require any hardware components. Thus, hardware limitations play a minor role; still, these limitations could be simulated if needed (e.g., to simulate sensor limitations [13] or the limited fields of view of AR HMDs [20]). Inherently, without hardware implementations required, prototyping becomes less time-consuming, requires less technical knowledge, and becomes less prone to technical failures. Nonetheless, two additional factors are crucial to enable rapid prototyping of cross-reality systems: 1) a set of virtual objects to use and build up prototypes, and 2) intuitive interactions for object manipulation. Here, such virtual objects can be primitive abstract objects (e.g., cube, sphere) which can be combined to create more complex objects.

Characteristic 4: Multi-user Support. Working together allows collaborators to combine their knowledge and shape a collective solution that incorporates different perspectives. Moreover, by collaborating with others, users can take different roles (e.g., VR, AR) to experiment with asymmetric interactions. Thus, collaboration is an important feature for *VRception.* Collaboration can be synchronous or asynchronous (which is less often used in cross-reality systems) and it can be co-located or remote. Co-located collaboration enables users to work in the same space, allowing collaborators to experiment with close forms of interaction such as touch input. To quickly set up such co-located interactions, a system should incorporate means to host two different instances of the system running on multiple HMDs. Remote collaboration empowers users to bridge geographic distance and opens up the possibility for remote studies.

4 *VRCEPTION* - TOOLKIT

Based on our concept, we developed the *VRception Toolkit*, a multi-user toolkit for quickly and easily prototyping cross-reality systems. As follows, we introduce the different prototyping environments the toolkit offers and their respective workflows, and provide an overview of the iterative implementation of the *VRception Toolkit*.

4.1 Prototyping with the *VRception Toolkit*

Essentially, the *VRception Toolkit* provides two different environments to rapidly prototype cross-reality systems: 1) VR with a WYSIWYG (what you see is what you get) editor and 2) Unity (see Figure 2). By providing both environments, we can lower the barrier to entry with a simple-to-use VR editor, while not losing the ability for advanced customization. Moreover, for teams with different skill-sets, one can imagine having developers with advanced technical skills customize the environment in Unity and creating additional resources, while designers can utilize the VR environment to quickly try out different ideas.

4.1.1 Prototyping in Virtual Reality. In VR, users are immersed in a simulation of the reality-virtuality continuum. They are synchronized across their locations, represented by full-body avatars, communicate via voice chat, and their actions are recorded for complete replay. Users can open a menu containing predefined objects and a slider that allows users to transition on the continuum (see Figure 3a). By grabbing an object from the list, users can add it to the simulation, depending on the reality-virtuality continuum manifestation (slider position). Objects can be manipulated (translate/rotate/scale/duplicate/delete) and combined by "sticking" them together. Finally, users can add avatars representing different user types (real-world bystander/AR/AV/VR) that can be placed in the scene to quickly jump to their perspective and enable single users to prototype cross-reality systems (see Figure 3c). The according workflow is demonstrated in Figure 2. While this is most certainly the quickest way to prototype cross-reality systems, it comes at a price because users are limited to the objects provided in the virtual menu (it can be extended easily with additional objects).

4.1.2 Prototyping in Unity3D. Unity3D is a powerful development tool that allows relatively easy navigation and provides extensive functionalities. Our *VRception Toolkit* is implemented within Unity3D and we aimed to provide a well-structured project that can be easily extended in terms of functionality. In a similar fashion, our toolkit allows experienced developers to extend our scripts, enabling them to build richer interactions using the editor and C#. In Unity, developers can quickly add additional predefined objects to the menu (e.g., cylinder, projector screen, *.fbx file). Moreover, developers can load existing Unity scenes (e.g., scenes from prior projects) and use them as representations of specific realities (configurable: one can also simulate two virtualities). Additionally, developers can change the way the transitions between realities work.

4.2 Implementation of the *VRception Toolkit*

In the following, we present a reference implementation of *VRception*, which we refer to as the *VRception Toolkit*. We implemented the *VRception Toolkit* in Unity3D (2020.1.8f1) using the Oculus SDK[3]. Our implementation has two goals. First, we wanted to create a VR application that allows users to experience *VRception*, thus enabling quick prototyping of cross-reality systems in VR. Second, we wanted to provide a well-structured Unity3D project that empowers others to extend the functionality easily and build their own versions. Therefore, we published our source code on GitHub[4] under the MIT license, empowering researchers and practitioners to benefit from our toolkit. In the following, we describe our implementation of the characteristics listed above.

[3] Oculus Developer. http://developer.oculus.com, last retrieved March 14, 2022.
[4] *VRception Toolkit*. https://github.com/UweGruenefeld/VRception

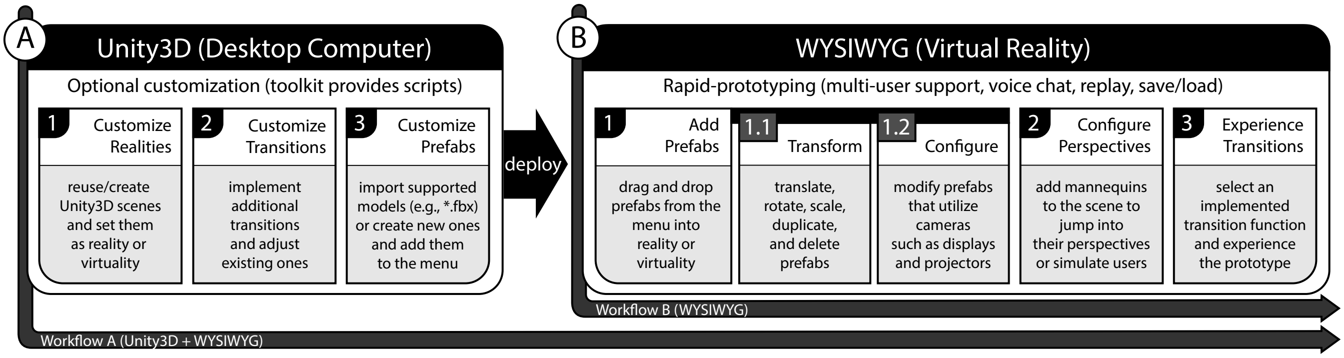


Figure 2: Workflows and Environments of the VRception toolkit. The Unity3D option is designed to maximize expert developers' ability to customized the toolkit. The WYSIWYG mode allows developers that are not experts in Unity to experiment with cross-reality systems; thereby, lowering the barrier to entry.

Reality and Virtuality. To present different realities, we make use of multiple scenes, each holding one world that can be designed independently. Our implementation currently supports two realities, e.g., reality and virtuality or virtuality-1 and virtuality-2. With our implementation, we can load any existing Unity3D scene as part of one of the two realities, allowing the reuse of existing projects. Additionally, we can have a shared scene containing shared objects that are visible in both realities, such as the player's avatar.

Interaction. Users have full control over the realities with their two controllers. Here, the left controller is mainly used to provide a virtual menu, which can be opened with a button on that controller. The menu contains a horizontal slider that allows users to transition between the two realities (cf. Figure 3a). Additionally, it contains a set of predefined objects. The users can drag these objects into the scene, attach them to one another, or manipulate them to create more complex systems, objects, or structures. To directly manipulate objects, users can select them with their right controller and translate, rotate, scale, duplicate, or delete them.

Gradual Transition Between Realities. In our toolkit, a horizontal slider — the *reality-virtuality slider* — allows users to transition between the two realities, with reality on the left side and virtuality on the right. The slider is a representation of the reality-virtuality continuum [41]. Positioning the slider knob at one of the ends will render only one of the two realities. Between the extreme positions, transparency is applied to gradually blend all objects from all realities, depending on the position (cf. Figure 1). Each user has a slider to independently switch between realities and different glasses on their avatars show their current reality. Objects from shared scenes are always visible and unaffected by the slider. We implemented this with two stacked cameras (one for each reality) and transparency-compatible shaders attached to all objects.

Additionally, our toolkit supports individual blending or remixing of realities via a feature that we refer to as *experiences*. Here, every *experience* can implement a highly customizable rendering of the different realities beyond well-known manifestations such as AR, AV, and VR. Such an *experience* could, for example, render from one reality only the objects closer to the observer while rendering everything of the other reality unconditionally.

Predefined Objects. To empower users to quickly prototype cross-reality systems, we created an initial set of objects. While the objects in the virtual menu can be changed and extended easily, we decided for four predefined objects as the default set of objects that ship with our prototyping tool (described below). During our development, we created many different objects (with some of them used to replicate the research prototypes in Section 5.2); however, some of the objects are less generic (e.g., the lightsaber created to replicate ShareVR [21]). Thus, we selected four objects to demonstrate our toolkit's potential. To create objects inside the VR environment, users simply drag them from the menu into the currently selected reality, which is set by the *reality-virtuality slider*. If the slider knob is more towards reality, objects spawn in reality, and vice versa.

We included two primitive shapes: cube and sphere. We selected them because they are great building blocks (e.g., demonstrated by the Game Minecraft[5]). Both objects can be manipulated and combined to represent more complex objects. For example, in Figure 5c, users formed a table and character from these shapes.

We implemented a display that allows one to bridge realities. While it exists in one reality, it shows the other (cf. Figure 3b), depending on the *reality-virtuality slider*. To realize the virtual displays, we use an additional camera that renders onto a texture attached to the display. To control the displays, users can adapt the position and direction of the camera independent of the display position. Both objects representing camera position and direction can also be attached to other objects. We selected the display object as many research prototypes use them (c.f., Table 1).

Finally, we implemented a projector that works similarly to the displays. However, instead of rendering the camera texture onto a plane, it projects it into the scene (cf. Figure 3c). Projectors also allow the user to adapt position and direction of the camera. We selected projectors because they are found in many prototypes [26, 31, 68].

4.3 Iterated Implementation of the Toolkit

After the expert interviews (see Section 6), we iterated our implementation in preparation for the design workshop (see Section 7), implementing collaboration and integrating the expert feedback.

[5]Game Minecraft. https://www.minecraft.net, last retrieved March 14, 2022.

(a) Virtual menu attached to controller. **(b) Example of display showing reality.** **(c) Example of projector showing virtuality.**

Figure 3: Implementation details of the *VRception Toolkit*, showing a) the virtual menu attached to the user's left controller, b) a virtual display that renders reality on the screen (blended in reality for orientation), and c) a projector that projects virtuality on the floor (blended in virtuality for orientation). Additionally, in c) one can see the "Look At" and "Camera" objects, which allow the user to adjust the direction and position of the camera, respectively; similar objects exist for the display as well.

Networking. To enable multiple users to collaborate within the *VRception Toolkit*, we implemented network synchronization that keeps all clients in a consistent state. We used the Photon Engine[6] which allows up to 20 concurrent users (in the free version) without the need to host a dedicated server. Additionally, we implemented an in-game voice chat with 3D spatialized audio to allow collaborators to talk to one another using the Photon Voice feature. A test with five concurrent users on the Oculus Quest 1 showed no frame drops (stable 72Hz) and <250KB data transferred per minute.

Avatars. To represent collaborators in our *VRception Toolkit*, we adapted a rigged character from the Unity3D Asset Store[7] (cf. Figure 1). Moreover, we used inverse kinematic (IK) to map the controllers and headset to fitting poses of the avatar character. Specifically, we used the FinalIK package[8] that implements a variety of IK solvers such as CCD [32] and FABRIK [6] and performs better than the Unity3D built-in solver. Last, we adjusted the shirt color and hairstyle to give each collaborator a unique look.

Real-world Scan. To increase the realism of the reality within our *VRception Toolkit*, we decided to include a 3D scan taken from a private living room[9]. The advantage of such a real-world scan is that the scanning technology required for it has recently become available to more people (e.g., with the LIDAR sensors integrated in selected Apple products). Furthermore, compared to modeling with higher levels of realism, scanning can be done quickly and does not require any advanced skills, allowing developers to bring their own room into the *VRception Toolkit*.

Replay. The replay feature allows researchers to watch recorded sessions again, implemented as state-based replay. Here, we were inspired by previous work on analyzing user sessions in mixed reality [1]. The feature supports viewing within VR or within the Unity3D editor and uses a self-hosted database to store all changes that occur during a recording.

[6]PhotonEngine. https://photonengine.com, last retrieved March 14, 2022.
[7]Liam. https://assetstore.unity.com/packages/3d/characters/humanoids/humans/liam-lowpoly-character-100007, last retrieved March 14, 2022.
[8]FinalIK. http://root-motion.com, last retrieved March 14, 2022.
[9]Chalet in France. https://skfb.ly/6ZynL, last retrieved March 14, 2022.

5 SHOWCASES OF PROTOTYPING TOOL

We re-implemented six prototypes from prior work using our *VRception Toolkit*, demonstrating its potential. Therefore, we first give an overview of research prototypes proposed in previous work and then select six of these prototypes for re-implementation.

5.1 Selection of Cross-Reality Research

To better understand cross-reality research, we manually reviewed all papers (no keyword search) on cross-reality systems published in HCI and VR venues, including UIST, CHI, IEEE VR, MobileHCI, and SIGGRAPH. In our brief review, we focused on research that was published no earlier than 2015. We did not aim to compile a complete literature corpus; instead, our goal was to identify a variety of different systems and see if they could be replicated using our toolkit. Therefore, we first checked the title of each paper to identify relevant research. We then read the abstracts (or further sections if necessary) of all publications whose titles seemed relevant in order to identify relevant research prototypes. If a paper seemed relevant, we collected it in a spreadsheet (cf. [15]) and identified the relevant features of its prototype. From the selected papers, we classified three directions of interaction as possible: (1) unidirectional interaction from virtuality to reality (VR→RW), (2) unidirectional interaction from reality to virtuality (RW→VR), and (3) bidirectional interaction between reality and virtuality (RW↔VR). In Table 1, we present a selection of the collected research categorized into the three mentioned categories.

From Table 1, we selected two research prototypes from each category, resulting in a total of six prototypes. For each category, we selected two prototypes with several years between their publications (to include earlier and newer research), which differed in their implementation from a hardware perspective. For example, for "VR→RW," we selected one prototype that used a display and another that utilized a projector. For "RW↔VR," we selected one prototype for VR and another based on AR. We focused mainly on VR systems as they were more frequent and their nature of excluding reality was considered more interesting. Therefore, our final set of papers is as follows: [13, 21, 31, 36, 40, 68]; see Table 1.

Table 1: Examples of research papers that investigate cross-reality systems and interaction, ordered by publication year and sorted by direction of interaction. For example, RW→VR implies that users of this system transition from the Real World to VR. The selected prototypes are highlighted in light gray.

Authors	Short Title	Description	Direction	Year	Conference
Mai et al. [36]	TransparentHMD	revealing HMD user's face to bystanders	VR→RW	2017	MUM
Chan et al. [12]	FrontFace	attaching a front-facing screen to an HMD	VR→RW	2017	MobileHCI
Ishii et al. [29]	ReverseCAVE	reverse CAVE showing VR to bystanders	VR→RW	2019	SIGGRAPH
Hartmann et al. [26]	AAR	projector attached to AR-HMD	AR→RW	2020	UIST
Wang et al. [68]	HMD Light	sharing VR experience via VR-HMD	VR→RW	2020	UIST
McGill et al. [40]	A Dose of Reality	blending real-world objects into VR	RW→VR	2015	CHI
Nuernberger et al. [48]	SnapToReality	align objects in AR to the real world	RW→AR	2016	CHI
Hock et al. [27]	CarVR	using real-world motion for VR world	RW→VR	2017	CHI
Hartmann et al. [25]	RealityCheck	reconstruction of reality with depth sensing	RW→VR	2019	CHI
Cheng et al. [13]	VRoamer	generating VR experiences on the fly	RW→VR	2019	IEEE VR
Gugenheimer et al. [21]	ShareVR	co-located HMD and non-HMD users	RW↔VR	2017	CHI
Yang et al. [71]	ShareSpace	bystander can communicate need for space	RW↔VR	2018	UIST
Gugenheimer et al. [22]	FaceDisplay	touch displays attached to VR HMD	RW↔VR	2018	CHI
Kumaravel et al. [64]	TransceiVR	sync info between asymmetric users	RW↔VR	2020	UIST
Jansen et al. [31]	ShARe	interact via projector attached to AR-HMD	RW↔AR	2020	UIST

5.2 Re-implementation of Selected Research

We re-implemented the six selected research prototypes; see Figure 4 for an overview of the re-implemented systems. Our goal was to see how easily we would be able to replicate them in the *VRception Toolkit*. We used the prototyping workflow A (Unity3D + WYSIWYG; see Figure 2) and re-implemented each prototype in less than one hour.

TransparentHMD. The fundamental idea of *TransparentHMD* is to reveal the HMD user's eyes to bystanders and thereby reduce communication problems [36]. For our re-implementation, we attached our developed display component (cf. Section 4.2) to the HMD of the VR user. Then, we adjusted the position and clipping of the camera that renders onto the display to show the eyes of the avatar (see Figure 4a).

HMD Light. In their system, the authors attached a projector to a VR HMD, revealing the VR user's experience to bystanders [68]. To re-implement the system, we attached our projector component (cf. Section 4.2) to the HMD of the VR user. Then we implemented a script that controls the orientation of the projector to show the projection closer to the bystander (see Figure 4d).

A Dose of Reality. The authors envisioned being able to selectively embed real-world objects in the VR experience [40]. In our re-implementation, we focused on two of the proposed research prototypes, in which a bystander and a keyboard are integrated into the VR experience (see Figure 4b). Here, we created a custom *experience* (cf. Section 4.2) to fade in these objects, depending on their proximity.

VRoamer. In essence, *VRoamer* allows one to generate virtual worlds from the sensed physical environment on the fly [13]. To re-implement this system, we created a custom experience in which real objects are represented by virtual objects when the VR user gets within sensing range (see Figure 4e). For physical structures (e.g., walls), we replaced the texture; for other obstacles, we superseded the mesh and texture.

ShareVR. The *ShareVR* prototype utilizes floor projection and mobile displays to visualize the VR experience for non-HMD users and enable interaction between a VR user and a bystander [21]. We re-implemented both floor projection and mobile display attached to a controller held by the bystander (see Figure 4c). Moreover, we implemented lightsabers for the bystander and VR user.

ShARe. The authors of *ShARe* proposed using a projector attached to an AR HMD to share the AR experience with bystanders and to enable them to interact with the AR content [31]. For our re-implementation, we attached a projector to a HoloLens HMD, constructed a table and recreated a simplified version of the game board demonstrated in the original paper (see Figure 4f).

6 EXPERT INTERVIEWS

From the related work presented in Table 1, we replicated six systems [13, 21, 31, 36, 40, 68] using our *VRception Toolkit*. For each of the replications, we invited one of the authors as an expert to provide feedback on our concept, our tool, and the replication of their system. We asked them only about their system because we wanted to understand their individual prototyping experience.

6.1 Participants

Our six interviewed experts (5 male, 1 female) were between 21 and 35 (M=28, SD=5) and had 2 to 7 years of experience in VR/AR development (M=4, SD=2). In addition, they conducted research on cross-reality interaction, personal fabrication, and HCI. All of them had hands-on experience in prototyping cross-reality systems and had prototyped at least one previously. All interviewees used their own VR headset (i.e., Quest 1 or 2) to experience the replicas.

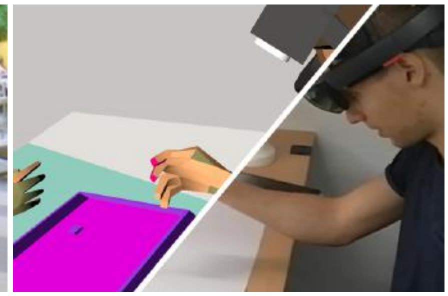
(a) TransparentHMD [36].

(b) A Dose of Reality [40].

(c) ShareVR [21].

(d) HMD Light [68].

(e) VRoamer [13].



(f) ShARe [31].

Figure 4: Re-implementation of six selected cross-reality systems proposed in previous work. For each system, we present the re-implementation in the *VRception Toolkit* left and the original system right (right pictures taken from the original papers; cf. citations). Figures a) and d) are VR→RW, figures b) and e) are RW→VR, and figures c) and f) are RW↔XR.

6.2 Procedure

In advance of the interview sessions, we asked the experts to launch the replicated system, which we had sent them beforehand, on their VR device for a few seconds to ensure it would run during the interview. All experts provided written informed consent upfront via email. Via Zoom, we presented a slide deck to a) set the context of the interview, b) showcase a variety of different cross-reality prototypes based on recent papers, including the interviewee's own paper, and c) introduce the interviewees to the functionality of the *VRception Toolkit*. All experts experienced their prototype system in the *VRception Toolkit* during the interview session. The interviews took on average about 60 minutes. The semi-structured interviews were guided by the following three topics:

Topic 1 - *VRception* This topic aimed to elicit the experts' opinions on the greatest challenges of cross-reality interaction research. Then, we presented a concept video for *VRception* explaining its different capabilities. We also asked for their opinions on how *VRception* can support researchers.

Topic 2 - *VRception Toolkit* We asked each of our interviewees to walk us through their own prototyping process for their cross-reality system and asked them how *VRception Toolkit* could have helped during the development process.

Topic 3 - Replicated System Experts experienced their replicated prototype using their VR headset while we elicited insights into the quality of our replication and the *VRception Toolkit*. We concluded with a short section about experts' long-term feature requests, what they would like to explore with the *VRception Toolkit*, and asked them if they had any additional thoughts or opinions.

6.3 Data Analysis

We applied open coding on our interview data, followed by an inductive category development. We did this to find patterns of experts' opinions and thoughts about the *VRception Toolkit*. Once all the interviews were completed, four researchers transcribed all audio recordings and open coded the transcriptions. This process generated 286 open codes. We then conducted an online affinity diagram [23] of the open codes. Next, we organized the codes into groups, which were then further refined into themes using an online whiteboard[10]. We visited the transcript and audio recordings again when additional information was needed during the analysis.

6.4 Results

We identified four main themes, which we outline below. We use participant IDs (P1 - P6) and the pronoun "they" for all participants to ensure anonymity.

6.4.1 Opportunities and Challenges of VRception. In the interviews, the experts highlighted the increase in XR research (P2 - P6) and its potential (P2, P5, P6). They also underlined the challenges of hardware prototyping and technical challenges (P1, P2, P4, P5). The experts saw great value in the *VRception Toolkit* as a tool to overcome the aforementioned challenges of physical prototyping (P1, P2, P5, P6). The experts (P1, P4, P5, P6) further pointed out that the *VRception Toolkit* is great for supporting social interaction and its design is beneficial due to its flexible and remote collaboration

[10]Miro. https://miro.com, last retrieved March 14, 2022

capabilities. Here, they saw the clear benefit of having the physical constraints and hardware limitations removed when using the *VRception Toolkit* to simulate the whole XR interaction (P1, P3, P4). In comparison to co-located collaboration, however, they criticized the lack of haptic feedback (P1, P2, P4).

Finally, the experts commented on the difficulty of simulating the real world (P1 - P3, P5, P6) and the possible threats to validity of results obtained using *VRception* (P1, P2, P4, P6).

6.4.2 Cross-Reality Prototyping Challenges. When asked what prototyping challenges researchers face when conducting cross-reality interaction research, the experts generally agreed that "Hardware is hard" and that the available hardware often drives their research. P1, for example, voiced that hardware limitations forced them to adjust their research focus: "[I would have liked] to explore, for example, projecting on the user's body, but due to the hardware limitation, we [could not] do that". Other comments were about the prototype's weight (P1, P2), its instability in the wild (P1), the lack of appropriate hardware components such as high-resolution depth cameras (P6) and tracking systems (P2), the difficulties of building two isolated experiences (P1, P5), and the interplay between multiple devices and software/hardware components (P1 - P3, P6). P1, for example, stated that "the calibration process is a nightmare [...] I would not do that again" and P2 raised further issues around the calibrations and alignments. P6 also expressed that they had to spend a lot of effort on the actual implementation and synchronization. According to our experts, these hardware prototype systems often have only a short lifetime and many of their prototype systems are no longer available or the software on which they run is deprecated (P1, P5).

All experts but P3 wondered about the general viability of running a prototype evaluation fully in VR using the *VRception Toolkit*. For instance, P6 stated that they "would worry slightly that you are losing something of the validity there because people are not getting to actually experience [the system]." P1 also argued that field studies cannot be replaced using the *VRception Toolkit*. However, P1 did argue that "for laboratory experiments [...] VR is enough."

6.4.3 Opportunities and Challenges of the Toolkit. All experts agreed that the *VRception Toolkit* provided a rapid prototype of their implementations that is not possible when building it using hardware. In general, the experts saw the tool as a flexible, interactive playground for prototyping (P1 - P3, P5, P6). They further commented that improvements in hardware and software technology would be possible in the future (P1, P4 - P6). Overall, they valued it as an all-in-one system (P1, P5) with a low entry barrier, as prototyping can be done without coding (P1, P3, P6).

After the experts experienced their prototype using the *VRception Toolkit* and tested its current capabilities, they highlighted implementation drawbacks such as the limited availability of building blocks (P5) and the fact that avatars could not move their arms and fingers (P5). A more general concern was that their prototype was not 100% replicated, e.g., we did not implement all the rooms (P5). On the other hand, P4 argued that it is possible to be more precise when building the replica, but in the end, the "real distortion of the projection and a re-projection" would still be missing. Finally, they asked for multi-user support (P2, P5).

To overcome these limitations, thereby allowing implementation of a perfect copy of existing prototypes, the experts asked for a number of additional features. P2 and P6 asked for a more realistic real-world simulation using a LIDAR scanner or a 360 recording to address their concern over distinguishability of the VR worlds. Other feature requests include hand tracking (P2, P4), shadows (P2), event-driven transitions (P6), and object alignment (P6).

6.4.4 VRception *and its Use Cases.* During the interviews, our experts mentioned different applications for which our *VRception Toolkit* could be suitable. There was a general consensus that the *VRception Toolkit* is a promising tool for creating prototype implementations of cross-reality interaction systems, especially as a preceding component of a real-world deployment. P1, for example, voiced that our presented toolkit is promising for quick prototype developments where the interactions are experienced in an initial state. P3 further stated that the *VRception Toolkit* is especially interesting for the prototyping phase because it opens the potential of prototyping and experiencing systems in different virtualities. Other use cases included using the *VRception Toolkit* for interdisciplinary remote research, small-scale evaluations, ideation sessions, and educational purposes. Our experts mentioned that the *VRception Toolkit* could help them to visualize and prototype their system in an easy and fast way (P2 - P4) and could even allow them to conduct interdisciplinary research fully remotely (P3, P4). P1 further said that the *VRception Toolkit* enables researchers and designers to focus more on the research itself rather than having to deal with hardware issues. One expert, P2, even mentioned that the *VRception Toolkit* could be used for educational purposes, as it removes the complexity of creating cross-reality prototypes and enables students to prototype whatever they imagine in an effortless way. Similarly, P6 suggested that we think big and beyond cross-reality interaction: "I'm sure that other research areas could apply that same thing, and if your tools could enable that then, maybe that's a whole subset of research that you're opening up."

6.5 Discussion

For the interviews, we derived recurring themes from the expert statements, which we discuss in the following.

Overcoming Hardware Limitations. Several experts pointed out that physical prototyping is strongly constrained by technical limitations. This is in line with previous work that reports blurred displays [68], imprecise servo motors [26], low projection luminance [29], limited sensor capabilities [13], and uncomfortable prototypes [22, 26, 31]. While it certainly makes sense to respect hardware limitations when the goal is to develop a functioning system with state-of-the-art hardware, they overall restrict researchers' possibilities to explore novel cross-reality systems and interactions. In some cases, certain hardware characteristics can even pose a potential safety threat, such as when laser technology is used [26]. Our experts agreed that the *VRception Toolkit* offers great value for overcoming the aforementioned challenges that arise during physical prototyping. Furthermore, our experts highlighted that they are convinced that *VRception* makes prototyping cross-reality experiences easier, as it does not require spatial calibration of the different realities and allows quicker iterations.

Collaboration and Remote Studies. Experts highlighted that *VRception* is great for supporting social interactions and their design, as multiple players could meet in the *VRception Toolkit* and design and explore collaboratively. Furthermore, *VRception* enables researchers to conduct remote studies since multiple participants and researchers can be immersed together. Since the start of the currently ongoing pandemic, researchers have proposed various ways of conducting remote studies in VR [51, 52, 54]. Here, *VRception* adds another valuable approach to conduct these studies when investigating cross-reality interactions. To support remote studies and collaboration in the *VRception Toolkit*, we added network synchronization, avatars, voice chat and a replay system as described in Section 4.3.

Validity of User Studies. The experts raised concerns that it remains unclear to what degree results from a user study with the *VRception Toolkit* are valid and transferable to hardware implementations of the same system. We agree with these concerns and acknowledge that *VRception* will not replace user studies with hardware prototypes. Nonetheless, previous work has shown the potential of prototyping in VR (cf. Section 2.2). Thus, we argue that *VRception* allows one to gain insights into hardware implementations without the need for actual hardware prototyping. To improve the validity of the *VRception Toolkit*, we followed the experts' advice and integrated a more realistic reality by utilizing a 3D scan of a real-world environment (see Section 4.3).

7 DESIGN WORKSHOP

The goal of the workshop was to understand how feasible our *VRception Toolkit* is for prototyping cross-reality systems. We were interested in how long it would take participants to address relevant problems from the domain of cross-reality interaction and come up with suitable solutions. Moreover, we aimed to understand how usable the *VRception Toolkit* is, how demanding it is to prototype cross-reality systems using our toolkit, and how users experience the prototyping process in *VRception*. For the design workshops, we used the prototyping workflow B (WYSIWYG; see Figure 2)

7.1 Apparatus

We used the implementation described in Section 4.2. Participants joined the workshop with their VR headset (i.e., Oculus Quest 1 or 2). Based on the comments from our experts, we extended our toolkit to support multiplayer, avatars based on inverse kinematics, voice chat, and replay.

7.2 Procedure

The workshop was conducted fully remotely via Zoom. We invited participants in pairs to collaboratively develop cross-reality prototypes. In the beginning, we synced participants' knowledge about cross-reality interactions by discussing the reality-virtuality continuum [41] and presenting five different research papers (cf. [26, 34, 35, 40, 68]). Thereafter, we introduced *VRception*. We then showed a 5-minute video explaining the *VRception Toolkit* and followed that with a 10-minute practice session. An experimenter joined in the application as well to address questions of participants via the in-game voice chat and to demonstrate functionalities on request. Afterwards, we started with the main part of the study in which participants built two prototypes in the *VRception Toolkit*.

We presented two scenarios to the participants and asked them to develop a prototype for each one. In both scenarios, they had to imagine that they were creating their prototypes to help a 3D designer who enjoys crafting in VR. In the first scenario, we explained that the designer has a TV running in the background while crafting; however, now they want to have the TV in VR to continue watching while creating 3D models. In the second scenario, we explained that the designer had an urgent assignment they needed to finish, but a friend was already there and wanted to see what the designer was crafting in VR. For each scenario, one of the two participants could initially introduce their idea of how to address the problem and thereafter, both were asked to collaborate to find the best implementation of this idea. After each session, participants could take a short break.

After both prototyping scenarios were completed, we asked the participants to fill out a System Usability Scale (SUS) [11] and a raw NASA-TLX (TLX) [24]. We ended the workshop with a semi-structured interview.

7.3 Participants

We had 8 volunteer participants (1 female, 7 male) with a mean age of 27 ($SD = 3$) from three different countries (Germany, France, and Brazil), recruited through social media and mailing lists. None of them had taken part in the previous interview study. For the workshop, we grouped participants into random pairs. We selected participants with prior knowledge in VR/AR development to ensure participants had experience with prototype development. On average, the participants stated that they had 2.3 years of experience ($SD = 3.4$) in developing VR/AR prototypes.

7.4 Results

All pairs were able to address both prototyping scenarios. Each session lasted about 100 minutes on average.

7.4.1 Prototypes from Participants. Overall, the workshop participants created eight prototypes, four for each prototyping scenario described in Section 7.2. In Figure 5, we present a selection of four prototypes, two for each scenario. The participants decided to use a display to bridge realities five times, while they chose the projector three times. In three out of the four workshops, the participants tried both a display and a projector during the first task. In two cases, they settled on using a display, and in one instance, they decided on a projector. For the first task, in which they were asked to bring the television (TV) from reality into virtuality, they implemented the following four ideas: 1) P1 and P2 created a virtual screen with the same size and position as the TV (see Figure 5a), 2) P3 and P4 created a virtual display that is attached to the user and always shows the TV (see Figure 5b), 3) P5 and P6 decided to use a projector to show the TV on the floor, and 4) P7 and P8 created a large screen and rendered the TV screen on it. For the second task, in which we asked participants to show the virtuality experience to a real-world bystanders, they had the following four ideas: 1) P1 and P2 created a display that works as a window to virtuality (see Figure 5c), 2) P3 and P4 used a display as well but attached the *look at* object to the VR user's body to follow them, 3) P5 and P6 used a combination of four projectors attached to the VR user's body to project the virtuality onto the floor in the real world (see Figure 5d), and 4) P7 and P8 created a large canvas in the real world and projected the virtuality onto it.

7.4.2 Quantitative Results. First, we looked into how long participants took to prototype a solution for the given scenario. Each pair of participants had two tasks: VR to real world and real world to VR. Hence, we had eight prototyping trials in total, which took an average time of 8 min 17 sec (Min=4 min 22sec, Max=15 min 47sec). The longest trial was for the first task, during which the participants tried out two different solutions and had their initial solution implemented in less than 7 minutes. However, they then reconsidered and tried to attach a projector and canvas to the body, which took more time.

The System Usability Scale (SUS) [11] results yield a mean score of 76.6 (SD = 10.6), rendering the overall usability of the *VRception Toolkit* as "good" [9]. Participants were most split for the last question (5-point Likert item), "I needed to learn a lot of things before I could get going with the system," giving a median of 3-neutral (SD = 1.3). Moreover, the mean raw NASA-TLX showed lower task load, with 30.6 of 100 points (SD = 9.0). The mean scores of the subscales in ascending order are: frustration 3.3 (SD = 1.6), physical demand 3.6 (SD = 1.6), effort 6.1 (SD = 3.0), temporal demand 6.4 (SD = 4.0), performance 7.0 (SD = 4.2), and mental demand 10.4 (SD = 4.0).

7.4.3 Qualitative Results. For the qualitative analyses, we applied open coding on the user feedback, followed by an inductive category development. After transcribing the interview, open coding generated 145 codes. We then created an online affinity diagram [23] for the open codes.

All participants gave general positive comments about the *VRception Toolkit*. For instance, P6 said "I wanted to stay. [...] the whole application was really good to implement [in]." Moreover, they stated that it is fun (P3, P4, P6), easy to use (P2, P5, P7), and interactive (P1, P3, P8). Moreover, P1 and P2 pointed out that the simulation environment had a positive effect on their creativity, enabling them to explore new ideas.

When we asked participants about issues with the *VRception Toolkit*, all participants but P6 stated that the controls are rather complex. On the other hand, six participants reported that, after a learning period, they were familiar with the controls (P1, P2, P5, P6, P7, and P8). For instance, P7 said "I needed some more time to get used to the tool – maybe like 2 minutes."

In terms of the prototyping experience, participants reiterated that the *VRception Toolkit* is fast and easy to use (P2, P7). Moreover, two participants stated that they could clearly distinguish between the two worlds (P1, P2) and only one commented negatively on the fact that both worlds are virtual (P7). Finally, seven participants (P1-P3, P5-P8) added that if they would need to build the same setup in the real world, it would take weeks or even months to complete. Three of these (P2, P5, P6) further noted that this is due to the complexity of the real-world implementations.

All participants stated that the collaboration in VR was nice and worked well. They were especially surprised that it functioned well, given the fact that they were not co-located. The only downside was stated by P2: that they would have liked a better way of identifying who spoke, which in their opinion could be solved by better spatial audio. In addition, P1 wondered how the system would be affected by having more collaborators.

All participants gave comments on features they would like to see in the next iteration of the toolkit. Here, three participants (P1-P3) wanted to be able to jump to specific positions on the Reality-Virtuality Continuum. Other requested features including real world object scanning, additional rooms, a context menu, interaction between the objects, and the option to attach scripts to objects. For enhanced collaboration, P8 asked for a out-of-view visualization of the collaborators and lip synchronization, cf. Aneja et al. [4]. Finally, six participants (P1-P4, P7, P8) asked for more assets to use.

All participants could envision various examples of how to use the *VRception Toolkit*. The first use case was obviously for prototyping during the design of new systems and the evaluation using our toolkit. Our participants saw great potential to use the toolkit for educational purposes and to explain ideas to others. Finally, participants saw how the system can be used to engage with friends and collaborators, but they would have liked to also include real bystanders while being co-located, thus making it more collaborative.

7.5 Discussion

Rapid Prototyping. During the design workshop, participants were asked to collaboratively prototype solutions for two different problem types: RW→VR and VR→RW. Participants proposed a working solution in all cases and for each of the problems. Interestingly, the solutions developed by the participants differed, with no strong overlap among the solutions (cf. Section 7.4.1 and Figure 5).

Participants took, on average, less than 10 minutes to create their solutions. Moreover, we observed a decrease in the average prototyping time for the second task, from 9 min 35 sec in the first task to 6 min 59 sec in the second task. This suggests that it does not take long for one to become familiar with our toolkit. Overall, we argue that our results provide evidence that the *VRception Toolkit* allows rapid prototyping of cross-reality systems. The participants agreed and described the toolkit as fast and easy to use, remarking that it would have taken weeks or months to prototype their solutions with actual hardware.

Remote Collaboration. The participants highlighted that the collaboration was well-implemented. All participants felt connected to their collaborator, with some saying that they consider the collaboration in the *VRception Toolkit* to be better than real-world collaboration because they felt less distracted (P5,P6) and more connected (P7) throughout the different realities. The latter is especially difficult to achieve in real-world environments, which is why the *VRception Toolkit* provides a built-in solution to bridge realities via the slider in the virtual menu (cf. Section 4.2). Still, the lack of lip synchronization and the limited spatial audio on the Oculus Quest headsets negatively impacted the collaboration experience. We suggest implementing additional visual cues to overcome the audio limitations. For example, in addition to lip synchronization, it could be beneficial to include an icon that shows who is talking.

Usability and Workload. The *VRception Toolkit* received a good rating in terms of usability [9]. However, we also found that the interface was initially overwhelming for participants. To enable

(a) Virtual Screen for Television. **(b) Body-attached Display.** **(c) Window to Virtuality.** **(d) Worn Quad Projectors.**

Figure 5: Example prototypes from the design workshop. In a) and b), the participants' goal was to bring the television from reality into virtuality. In c) and d), participants aimed to give a bystander a glance at their actions in the virtual world.

users to rapidly prototype with our toolkit, we mapped all its functionalities to controller buttons. We also provided tooltips so that participants could find their desired action while using the *VRception Toolkit*. Some participants stated that they liked the quick actions we provided, while others said that they would have preferred a context menu that provides all possible actions as visual representations. In line with Shneiderman's eight golden rules [57], we recommend inclusion of both options to "enable frequent users to use shortcuts" while "reducing short-term memory load" with contextual actions.

Concerning the task load, the participants rated the mental demand highest. We think that two factors contributed to this: 1) interface complexity and 2) difficulty of distinguishing between realities. As the former point is addressed above, we continue by discussing the latter. After the experts highlighted the fact that having both realities in VR could be confusing, we included a real-world scan to make the differences more clear (see Section 4.3). Nonetheless, the predefined objects (e.g., projector or displays) still look the same in both realities. Here, we recommend using different shaders/materials for the different realities (e.g., toon-shading for virtuality objects) to help users to better distinguish between the objects.

8 LIMITATIONS

Some specific decisions we made are worth discussing.

Prototyping with the VRception Toolkit. We re-implemented a set of six cross-reality systems with our *VRception Toolkit* in Unity3D (cf. Section 5.2). Thereby, we could showcase the potential of the *VRception Toolkit* and gain insights from in-depth interviews with the authors. However, prototyping in Unity3D does not rely on our set of predefined objects; thus, it offers more flexibility than prototyping in Virtual Reality, as it is not restricted by what objects are available. Our goal is to provide users of the *VRception Toolkit* with a promising set of objects that are frequently used when building cross-reality systems, such as projectors (e.g., [21, 30, 68]), displays (e.g., [21, 22, 36]), and additional spheres and cubes that enable users to model simple geometry. Nonetheless, our current implementation focuses mainly on displays and projectors. However, this set of primitives can easily be extended in the future by integrating objects such as depth cameras.

Missing Hardware. We also want to highlight that although the absence of physical limitations can be interpreted as an advantage of *VRception* over traditional real-world prototyping, simulating real-world conditions can sometimes be at the center of a researcher's investigation. In such situations, simulating real-world conditions (e.g., real-world motion [27]) requires additional effort.

Validity of User Studies. Finally, we cannot claim that cross-reality system evaluations using *VRception* achieve high validity (e.g., evaluating a cross-reality system through a user study conducted in *VRception*). The value of evaluations conducted in *VRception* remains unclear. We leave this for future work, where we plan to conduct comparative evaluations of cross-reality systems in *VRception* and in the real world with actual hardware to pinpoint potential similarities and differences between the two approaches. Nonetheless, the main focus of *VRception* was to highlight its ability as a prototyping tool, not as an evaluation tool.

9 RESEARCH OPPORTUNITIES

We identified five opportunities and implications for future work in cross-reality system and interaction research and practice, which we will outline in the following paragraphs.

Prototype for Reality and Virtuality. VRception offers researchers and practitioners a novel approach to prototype cross-reality systems and interactions. Essentially, we introduce a tool for the early prototyping phase that allows one to start without physical prototyping. Thus, one can rapidly create and test different solutions without hardware expenses or physical prototyping skills. Moreover, *VRception* empowers researchers to explore novel systems and interactions that are not yet possible to build with current hardware, allowing them to focus more on users' needs and less on hardware limitations. For the future, we envision two research directions that would benefit our approach: 1) virtual clones of existing hardware, and 2) comparative evaluations that compare prototypes developed with *VRception* to their real-world implementations as discussed in the limitations section. Currently, we implemented a universal display and projector object; however, more virtual clones of existing hardware are possible. For instance, we envision the addition of a depth camera that utilizes the z-buffer of its render-texture to visualize depth information.

Conducting Remote Studies. The networking feature allows one to use the toolkit not only in co-located settings, but also to conduct remote studies. Thus, it allows researchers to continue researching cross-reality systems and interactions during the ongoing pandemic, offering an alternative approach to other recently proposed methods [51, 52, 54]. Moreover, it lowers the barrier for study participation, as it takes geographic location out of the equation; thus, it enables one to conduct studies with a more diverse population.

Communication of Ideas. Our *VRception Toolkit* allows researchers to communicate their prototype ideas more easily. Currently, two options exist: 1) record videos with a scripted camera drive directly in Unity3D, or 2) repeat the process of creating and designing a prototype (cf. Section 4.3). Here, our toolkit offers a new approach for recording videos across realities, which has recently received more attention in research [44]. Moreover, replay functionality allows collaborating researchers to simply share their recordings and enable others to replay the complete prototyping process, alter the prototype, and share their changes.

Research on the Continuum. To our knowledge, little research focuses on prototypes embracing the complete reality-virtuality continuum from Milgram and Kishino [41]. So far, only fewer transitional interfaces (systems that allow users to transition on the continuum) have been proposed. However, experts expect an increase in headsets that do not exclusively offer AR or VR, but instead allow users to transition between different manifestations, underscoring the need for more research in this area [61]. Moreover, foundational work exploring the continuum and revisiting important concepts aids in the development of a shared language, which benefits researchers [59]. By simulating reality and virtuality in VR, we open up the possibility of exploring these topics more easily.

Education and Learning. The interviewed experts and participants of our design workshop highlighted that *VRception* would be a great resource for teaching and explaining the reality-virtuality continuum in a vivid way. We agree and see great potential in this use-case. Also, many existing research prototypes can be quickly replicated as lo-fi versions, allowing learners to explore cross-reality systems and easily test possible extensions.

10 CONCLUSION

We presented *VRception*, a concept and toolkit for rapid prototyping of cross-reality systems. To evaluate our concept and toolkit, we replicated six cross-reality systems from previous work, conducted expert interviews with the authors of these systems, and ran a subsequent evaluation with VR/AR practitioners. The experts unanimously agreed that we were able to replicate the core functionalities of their systems using the *VRception Toolkit*. Moreover, they highlighted the great potential of *VRception* to not only overcome hardware limitations, but also to enable remote collaboration and studies in the context of cross-reality systems and interactions, allowing broader research on the subject. During the evaluation with VR/AR practitioners, we gathered evidence for the rapid-prototyping character of our toolkit and confirmed its good usability. They were able to prototype and experience cross-reality systems in about eight minutes, which demonstrates how quickly users can blueprint these systems with the *VRception Toolkit*. We conclude our work by outlining research opportunities and their implications for the future of cross-reality research. We argue that cross-reality systems and interactions should be addressed further in future prototyping tools since they are becoming a fundamental type of interaction for augmented and virtual reality applications.

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