HaRT - The Virtual Reality Hand Redirection Toolkit

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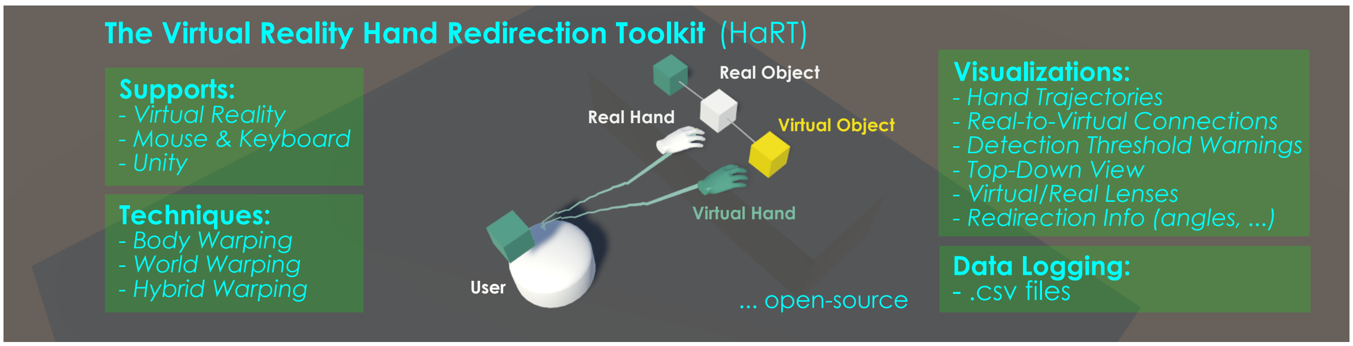

Figure 1: We present the *Virtual Reality Hand Redirection Toolkit* (HaRT) – an open-source Unity package for researchers and developers.

ABSTRACT

Past research has proposed various *hand redirection* techniques for virtual reality (VR). Such techniques modify a user's hand movements and have been successfully used to enhance haptics and 3D user interfaces. Up to now, however, no unified framework exists that implements previously proposed techniques such as body warping, world warping, and hybrid methods. In this work, we present the *Virtual Reality Hand Redirection Toolkit* (HaRT), an open-source framework developed for the Unity engine. The toolkit aims to support both novice and expert VR researchers and practitioners in implementing and evaluating hand redirection techniques. It provides implementations of popular redirection algorithms and exposes a modular class hierarchy for easy integration of new approaches. Moreover, simulation, logging, and visualization features allow users of the toolkit to analyze hand redirection setups with minimal technical effort. We present the architecture of the toolkit along with the results of a qualitative expert study.

CCS CONCEPTS

• **Human-centered computing → Virtual reality**; *User studies*; *Visualization toolkits.*

CHI '21 Extended Abstracts, May 8–13, 2021, Yokohama, Japan

ACM ISBN 978-1-4503-8095-9/21/05…$15.00
https://doi.org/10.1145/3411763.3451814

KEYWORDS

hand redirection, reach redirection, haptic retargeting, redirected touching, toolkit

ACM Reference Format:
André Zenner, Hannah Maria Kriegler, and Antonio Krüger. 2021. HaRT - The Virtual Reality Hand Redirection Toolkit. In *CHI Conference on Human Factors in Computing Systems Extended Abstracts (CHI '21 Extended Abstracts), May 8–13, 2021, Yokohama, Japan.* ACM, New York, NY, USA, 7 pages. https://doi.org/10.1145/3411763.3451814

1 INTRODUCTION

Virtual reality (VR) is a human-computer interface that stands out by addressing a wide range of the user's senses. Immersive virtual environments (IVEs) are conveyed to the user by means of visual and auditory stimulation, these days increasingly enriched by haptic sensations. Coordinating the user's sensory input is a challenging task and VR can involve sensory discrepancies, i.e. mismatches between the user's perceptual channels. When the sensory input is in conflict, the visual perception usually dominates other sensory channels, for example discrepant proprioceptive information such as the position or movement of limbs. This phenomenon of visual dominance [12] has opened up a design space for techniques that make use of such discrepancies. Prominent examples are *redirected walking* (RDW) [23] and *hand redirection* (HR) [4, 18] – both breaking with the 1-to-1 mapping of the real and virtual environment.

The latter technique has recently received significant attention in the HCI and VR research communities as it can be used to realize enhanced proxy-based haptic feedback [16] for VR. Hand redirection allows the VR system to control the user's physical reach, e.g. by displacing the virtual hand rendering, which results in an altered physical hand trajectory as the user (subconsciously) compensates for the mismatch while reaching for a physical prop. The technique can be used to implement *haptic retargeting* [4] allowing multiple dislocated virtual objects to be represented by a single prop, and *redirected touching* [18] allowing a prop to provide haptic feedback also for differently shaped virtual counterparts. Moreover, HR can enhance encountered-type haptic systems [2, 13] and improve ergonomics in VR [21].

As the number of applications that can benefit from a use of HR increases, the number of different algorithms for redirecting the user's hand movement does as well. Up to now, however, no common framework or platform exists, which can serve as an entry point for researchers and practitioners interested in testing, using, improving, or evaluating HR. Knowledge and implementation details about HR techniques are only available in research papers which leads to algorithms being continuously re-implemented, test scenarios being re-build from scratch, and the general development and evaluation of isolated solutions. The lack of reference implementations for the most common techniques impedes comparisons with new HR approaches and hinders practitioners of non-research applications to apply HR.

To address this need for an easy-to-use framework, and inspired by the efforts previously taken in the domain of redirected walking [3], we present the *Virtual Reality Hand Redirection Toolkit* (HaRT). Our toolkit is an open-source Unity package and provides reference implementations of different HR techniques that have been proposed and studied scientifically in the past. It comes with pre-built scenes and allows to easily add new HR algorithms by exposing a useful class hierarchy and related data structures. Documented in an online wiki with step-by-step tutorials, the toolkit aims to lower the barrier to HR development. In addition to supporting the most common VR systems, it also comes with a simulation functionality that enables testing and developing HR scenarios without a VR system. Moreover, logging and visualization features provide support for evaluations and VR application development. This paper introduces the structure and main features of HaRT, and reports on a first qualitative study conducted with expert VR developers.

2 BACKGROUND & RELATED WORK

The concept of non-1-to-1 mappings of real to virtual movement has been subject of HCI research for decades (cf. the Go-Go technique [22]). The idea of hand redirection for VR, as covered by our toolkit, however, has been introduced in the search for techniques that help overcome the limitations of proxy-based haptic feedback [15, 16] (cf. early work by Kohli [18] and recent work by Azmandian et al. [4]). In the following, we provide a brief overview of different approaches to HR, which are conceptually categorized as either *body warping*, *world warping*, or *hybrid warping*.

2.1 Body Warping

A common approach to HR, characterized by being comparably simple to set up and yet reliably redirecting, is *body warping*. The idea of body warping is to offset the rendering of a virtual limb (typically the virtual hand) from the tracked physical position of the real limb. As the immersed user reaches for a virtual target with the displaced virtual hand, the user needs to compensate for the real-to-virtual mismatch by moving the real hand in the direction opposite to the offset. Only by this, the user can ensure that the virtual hand visually arrives at the target. This approach is typically implemented by scripts that frame-wise update the offset of the virtual hand. The prominent techniques of Azmandian et al. [4], Cheng et al. [8], Han et al. [14], and Zenner and Krüger [30] continuously increase this offset as the user's real hand closes in towards the physical destination. Our toolkit ships with built-in reference implementations of these algorithms. Other approaches apply an instantaneous (or constant) offset during the entire reach motion (cf. Han et al. [14] and Benda et al. [5]). If below corresponding detection thresholds, such offsets, either continuously changing or instantaneously applied, can go unnoticed by users as has been shown in perceptual experiments [1, 5, 7, 10, 19, 30]. Our toolkit includes a real-time visualization indicating whether or not such thresholds are exceeded.

2.2 World Warping

The second class of HR techniques maintains a 1-to-1 mapping of the real and virtual body and instead applies changes only to the mapping of the real and virtual world. *World warping* techniques, such as the approach of Azmandian et al. [4], rotate the IVE to align real and virtual objects. Such changes to the virtual scene are commonly applied at moments in which users are less sensitive to detecting changes, such as during head movement [29], or by leveraging change blindness [20]. As a result of aligning the spaces in a way that a target's position and rotation matches in both the virtual and real world, the hand can reach the target visually and physically without additional distortion. Our toolkit supports rotational, translational, and combined world warping inspired by the work of Azmandian et al. [4].

2.3 Hybrid Warping

A third class of HR approaches makes use of a combination of both previously introduced strategies. *Hybrid warping* techniques both offset the virtual hand rendering from its physical position while also modifying the mapping of the virtual to the real world. Hybrid warping is used for both haptic retargeting [4] and redirected touching [17, 28]. A general approach to hybrid warping involves defining a set of real points p_i in the physical coordinate system, each assigned a 3D offset vector $\vec{o}_i$ which defines the corresponding warped virtual point $v_i = p_i + \vec{o}_i$ in the IVE. For any physical point p in between these reference points, the corresponding offset vector is interpolated [18]. As a result, a real-to-virtual offset is defined at any position in space and used to offset renderings of the virtual body or scene geometry. Our toolkit implements a hybrid warping technique based on inverse distance weighting [27].

2.4 Toolkits for VR Research and Development

Researchers and developers in the field of VR mostly use a common set of hardware (i.e. VR head-mounted displays (HMDs), tracking systems, etc.) and software (i.e. 3D engines, SDKs, etc.). This has led to the evolution of toolkits made by researchers in the field of HCI and VR, which are used by researchers and VR practitioners. Examples include the *User Experiment Framework* (UXF) [6], the

VR Questionnaire Toolkit [11], the *Immersive Notification Framework* [31], and, most related to our work, the *Redirected Walking Toolkit* [3]. The latter inspired the development of the HaRT and implements methods for RDW in an easy-to-use and easy-to-extend way, supported by additional functionality to simulate and analyze RDW scenarios. Our proposed HR toolkit joins the ranks of the aforementioned frameworks and expands the possibilities for VR developers and researchers to access HR reference implementations.

3 THE VIRTUAL REALITY HAND REDIRECTION TOOLKIT

The proposed *Virtual Reality Hand Redirection Toolkit* (HaRT) targets one of the most widely used 3D engines in the field of VR (i.e. Unity) to provide convenient access to common techniques of body warping, world warping, and hybrid warping. As a Unity package, it can easily be integrated into existing projects, offers pre-implemented algorithms and sample scenes, and exposes a modular class hierarchy with convenient data structures for easy extension. An online wiki in the open-source repository documents the framework, which encompasses real-time visualization and analysis features. Using the toolkit, it is no longer required to set up a VR system in order to work on HR as real movements can be simulated using only mouse and keyboard. In the following, we introduce the architecture of our toolkit.

3.1 Conceptual Overview

The toolkit is based on three central components. At its core, the *Hand Redirection Component* encompasses the implementation of the different HR algorithms alongside required classes, data structures, and HR management logic. The *User Movement Component* integrates common VR SDKs and implements a script to use mouse and keyboard to move the real hand when no VR system is available. Visualizations and logging functionality are implemented as part of an *Analysis Component*. The toolkit and the wiki with a documentation and tutorials can be accessed online[1].

3.2 Hand Redirection Component

As part of the *Hand Redirection Component*, the `Redirection Manager` script represents the heart of the HR integration in a Unity scene. Using its Unity Inspector interface, shown in Figure 2, central parameters and settings can be applied (e.g. defining which objects in the scene belong to the real, and which to the virtual world). Moreover, the `Redirection Manager` starts and ends individual redirections. Each mapping of a virtual to a real object is represented by a `Redirection Object` script, which is added to the virtual object that is to be mapped. The script holds a set of references to `Virtual-To-Real Connection` objects in the scene, each representing an individual mapping of a physical location (i.e. p_i – see explanation of hybrid warping in subsection 2.3) to the corresponding virtual location (i.e. v_i). By this, `Virtual-To-Real Connection` objects define the individual real-to-virtual offsets present in the scene, which can be adjusted manually in the Unity Editor. Redirection techniques can be set for each mapping individually (via the corresponding `Redirection Object`) and a default technique can be set in the `Redirection Manager`. To trigger custom application code in response to the redirection, custom event callbacks can be registered that will be triggered, for example, when a redirection starts or ends.

The HR techniques are implemented as individual scripts inheriting from the base classes `BodyWarping`, `WorldWarping`, or `3DInterpolation`. Each technique realizes their respective logic by overwriting an `Init()` (called upon activation of a redirection), `ApplyRedirection()` (called frame-wise during redirection), and `EndRedirection()` (called upon termination) method. Within these methods, developers have access to all relevant data structures (e.g. real and virtual target locations). Due to this modular architecture, new HR algorithms can be added easily by inheriting from one of the base classes or pre-implemented approaches. In order to add HR support to a scene, users of the toolkit can simply drag a prepared prefab (`hrt_core`) into their scene, or start off modifying a sample scene. Due to its illustrative nature, we chose the 3-cubes-illusion presented by Azmandian et al. [4] as a sample scene scenario shown in Figure 1 and Figure 2.

With the body warping techniques of Azmandian et al. [4], Cheng et al. [8], Han et al. [14], and two variants of the algorithm of Zenner and Krüger [30], a rotational, translational, and combined world warping approach inspired by Azmandian et al.'s work [4], and a 3D interpolation method inspired by Kohli's work [18], our toolkit encompasses nine pre-implemented techniques. In the future, we look forward to integrating additional algorithms.

3.3 User Movement Component

The *User Movement Component* is responsible for processing the user's motion input, i.e. typically the real head, hand, or controller movement. The toolkit is designed to work with the widely-used VR platform SteamVR, supporting HTC Vive[2] systems and Oculus Rift[3]. Additionally, the toolkit supports tracking the real hands with Leap Motion[4]. For quick testing of a scene, toolkit functionality, or novel HR concept, however, setting up a VR system seems tedious. For this reason, the toolkit includes a script that allows users to simulate real head and hand movements in a scene using mouse and keyboard. The movement method can be set via a dropdown menu in the `Redirection Manager`.

3.4 Analysis Component

The *Analysis Component* implements additional functionality that aims to lower the barrier to understanding, evaluating, and debugging HR techniques and scenes. The toolkit creates log files in the `.csv`-format, which store for each frame a timestamped data set consisting of basic information about an applied redirection such as the positions and rotations of head and hands, selected target, and HR technique. The resulting files can be used, for example, to analyze hand trajectories. Moreover, the *Analysis Component* provides five real-time visualizations to support developers, each of which can be individually switched on and off. Figure 2 depicts the *Scene Overview* visualization, which effectively implements the concept of a real-, and a virtual-world lens only displaying the content of

[1] Source code, documentation, and tutorials of the *Virtual Reality Hand Redirection Toolkit* (HaRT): https://github.com/AndreZenner/hand-redirection-toolkit

[2] https://www.vive.com/

[3] https://www.oculus.com/rift/

[4] https://www.ultraleap.com/product/leap-motion-controller/

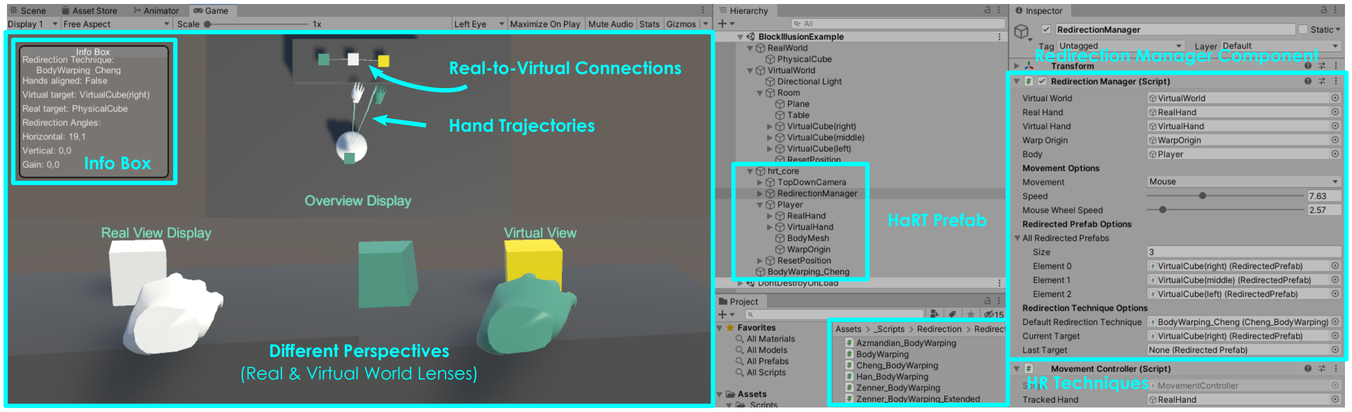

Figure 2: User Interface of the HaRT inside Unity with the `Redirection Manager` exposing central settings and parameters.

the respective environment. These lens views are complemented by a top-down scene overview rendering both virtual and real objects simultaneously. *Trajectory Renderings* display the path traveled by the real and virtual hands in the 3D scene for visual comparison, and *Real-to-Virtual Object Connections* are displayed as line renderings during Edit and Play mode in Unity. This provides an overview of the real-to-virtual mappings configured in the scene. In order to create comfortable experiences, developers can also configure detection thresholds in the Unity Inspector view of the `BodyWarping` scripts. As shown in Figure 3, *Threshold Warnings* then visually indicate if a redirection is going to be unnoticed by users (i.e. below thresholds), or not. Finally, an *Info Box* rendered in the Play view in Unity summarizes the current status of redirections at runtime.

4 QUALITATIVE EXPERT STUDY

To shed light on the usability of the toolkit and gather feedback from the target user group, we invited experts in Unity and VR development with an academic or industry background to participate in a remote user study. The study was approved by the Ethical Review Board of the Faculty of Mathematics and Computer Science at Saarland University. In this study, the experts were asked to use the toolkit and its wiki to solve a set of representative tasks using Unity. The goal of the evaluation was to collect whether the toolkit is supportive when (1) setting up an HR scenario, (2) comparing two different HR techniques, and (3) implementing a new HR technique. Moreover, we asked participants (4) whether or not they regard the visualization features as useful.

4.1 Methodology

Our study was conducted remotely via Microsoft Teams and was designed as an *observation* of different interactive tasks that participants completed using the toolkit, interleaved with *assessments of the user experience*, and concluded with a *semi-structured interview*. During the interview, participants were encouraged to think aloud and the experimenter observed the participant's interactions inside Unity through activated screen-sharing. The study did not involve a VR system, instead participants simulated their head and hand movements using the mouse and keyboard. Participants were sequentially introduced to four different tasks with varying complexity and independently solved these tasks by using only the information available in the toolkit and wiki. Interviewers observed this process, took the time for each task, took notes of problems, filled a binary task completion file for each task, and only intervened if participants could not solve tasks by themselves. After each task, participants filled out a short version of the *User Experience Questionnaire* [25, 26] (UEQ-S). Upon completion of all tasks, participants rated the usefulness of the toolkit's visualization features by stating their agreement to the statement *"The <Visualization> was useful"* on a scale from 1 (= fully disagree) to 5 (= fully agree). In the concluding semi-structured interview, participants were asked about the advantages and disadvantages of the toolkit, as well as their ideas for future improvements. The interviews were analyzed by means of a *thematic analysis*. Each session lasted approximately two hours and was recorded after the participant gave informed consent.

4.2 Participants

$N = 5$ experts (1 f, 4 m) with solid knowledge in Unity and experiences in VR development volunteered to take part in the study. Knowledge of HR was not a requirement and only two experts had first-hand experience in implementing HR, while all others only experienced HR as a user before, or only heard of the concept but never experienced it. Participants were between 23 and 27 years old and every participant completed the interview.

4.3 Procedure

At the beginning of the study participants joined the video call and completed a consent form. The experimenter then introduced the concept of HR and the way that body warping and world warping works from a technical perspective. After this, participants were granted access to the toolkit and wiki. Their first task was then to read an introductory section in the toolkit's documentation, followed by creating a new Unity project and starting the screen-sharing.

Participants completed four different tasks. The first task asked them to execute the *Getting Started* instructions in the wiki, i.e.

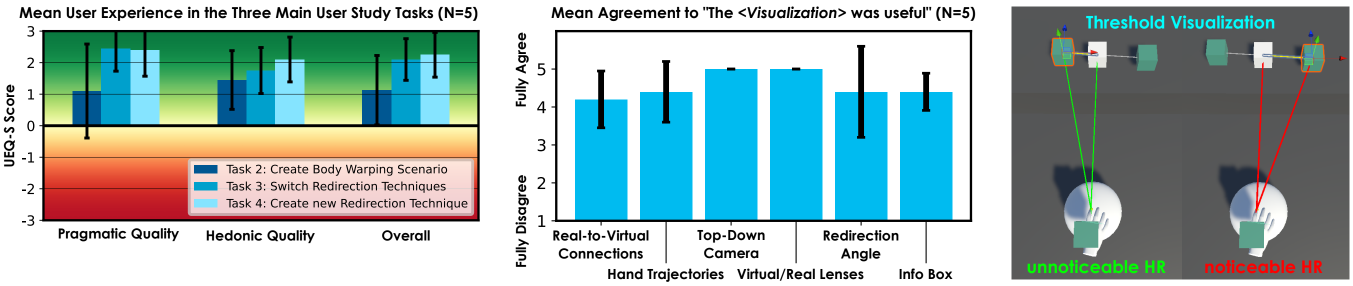

Figure 3: Left: UEQ-S results. Center: Avg. agreement to the statement *“The <Visualization> was useful”.* Right: Threshold Visualization.

downloading and importing the Unity package, followed by opening and testing a provided sample scene. Once completed, participants were to *Create a Body Warping Scenario*. They were instructed to set up a redirection scenario similar to Azmandian et al.’s [4] 3-cubes-illusion. For this, a prepared scene and 3D models were provided. The task focused on adding a pre-implemented HR technique to the scene and correctly configuring the `Redirection Manager`. In the third task participants had to *Compare Redirection Techniques* by adding two different HR algorithms to a single scene. *Adding a New Redirection Technique* was the goal of the last task. Here, the experimenter provided pseudo-code for an HR algorithm that participants were to extend the toolkit with. To achieve this, participants added a new script implementing the pseudo-code using the toolkit’s class hierarchy and data structures. After each task, participants answered a UEQ-S questionnaire through LimeSurvey. At the end, the toolkit’s visualization features were introduced to the participant, who rated their usefulness. A semi-structured interview concluded the study.

4.4 Results

The observations revealed mostly positive user experiences, while also surfacing some usability issues of the evaluated version of the HaRT. Most of the errors made in the study concerned setting up the virtual scene while re-building the 3-cubes-illusion. Here, for example, some participants wrongly placed `Virtual-To-Real Connection` objects in the scene, sometimes forgot to configure all settings inside a script, or assigned the HR techniques only locally for individual warps instead of configuring them as the default redirection technique. Also, participants occasionally skipped a step described in the wiki. We assume some of these issues were rooted in the observed behavior of the participants, as four out of five only quickly read over the instructions in the wiki and approached the tasks mainly relying on their general Unity knowledge and a trial-and-error method to explore the toolkit. This, and a strong focus of the participants on the example pictures in the wiki, resulted in them missing steps only described in the textual documentation. One of the participants, in contrast, first completely read all relevant sections in the documentation before working on the tasks in Unity. This participant did not make any mistakes throughout the study.

Concerning the toolkit’s usability, the results of the UEQ-S regarding pragmatic, hedonic, and overall quality are summarized on the left in Figure 3. The mean scale results show a positive evaluation of the toolkit’s usability across all tasks, with the most complex and error-prone second task being rated lowest but still in the neutral to positive range [25]. It is noteworthy that our study did not involve a counterbalanced order of tasks since they built up on each other. Increased familiarity with the toolkit could thus be a reason for increased usability scores in later tasks. This, in turn, would provide a first indication that users can get familiar with the toolkit already after a relatively short time.

As can be concluded from the results depicted in the second plot from left in Figure 3, participants perceived all visualization features included in the toolkit as highly useful. The thematic analysis of the semi-structured interviews provided additional insights into the experts’ opinion of the toolkit. When asked about the toolkit’s advantages, all experts agreed that the toolkit and involved workflows save time. Moreover, four experts mentioned that they perceived it as effortlessly to switch between different HR techniques inside the toolkit. Three experts also mentioned that they like the toolkit’s structure, and the overview visualization for quick testing, perceived it as easy to add a new HR technique, and found that the toolkit provides the basic functionality required to work with HR. Themes regarding the toolkit’s disadvantages and potential improvements were mostly mentioned only by individual experts. Most importantly, here, experts proposed to make the wording of some components of the toolkit more intuitive, and to improve certain instructions in the wiki as, for example, the relationship between a `Redirection Object` and a `Virtual-To-Real Connection` object was perceived as confusing by one expert.

5 DISCUSSION & LIMITATIONS

Our first evaluation with expert users revealed that the toolkit’s general structure allows to achieve its main goals. The experts’ performance and feedback indicates that the toolkit is supportive when (1) setting up a new HR scenario, (2) comparing two HR techniques, and (3) implementing novel HR algorithms. Moreover, (4) the visualization features offered by the toolkit were perceived as useful when working with the toolkit in a non-VR mode. Our user behavior observations further highlighted the importance of intuitive wording inside the class hierarchy and documentation, which can inform future iterations of the wiki. Additionally, the experts underlined that video instructions and animations inside the documentation should ideally cover all steps of a tutorial. We also inferred from the expert interviews that, in order to provide a clean and helpful documentation, the wiki should separate basic explanations of HR concepts and background information from step-by-step tutorials. This would make it easier for users of varying experience level to find relevant information. Despite the shortcomings of the wiki at the time of evaluation, our observations and collected usability results indicate that users can get acquainted with the toolkit quickly. In summary, the toolkit was found to be time-saving and a helpful support when working with HR in Unity.

At this point we also like to mention central limitations of the evaluation presented here. Most notably is the small sample size as we only recruited $N = 5$ experts, which does not allow us to draw statistically significant conclusions. Moreover, constrained by the COVID-19 pandemic situation in November 2020, we conducted our study in a remote setting and tested the toolkit's functionality in a non-VR mode only, which might have impacted the experts' impression of the toolkit. Lastly, to maintain a reasonable study duration, we reduced the scope of our evaluation to body warping. Testing further functionality (e.g. logging) and HR techniques (e.g. world and hybrid warping) is left to future studies.

6 CONCLUSION & FUTURE WORK

Up to now, integrating HR into VR projects required careful research and re-implementation of existing algorithms, detailed information about which often only being available in academic research papers. Motivated by these circumstances that hinder a wider adoption of HR, we present the *Virtual Reality Hand Redirection Toolkit* (HaRT), a lightweight framework for the integration of HR into Unity projects. The toolkit is designed to serve as a central contact point for the VR research and development community interested in experimenting with, integrating, or improving HR. It offers easy access to reference implementations of techniques proposed in past research, and exposes a useful class hierarchy and data structures to ease the implementation of novel HR algorithms. It supports the most common VR systems, offers a non-VR mode, and a range of logging and visualization functionalities. Moreover, a detailed documentation including videos and tutorials provides a starting point for those new to the concept of HR and experts alike. A first user study with $N = 5$ expert Unity developers indicated the toolkit to be well-structured, providing the basic functionality required to work with HR, time-saving, and fast to get acquainted with.

In the future, we will further optimize the toolkit's documentation based on the expert feedback and plan to evaluate it with a greater sample size. This follow-up investigation might be conducted in-the-wild by reaching out to the GitHub audience. Furthermore, as the field develops, we plan to add more tutorials, sample scenes, and HR techniques. Future development might also focus on adding a target prediction functionality (e.g. leveraging eye tracking), support for pseudo-haptic techniques [9, 24], or implementing a similar toolkit for other 3D engines (e.g. Unreal). Finally, we look forward to integrating ideas, contributions, and feedback of the community.

ACKNOWLEDGMENTS

We thank all expert Unity developers that participated in our study for their time and valuable feedback. This research was funded by the Deutsche Forschungsgemeinschaft (DFG, German Research Foundation) – project number 425868555; 450247716.

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