Opportunities for Novel Interactions with Virtual Realities

Dissertation

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ABSTRACT

Virtual Reality (VR) is entering a wide range of professional and leisure contexts, such as remote collaboration and work meetings, training and gaming simulations, well-being applications, and social gatherings. Although VR devices have increased in technical fidelity and nowadays allow for rich visual and auditory output, making people perceive VR as similar to physical reality remains challenging. Current VR systems mainly rely on controllers as the primary input channel. While this works for many scenarios, it does not resemble the interaction that users expect from their experience in physical reality. Further, considering output modalities, controllers cannot render the complex haptics of virtual objects with which VR users may interact while immersed in VR.

To make VR truly immersive and increase the presence of VR users within the underlying Virtual Environment (VE), VR systems should enable natural interaction known from reality. For example, a virtual door should be opened using a door handle just like a physical one. At the same time, VEs should react accordingly to the user's behavior by providing plausible feedback (e.g., creating a feeling of stiffness when the user reaches towards a virtual wall). To venture towards this form of VR, we must consider aspects that impact the interaction opportunities of VR users.

In this thesis, we address conflicts between the real world and VR because such conflicts can impede interaction within VEs. Next, we research ways to integrate the real world into VR to allow familiar and natural interaction with objects of interest. Finally, we introduce enhancements for haptics that enrich VR beyond what is possible with state-of-the-art controllers. Thus, we present research structured along three research themes.

In the first theme – *"Avoiding Conflicts with the Real World"* – we enhance redirected walking through Electrical Muscle Stimulation (EMS) and thereby minimize the physical space needed for natural locomotion in VR. Further, to use the available space more efficiently, we employ non-Euclidean virtual architectures that allow one to create an illusion of a VEs that exceeds the available physical space. We then evaluate ways to utilize distractions to guide attention in VR, thereby making these illusions less conspicuous.

In the second theme – *"Integrating the Real World"* – we integrate real-world objects into the VR experience. We investigate ways to include objects from the real world in VR as well as what advantages the VE can provide compared

to reality by manipulating virtual physics. In addition to integrating physical objects, we continue integrating neurological responses of VR users to control the virtual narrative via Brain Computer Interfaces (BCIs). In particular, we improve the sensing capabilities of VR devices by including neurological responses. Here, we design corresponding stimuli in such a way that they naturally blend into the VE.

In our third theme – *"Enriching the Virtual World"* – we focus on the haptic enhancements of virtual experiences. First, we enrich experiences that occur in more than one location. In particular, we enhance remote VR collaboration using haptic props by investigating different manipulation strategies that enable shared ownership of physically separate objects. Next, we investigate the deployment of flying User Interfaces (UIs) in VR. Here, we use drones equipped with 3D-printed input devices as haptic end effectors. We developed a system that autonomously positions the drones around VR users, thereby providing haptic feedback at the physical position at which users would expect to feel a virtual object when reaching out for it.

In conclusion, we introduce a wide array of interaction enhancements for VR. With that, we contribute insights that can help to shape future VR experiences, thereby bringing VR closer to becoming a ubiquitously employable technology. We complete this thesis by outlining our ideas of promising future research endeavors that can drive us toward the ultimate form of VR – a simulation indistinguishable from reality.

ZUSAMMENFASSUNG

Virtuelle Realität (VR) hält Einzug in eine Vielzahl von Berufs- und Freizeitaktivitäten, wie virtuelle Zusammenarbeit und Besprechungen über Distanz, Schulungssimulationen und Spiele, Anwendungen für das Wohlbefinden sowie für gesellschaftliche Zusammenkünfte. Obwohl VR-Geräte technisch immer leistungsfähiger geworden sind und heute eine reichhaltige visuelle und auditive Ausgabe ermöglichen, wird VR von Nutzenden noch nicht als vergleichbar zur physischen Realität empfunden. Aktuelle VR-Systeme verlassen sich hauptsächlich auf Controller als primären Eingabekanal. Das funktioniert zwar für viele Szenarien, ähnelt aber nicht der Interaktion, die Nutzende von ihrer Erfahrung aus der physischen Realität kennen. Außerdem können Controller, wenn man Ausgabemodalitäten berücksichtigt, nicht jegliche, meist komplexe, Haptik virtueller Objekte nachempfinden, mit welchen VR-Nutzende interagieren können, während sie in VR eintauchen.

Um VR hoch immersiv zu gestalten und die Präsenz von VR-Nutzenden in der zugrundeliegenden virtuellen Umgebung zu erhöhen, sollten VR-Systeme natürliche, aus der Realität bekannte Interaktionsformen ermöglichen. Zum Beispiel sollte eine virtuelle Tür mit einem Türgriff geöffnet werden können, genau wie eine reale Tür. Gleichzeitig sollten virtuelle Umgebungen auf das Verhalten von Nutzenden eingehen, indem sie plausibel reagieren (z.B. Nutzende sollten ein Gefühl von einer starren Wand erfahren, wenn sie nach einer virtuellen Wand greifen). Um sich dieser Form von VR anzunähern, müssen Aspekte berücksichtigt werden, welche sich auf die Interaktionsmöglichkeiten von VR-Nutzenden auswirken.

Diese Arbeit befasst sich mit Konflikten zwischen der realen und der virtuellen Realität, da diese Konflikte die Interaktion innerhalb virtueller Umgebungen einschränken können. Als nächstes werden Möglichkeiten zur Integration der realen Welt in VR erforscht, um eine vertraute und natürliche Interaktion mit Objekten von Interesse zu ermöglichen. Schließlich werden Verbesserungen für haptisches Feedback vorgestellt, welche VR darüber hinaus bereichern, was mit modernen Controllern möglich ist. Folglich ist diese Arbeit in drei Forschungsthemengebeite unterteilt.

Im ersten Themengebiet – der *“Vermeidung von Konflikten mit der realen Welt”* – werden Verbesserungen des umgelenkten Gehens (engl. Redirected Walking) mittels elektrischer Muskelstimulation (EMS) vorgestellt. Dadurch kann der benötigte physische Raum für das natürliche Fortbewegen in VR minimiert werden. Um den verfügbaren physischen Raum effizienter zu

nutzen, können nicht-euklidische virtuelle Architekturen eingesetzt werden, die es ermöglichen, die Illusion einer virtuellen Umgebung zu schaffen, die den verfügbaren physischen Raum übersteigt. Um diese Illusionen weniger auffällig zu gestalten, können Ablenkungen genutzt werden, um die Aufmerksamkeit von VR Nutzenden zu lenken und somit Eigenschaften der Umgebung zu verstecken, welche ansonsten Nutzenden suggerieren würden, dass die zugrundeliegende Umgebung in der Realität nicht möglich sein kann.

Im zweiten Themengebiet – der *“Integration der realen Welt”* – werden Teile der echten Welt in virtuelle Erfahrung miteinbezogen. Es wird sowohl untersucht, wie Teile der realen Welt in VR einbezogen werden können, als auch welche Vorteile die virtuelle Umgebung im Vergleich zur Realität bietet, wenn die virtuelle Physik manipuliert und somit zum Vorteil von Nutzenden verändert werden kann. Neben der Integration physischer Objekte wird auch die Integration neurologischer Reaktionen von VR-Nutzenden untersucht, um virtuelle Erfahrungen über Gehirn-Computer-Schnittstellen zu steuern. Insbesondere stehen Verbesserungen der sensorischen Leistung von VR-Geräten im Fokus. Dabei werden entsprechende Stimuli so gestaltet, dass sie mit der virtuellen Umgebung verschmelzen.

Im dritten Themengebiet – dem *“Anreichern der virtuellen Welt“* – steht die haptische Anreicherung virtueller Erfahrungen im Fokus. Zunächst werden virtuelle Erfahrungen haptisch angereichert, die mehr als einen physischen Ort verbinden. Insbesondere werden Verbesserungen durch haptische Requisiten für die Zusammenarbeit auf Distanz untersucht. Genauer werden verschiedene Methoden erforscht, welche die Manipulation von räumlich getrennten physischen Objekten ermöglichen. Als nächstes wird der Einsatz von fliegenden Eingabeschnittstellen in VR erforscht. Dazu werden Drohnen mit 3D-gedruckten Eingabegeräten, welche als haptische Endeffektoren dienen, ausgestattet. Dazu wurde ein System entwickelt, das Drohnen autonom in der Nähe von VR Nutzenden positioniert. Dadurch wird haptisches Feedback an Positionen erfahrbar gemacht, an welchen Nutzende Feedback erwarten würden, wenn sie nach virtuellen Objekten greifen.

Zusammenfassend wird in dieser Arbeit eine breite Palette von Interaktionsverbesserungen für VR vorgestellt und erforscht. Die gewonnenen Erkenntnisse können dabei helfen, künftige virtuelle Erfahrungen zu gestalten und bringen VR damit näher, eine ubiquitär einsetzbare Technologie zu werden. Diese Arbeit schließt mit Vorschlägen von vielversprechenden Forschungsbemühungen ab, welche uns näher an die ultimative Form von VR heranführen können – eine Simulation, die von der Realität nicht zu unterscheiden ist.

Preface

In this thesis, I present scientific work that I have created over the last five years at the University of Duisburg-Essen.

As VR addresses its users on physical and physiological levels, I collaborated with experts within the domain of VR and related fields. Hence, this thesis is based on close collaboration with experts from the University of Duisburg-Essen and external and international experts bringing in knowledge from their respective fields. These collaborations resulted in publications which form the integral part of this thesis. The contributing authors (i.e., author and co-authors of corresponding papers) are clearly stated at the beginning of each chapter together with a reference to the publication, a video presentation, or video teaser when applicable. To emphasize the scientific collaboration, I use the scientific plural ("we") throughout this thesis.

Table of Contents

I

Introduction and Background

Chapter 1

Introduction

With VR, users can venture into a completely artificial, digital world that is only limited by its technical fidelity, interaction possibilities, and creator's imagination. Ideally, such a world would stimulate human perception in a holistic manner. The level of stimulation within such a world would be so sophisticated that a person could not distinguish between physical reality and the simulation. A person would be unaware that they are in a simulation unless they had prior knowledge to indicate as such or the system allowed them to become aware. VR has been studied since the 1960s to achieve an ever-increasing level of simulation quality [314, 489]. In 1965, Ivan Sutherland described a technology that would enable the highest possible level of simulation quality as the *"ultimate display"* [488]. In essence, the ultimate display is a computer that can manipulate matter to any degree. With this, computers would no longer be limited to a specific output device that is spatially restricted; instead, they would enter our world, fusing digital information with our physical reality.

Sutherland envisioned the *ultimate display* as such:

> *"The ultimate display would, of course, be a room within which the computer can control the existence of matter. A chair displayed in such a room would be good enough to sit in. Handcuffs displayed in such a room would be confining, and a bullet displayed in such a room would be fatal. With appropriate programming such a display could literally be the Wonderland into which Alice walked."*
>
> Ivan Sutherland [488]

To realize this vision, research has consistently introduced new approaches to tackle the many challenges that have arisen along the way. Such challenges include improving visual output to allow VR users to enter 3 dimensional (3D) worlds that are rendered in great detail [573] or providing rich auditory feedback, such as spatial audio output, to increase immersion [242]. With technical advancements in miniaturization, VR devices became standalone and mobile, and thus, more versatile and ubiquitous [165]. Although research has generated a wide variety of improvements, a huge gap remains between Sutherland's vision of the *ultimate display* and current VR systems. This provides novel research opportunities. Therefore, we identified three themes and corresponding research challenges that we tackle in the scope of this thesis (see Figure 1.1, Part III, Part IV, and Part V).

First, we address emerging conflicts of VR and the real world. Here, we aim for a reduction of unintended encounters with physical objects to improve immersion into VEs. Second, we address the integration of the real world into VR. We consider physical objects and their appearances in VR. We investigate how VR users perceive and use virtually manipulated physical objects. We also investigate ways to integrate novel sensing techniques to provide VR users with additional interaction modalities. Third, we enrich the interaction with VR beyond an individual location and introduce our approach: to position haptic end effectors around VR users in an automated fashion.

In Sutherland's vision, a computer is used to control matter. As long as this is not possible, unintended encounters with physical reality can disrupt the virtual experience. However, encounters with reality do not always induce adverse effects in virtual experiences. Integrating physical objects into VEs [119, 220] or interacting across multiple forms of virtually-created experiences can benefit users [85]. This form of interaction between different virtual worlds and physical reality has recently become a new domain of research – *Cross-Reality (CR) systems* and *CR interaction* [453]. In this sense, we should understand the current form of VR in a different way: as a technology that is inextricable from physical reality. Consequently, we should investigate this relationship to generate the greatest benefit for VR users.

Today's commercial VR systems allow for rich visual and auditory experiences. Beyond that, there are other important factors that impact such experiences to a large extent. For instance, the human sense of touch remains under addressed [101]. At the same time, the environment surrounding VR users is critical in terms of interaction possibilities. For example, if there is not enough physical space to walk around freely in VR, then the potential of VR

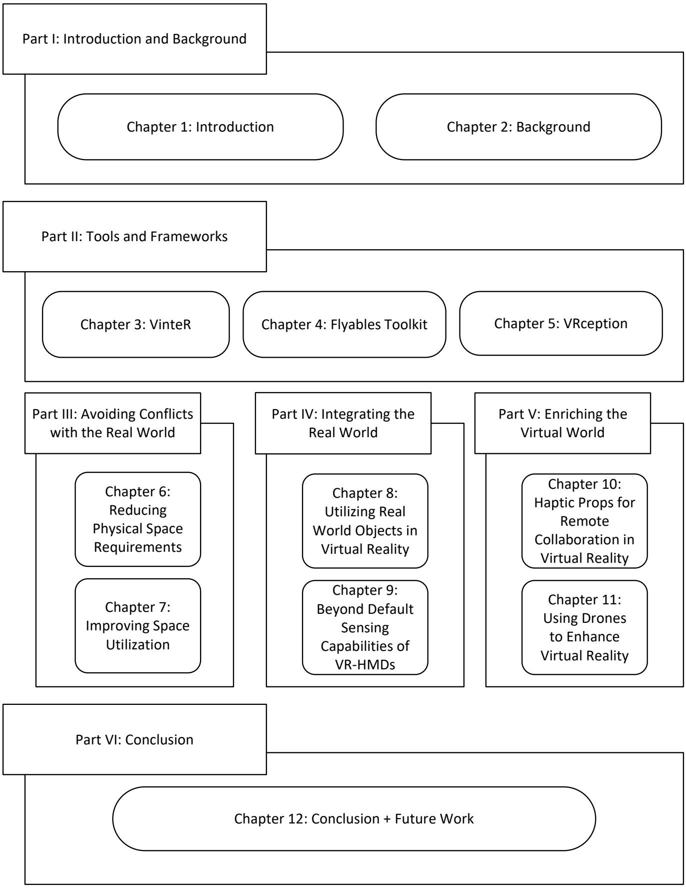

Figure 1.1: Thesis outline with the introduction and research background (this part), research tools (Part II), the three main research themes (Part III, Part IV and Part V), and finally the conclusion and future work (Part VI).

is limited. Furthermore, bystanders may interfere with virtual experiences (e.g., a bystander walks by a VR user and thereby advances into their tracking space [546]). Therefore, it is of utmost importance to carefully consider the surrounding environment, persons, and obstacles in order to avoid conflicts with the real world. By doing so, one mitigates the adverse side-effects that can impact the virtual experience. Such awareness is required to keep a user safe from dangerous encounters with other persons or obstacles when the user is highly immersed in VR. Avoiding such conflicts with the real world can be seen as a CR interaction, but in reverse. In other words, we decrease the interaction between the real and virtual worlds to improve the experience of the VR user.

Avoiding conflicts with the real world remains an important subject in research; however, the experiences in virtual worlds can also be enhanced by incorporating real objects. For example, by integrating corresponding physical objects into VR, one allows the VR experience to include intentional encounters with the real world [119]. This can improve the presence of VR users [220] or make their experiences more realistic and satisfactory [36]. Haptics can enhance the performance of VR users, and is therefore an important aspect to consider when implementing virtual experiences [56]. Beyond what is possible in reality, VR offers a means to bypass certain physical restrictions through the creation of illusions [478]. In this sense, we can manipulate the perception of VR users, thereby generating VR experiences that appear similar to Sutherland's reference of Alice's walk into Wonderland. Furthermore, this can enhance interaction in certain VR scenarios, such as collaboration or computer-supported work (e.g., sketching or design). For example, users could be provided with supernatural abilities (e.g., seeing through objects) inside a VE [120]. This would provide the user with the ability to perceive their workspace in a new way or obtain an enhanced view of physical objects. Such possibilities would be difficult to implement in the real world. Further, through appropriate stimulation, VR users can be tricked into believing that virtual objects are actually physical ones [172]. To achieve this, VR systems must be capable of creating plausible illusions (i.e., generating virtual scenarios that react to their users in such a way that the illusions match the users' expectations [456]).

The integration of the real world is not limited to the physical environment and its objects. To enhance the interaction in VR, we can also continue to develop the integration of the VR users themselves. Increasing the presence of VR users can be accomplished by providing them with further interaction modalities. Recently, VR devices and associated frameworks have begun to integrate various physiological and neurological sensors [350]. This sparks novel research as findings from other research domains become accessible (e.g., neuroscience [518]). The integration of corresponding interaction paradigms allows for new means of interaction. For example, BCIs can be used to interact via brainwaves [339]. This can make future VR systems more accessible to users that have difficulty using controllers or other input devices that rely on physical input modalities. BCI-based interaction channels and approaches have shown great potential for impaired groups of the population [288]. The integration of the underlying interaction paradigms in VR is by no means trivial, as they were not designed to be used in VR. Therefore, we believe that it is important to investigate ways to employ these interaction modalities in VR in order to increase the number of interaction possibilities of VR users [350]. Thereby, we can also enhance the presence of users within VEs (i.e., VR users have the feeling of *"being there"* [61]).

Integration of the real world in VR has many promising aspects, but Sutherland envisioned control of matter by the *ultimate display*. While working towards this vision, several researchers have introduced approaches that enrich the virtual world through haptic feedback by using specifically designed haptic props [586, 584], robot arms [543], or flying haptic props mounted on drones [3, 210]. While this works well in a single location, new challenges arise when we want to manipulate haptic objects that are distributed among multiple VR users in remote locations. While VR allows collaborators to meet virtually in 3D space using rich visual and auditory feedback, the manipulation of haptic objects over distance remains challenging. Hence, if we want to enrich the virtual experience through haptics, we can implement methods that allow for an indirect manipulation of remotely located haptic objects.

In Sutherland's vision, a computer can actively control matter. Essentially, this means that a VR system of similar technical fidelity must allow for haptic encounters in the 3D space around the VR user. Previous research utilized drones to position haptic props around the user with respect to the virtual world [3, 251, 210]. In other words, the drones mimicked the haptic feedback of the virtual objects that were expected by the VR user at corresponding locations. For example, a fish in front of the user in VR would be represented by a drone that would position itself in the air in front of the user in physical reality [210]. In principle, we can see these drones as the matter in Sutherland's vision of the *ultimate display*, but certainly with many limitations. Drones are magnitudes larger than atoms and produce noise when flying. Most importantly, they are primarily designed for flying, which makes it challenging to use them as haptic end effectors. Still, drones provide a lot of flexibility since they can move through 3D space, remain stationary in the air, and apply force in specific directions [198, 1, 567]. Drones are not only a focus of research in the field of VR [80, 134, 199]. Technical advancements [366], novel form factors [4], and insight into the perception of drones [79, 266] all offer interesting opportunities for their integration into future VR systems. As drones can be managed autonomously by a VR system and corresponding computational controlling, it is important to understand how we can use this technology to enrich virtual experiences in a proactive manner.

1.1 Vision

We believe that, through consideration of the three aforementioned themes, VR can fulfill its potential and become a ubiquitous technology. In the future, technology will allow us to blend physical reality and virtuality [464]. Therefore, we suggest that it is important to not view VR as a technology that absorbs its users and lets them spend time in a simulation. To a greater degree, VR can enhance our abilities in many contexts, similar to other disruptive technologies such as personal computers (PCs) or smartphones. In line with this, we suggest that VR is a powerful technology that can enhance our professional and private activities in many ways (e.g., by fostering remote collaboration, transforming education and education accessibility, or allowing for social experiences uninhibited by physical or political restrictions). To achieve this, VR must consider the real world in order to function without disruption. To support people with daily tasks or at work, VR must also allow us to integrate parts of the real world. Finally, VR must provide us with an interface that addresses us as human beings as a whole, with all of our senses and expectations. With this, VR would have the potential to impact many areas of our future lives.

1.2 Research Questions

In this thesis, we introduce a wide array of research along the following three main research themes and corresponding Research Questions (RQs). The RQs are outlined in Table 1.1.

With the first theme – *Avoiding Conflicts with the Real World* – we address the conflicts that can emerge between physical reality and the virtual world. To minimize such conflicts, we introduce approaches to enhance natural locomotion in VR. Here, we aim to limit the number of encounters with physical obstacles while one walks naturally in VR. Hence, we investigate approaches that can minimize the physical space needed for natural locomotion (**RQ 1**). The investigation of novel approaches for the reduction of physical space requirements is important for the deployment of future VR systems in a wide range of locations (e.g., households or work spaces). These locations do not often provide the physical space needed for VR experiences that involve vast VEs. Traveling through these VEs via natural locomotion provides high immersion [481], is familiar to most VR users, and reduces simulator sickness

Research Question	#RQ	Part
Avoiding Conflicts with the Real World		
How can we reduce the physical space needed for natural locomotion in VR?	RQ 1	Part III
How can we use the available physical space more efficiently for natural locomotion in VR?	RQ 2	Part III
Integrating the Real World		
How can we enhance the user's virtual experience by manipulating the appearance of real-world objects in VR?	RQ 3	Part IV
How can we integrate BCI-based sensing to provide additional interaction modalities in VR?	RQ 4	Part IV
Enriching the Virtual World		
How can we enhance remote collaboration in VR through passive haptic props?	RQ 5	Part V
How can we deploy flying UIs to provide haptic feedback in VR?	RQ 6	Part V

Table 1.1: Summary of the RQs that we address in the scope of this thesis.

compared to other locomotion techniques such as joysticks [269]. Therefore, there is a need for novel methods that reduce the physical space required for walking in VR. For the same reasons, it is important to investigate approaches that allow for more efficient utilization of the available physical space (**RQ 2**). In VR, we can create illusions that allow one to render vast VEs within limited physical space. To make these illusions believable, we can guide the VR user's attention to distract them from indicators that otherwise would reveal the illusion. As long as the illusion holds, VR users believe themselves to be traversing vast VEs. This can make the walking experience less prone to immersion-breaking encounters that occur due to physical space restrictions. It also allows for the deployment of VEs that virtually exceed the physical space available.

With the second theme – *Integrating the Real World* – we investigate approaches for blending the real world into virtual experiences. Here, we focus on integrating physical objects, such as tools. Thereby, we enhance the interaction with such objects by lifting restrictions that are inherent to the real world. Here, VR offers a means to conveniently manipulate the visual appearances of integrated objects. We can use that to enhance the experience of VR users when they interact with physical, real-world objects that appear in a different visual form in the virtual world (**RQ 3**). This can help the VR user to obtain a different view when we manipulate the appearance of the involved tools. Further, changing the virtual appearance can create illusions that visually indicate certain properties of physical objects, which might differ from reality. Through that, we can enhance the experience. Here, it is of utmost importance that we investigate to what degree such illusions remain undetected.

Besides physical objects, we can also integrate certain physiological properties of VR users. In this context, we investigate ways to enhance existing BCI-based interaction paradigms to broaden the interaction space of VR users (**RQ 4**). Here, we enhance interaction paradigms through novel stimuli design approaches that, in the context of VR, promise a more subtle and less disruptive interaction channel compared to state-of-the-art approaches, which are designed mostly for 2 dimensional (2D) displays [597]. As VR aims for immersive experiences, certain stimuli that are required for BCI-based interaction are not suitable for seamless integration into the virtual world. Therefore, it is important to investigate suitable stimuli designs that blend with the VE and, at the same time, are capable of eliciting brain responses that are algorithmically detectable. With such stimuli, we can preserve the immersion in VEs but still offer additional interaction modalities.

With our third and last theme – *Enriching the Virtual World* – we turn our research towards approaches that implement specific solutions that allow for enhancement of virtual experiences. Their sole purpose is to enhance VR; therefore, they lack meaning for the real world. In this context, we investigate methods to enhance remote interaction in VR through haptics (**RQ 5**). Tailoring systems that provide haptic feedback can enhance interaction with virtual objects. For instance, haptic feedback can improve input accuracy compared to VR controllers [280] or task performance [163]. Nonetheless, for remote VR collaboration, it is challenging to manipulate haptic props that are geographically distributed among multiple locations. Because of this, we investigate methods that allow for remote interaction using haptic props in a collaborative setting. Allowing haptic interaction in the context of remote collaboration in VR merges the benefits of both fields and is therefore worthy of further investigation.

We conclude our line of research in the field of haptics that are provided through flying haptic input devices (**RQ 6**). Providing haptic feedback through physical objects located at the matching physical positions of objects that are presented in VR allows users to interact in a natural manner. For example, reaching out to an object of interest, manipulating it physically, and finally stopping the interaction by releasing the object, is a familiar real-world experience. Therefore, we investigate ways to deploy haptic devices in 3D space via drones in order to mimic this interaction process in VR. Concretely, we investigate the suitability and applicability of well-known input devices that are mounted on drones. Through that, we are able to position the input devices in 3D space around a VR user. The VR users can expect the input device to be at the same physical position as indicated in VR. This allows the deployment of haptic input devices where the user expects them when physically reaching out for them. The corresponding haptic feedback matches the given virtual object because the drone-mounted input device has the same form-factor, and it thereby communicates affordance. In line with that, we investigate a novel research domain: we land drones on the human body and thereby provide insights that can benefit future drone systems that are worn on the body. In the context of VR, this would allow for mobile deployment. We envision VR users as wearing several drones on their bodies. At the start of the interaction in VR, the drones would automatically lift off, serve as haptic end effectors, and eventually land back on the user when no longer needed. With that, we pave the way for drone-enhanced VR systems that can be deployed ubiquitously.

1.3 Approach and Methods

In this thesis, we followed a generative design-driven and technology-focused approach [550]. This approach was the best fit for our informatics and technical background. As VR is strongly driven by technological advancements, we aimed to develop prototypes and corresponding artifacts using emerging and cutting-edge technologies. In this sense, we developed and evaluated a wide variety of research prototypes (i.e., hardware and software artifacts) as our contribution of knowledge. Through these systems contributions, we evaluated new interaction possibilities for VR users. Thereby, we gained insight into how users interact with virtual worlds, enhanced existing methods to make these worlds appear more realistic, and introduced new approaches for interaction with them. We did this by running user studies with each of our prototypes. In these studies, we gathered quantitative and qualitative data from our study participants. Here, we employed user tracking, questionnaires, and interviews. We utilized empirical methods to evaluate how our systems are perceived and used by our participants. The insights we gathered via our evaluations are presented in the form of publications, almost always accompanied by a video presentation and open-source code available for download, auditing, and further development.

1.3.1 Research Probes

For our research, we designed and developed an array of research prototypes with the goal of answering specific RQs. We based these prototypes on a reusable soft- and hardware infrastructure, which we developed and improved throughout the course of this thesis. This infrastructure provided us with the tools we needed to accelerate our research process. We constantly integrated new features to adapt to our research goals, integrate novel technology, and support us during our evaluations through task automation and controlling of our research workflows. This allowed us to tackle a wide range of open research challenges in the field of VR. As we tackled a diverse set of topics in this thesis, we aimed for the development of an infrastructure that provides reusable tools and frameworks that can support a variety of tasks. We introduce our tools and frameworks in Part II. The corresponding research probes are presented in Table 1.2, Table 1.3, and Table 1.4.

Along with that, we open-sourced many of our projects for other researches and practitioners to use, develop new features, or otherwise contribute to. Our projects include prototyping tools for mixed-reality systems [162] and distributed multi-user VR infrastructure [22]. With the *Flyables* toolkit, we integrate drones in VE to provide haptic input devices [31]. Further, we developed a framework for precise drone steering [33]. With that, we allow for future improvements as well as auditing of our prototypes. We envision these projects will be used by other researchers to collectively improve VR and how we interact with virtual worlds.

1.3.2 Evaluation Designs

With the developed research probes, we pursued user-centered investigations with the overall goal of enhancing interaction with VEs. Here, we focused on understanding how users would use the systems, how they perceive the virtual experience, and how they perceive the interaction in VR. To achieve this, we gathered quantitative and qualitative data from each evaluation.

Quantitative Evaluation To derive meaningful insights from the data we acquired, we employed a wide variety of quantitative measures. Through these measures, we extracted the answers to our RQs. We obtained objective, quantitative data by tracking the user (e.g., the user's motion or

Electroencephalography (EEG) data) and subjective data through questionnaires. We analyzed the gathered data using widely adopted statistical methods [126]. We employed measures such as Task Completion Time (TCT), error rates, and machine-learning classifier accuracies, among others. Further, we employed numerical methods and visual analytics to analyze the data samples of our participants, which were recorded during user sessions with our prototypes [7]. Here, we used standard methods from the field of regression analysis (e.g., the least-square method) or analytical methods from the field of signal processing (e.g., Fourier Analysis). This allowed us to analyze complex data and put forth insights that would not otherwise be accessible. To assess the subjective feedback, we made extensive use of standardized questionnaires. Here, we gathered feedback, for example, on perceived workload using the NASA Task Load Index (TLX), usability using the System Usability Scale (SUS), and perceived presence using questionnaires such as the Presence Questionnaire (PQ) or Igroup Presence Questionnaire (IPQ). To obtain a holistic picture of the evaluation outcome, we often complemented our evaluation with custom questionnaires, mostly consisting of Likert items. To support the findings from our results, we conducted a variety of statistical tests (e.g., Analysis of Variance (ANOVA), Friedman and Wilcoxon Signed-Ranks tests, among others). We chose tests according to the underlying type and distribution of the gathered data. We report the results in the form of descriptive statistics, accompanied by the statistical test results, data visualizations, and corresponding qualitative feedback.

Qualitative Evaluation To understand the needs and desires of users and to make sense of certain quantitative results, our quantitative assessments were always coupled with a qualitative component. Therefore, we conducted interviews during each evaluation. These interviews were semi-structured in order to obtain valuable knowledge beyond a static interview framework. To analyze the qualitative feedback and extract in-depth insights, we used an approach similar to *flexible coding* [107]. We employed a variety of analytical methods, such as joint qualitative coding, thematic analysis [64, 97], and affinity diagrams [183]. With this, we were able to derive themes from our analysis in a flexible manner. For example, thematic analysis allows for theme generation in two analysis forms, inductive and deductive [65]. Through inductive analysis, we could finds themes in the data that are not linked to the proposed RQs or coding framework while deductive analysis, allowed us to derive themes linked to our proposed RQs and our research interest. This helped us to find unexpected but also anticipated patterns in the gathered data. We present the results from our qualitative evaluations in the form of common themes and include quotes to convey the reasoning behind our participants' feedback. In Human-Computer Interaction (HCI), understanding the needs of the user beyond the quantitative outcome of evaluations is key. Thus, we generate comprehensive insights, provide the reasoning behind specific or unexpected results, and outline future research challenges.

1.3.3 Ethics

VR can manipulate human perception. Additionally, it is capable of rendering imagery that can induce unwanted neurological side effects, such as seizures. Therefore, it is of utmost importance that research in this field is conducted responsibly. In our evaluations, we ensured the safety of our participants and their data by various means. We conducted all of our user studies with the informed consent of our participants. The participation was entirely voluntary. We ensured that our participants understood that they could withdraw from our studies at any time without any negative consequences. At the beginning of each study, we informed our participants in both written and oral form about the study objectives, procedure, risks, and benefits. We addressed all open questions from our participants and developed their understanding of the presented experiment and technology. This is an important step because our studies involved prototypes that are unique and highly customized, and are therefore not entirely available to the general public. Users may not be familiar with such novel prototypes. Therefore, we informed our participants about their behavior and functionality. We excluded participants with certain medical conditions that would put them at risk (e.g., epilepsy). We always double-checked with our participants to ensure they met the participation requirements. If they did, we then retrieved informed consent to the study conditions in written form. For all of our evaluations, we followed the local ethical process[1] and the *ACM Code of Ethics and Professional Conduct*[2]. Due to the influence of VR on the human organism, we also conducted our study in accordance with the *Declaration of Helsinki*. To protect the data and privacy of our participants, we followed the General Data Protection Regulation (GDPR), which was enforced on May 25, 2018.

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[1] University of Duisburg-Essen – Good Scientific Practice, `https://www.uni-due.de/en/research_good_scientific_practice.php`, last retrieved on August 12, 2022

[2] ACM Code of Ethics and Professional Conduct, `https://www.acm.org/code-of-ethics`, last retrieved on August 12, 2022

1.3.4 Research Context

We conducted our research at the University of Duisburg-Essen between the summer of 2017 and the end of 2021. Early on, we sparked interest on both the student side and the university side by offering interesting Bachelor and Master theses and participating in competitions that resulted in numerous press releases[3]. Eventually, we entered the *Telekom Fashion Fusion & Lufthansa Flying Lab Challenge 2018*. Here, we were awarded a fashion and tech award. As part of the challenge, we designed *LYRA*, an information and communication system for in-flight services, including ordering beverages and meals and scheduling these requests to nearby flight attendants [29]. We developed *LYRA* with the *Ludwig Maximilian University of Munich (LMU)* and the *German Research Center for Artificial Intelligence (DFKI)*, as well as the software company *Xnet*. We conducted numerous studies involving a large number of students in several projects and theses. During our research, we sought to collaborate with other researchers in the field of HCI. We developed and evaluated the *Flyables* toolkit with Sven Mayer (*Carnegie Mellon University* and *LMU Munich*), which resulted in an honorable mention at *ACM VRST* in 2021. Together with Thomas Kosch (*Technische Universität Darmstadt*), we investigated novel designs of Steady State Visually Evoked Potential (SSVEP) stimuli to enhance BCI-based interaction in VR. With Jessica Cauchard (*Ben-Gurion University of the Negev*) and Martin Weigel (*Honda Research*), we investigated drone landing on the human body. Together with Florian Alt and Ken Pfeuffer from the *Bundeswehr University Munich*, we developed a distributed collaborative VR environment with haptic props. Thereby, we connected Munich and Essen to run a distributed user study. In a remote joint research endeavor together with Uwe Gruenefeld (*University of Duisburg-Essen*), Florian Mattis (*University of Glasgow*), Mohamed Khamis (*University of Glasgow*), Jan Gugenheimer (*Institute Polytechnique de Paris, Technische Universität Darmstadt*) and Sven Mayer, we developed and evaluated the *VRception* toolkit. The toolkit allows one to simulate CR systems completely in VR. The corresponding paper received an honorable mention at *ACM CHI* in 2022.

At the beginning of 2020, the COVID-19 pandemic reached Germany, and we had to adapt. In the following years, we had to modify our research methods to fit the situation. More specifically, we investigated methods for remote experiments in challenging research domains [28], conducted research in VR instead of in our lab [33] (see Chapter 11), and attended conferences and

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[3] Jonas Auda – News, `https://jonasauda.de/news/`, last retrieved on August 12, 2022

workshops remotely to network and present novel ideas [24]. To present our research, we tended to use media production to fulfill new requirements that came with the presentation of research contributions at remote conferences. Along with that, we made our media resources publicly available[4]. Despite these hurdles, we were able to consistently publish and present research at highly ranked conferences, as several publications were deemed exceptional by the research community. This eventually led to the two honorable mention awards from *ACM CHI* [162] and *ACM VRST* [31].

1.4 Summary of Research Contributions

The main contribution presented in this thesis is artifact-driven research that produces insight into the field of VR and focuses on the interaction possibilities of VR users. With the gathered insights, we introduce a wide array of contributions for *natural locomotion* in VR, *haptics* and *haptic illusions*, *physiological sensing*, and *remote interaction* in multi-user VR environments, as well as interaction and perception of *flying UIs* realized through autonomous flying drones. This practical approach is accompanied by extensive theoretical research in the field of CR systems. Taken together, we can draw a broad set of conclusions that take into account the interdependent nature of the underlying technology classes that form the Mixed Reality (MR) spectrum [328, 329].

1.4.1 Research Prototypes

We developed our prototypes to answer our set of RQs, which are presented in Table 1.1. In these questions, we turned our attention from research more related to reality and its interference with VR to investigating ways to mix reality with virtuality. Eventually, this led us to study VR enhanced by technical aids that are designed to simply mimic pure virtual content. The corresponding research prototypes are presented in Table 1.2 for Part III, along with a brief description and the research context. Part IV and Part V are presented in Table 1.3 and Table 1.4, respectively.

[4] YouTube Channel – Jonas Auda, `https://jonasauda.de/forward.html?res_id=youtube`, last retrieved on August 12, 2022

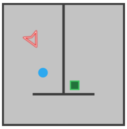
Prototype	Description	Chpt.
	The *Infinite Walker* prototype uses EMS to actuate the leg of a VR user while walking. In reality, the user's walking path is curved, but in VR, the user appears to be walking straight ahead.	6
	We developed a virtual *minimap* that helps one to navigate in VR. While providing navigational aids, the minimap also serves as a distractor from an *"impossible"* VE. To do so, the minimap shows a non-overlapping VE, but in reality, the physical space is shared among parts of the VE.	7

Table 1.2: The prototypes of Part III that we have developed within the scope of this thesis. Each prototype was used in a single research probe, each of which is presented in a dedicated chapter within this thesis.

1.5 Thesis Outline

This thesis is structured in six parts and consists of 12 chapters (see Figure 1.1). In the first part, we introduce our research topics and motivation and we outline our vision. Then, we introduce the foundations of VR, Augmented Reality (AR), and MR in general. With this, we include an extensive literature review in the field of CR interaction to illustrate how all of these technology classes are intertwined. In the second part, we introduce our tools, which we developed to power our research.

The next three parts form the integral research contributions, each of which focuses on one of our three themes – *"Avoiding Conflicts with the Real World"*, *"Integrating the Real World"* and *"Enriching the Virtual World"*.

In the last part, we conclude our theses and outline future research. Therefore, we compile an extensive summary of future research ideas, each of which promises to inspire and spark research in many directions, with the goal of improving virtual experiences.

Chapter 1 – Introduction This chapter introduces the topic of VR and outlines our undertaking by contextualizing the three main research parts. In addition, we introduce the vision of this thesis and formulate our RQs.

Prototype	Description	Chpt.
	The *VRSketch* system incorporates a pen in VR. While in reality the appearance of a pen or the holding hand cannot be easily manipulated, in VR we could render pen and hand with different levels of transparency. This allowed us to assess effects on sketching accuracy in VR.	8
	We *displaced* the hands of VR users to make physical objects appear smaller or larger in VR. We investigated to what degree such an illusion remains undetected by the user.	8
	We designed and developed SSVEP stimuli in the form of butterflies. These butterflies vary in shape and elicit SSVEP responses through either *flickering* or *flapping* wings.	9

Table 1.3: The prototypes of Part IV that we have developed within the scope of this thesis.

Chapter 2 – Background In this chapter, we introduce theoretical foundations, a historical classification of VR, corresponding related work, and useful visualization techniques.

Chapter 3 – VinteR – Interactive Virtual Realities In this chapter, we introduce our technical research middleware – *VinteR*. This middleware allowed us to set up our numerous research prototypes in a systematic and structured manner. *VinteR* allows streaming of spacial tracking data, integration of various data sources and containers (e.g., optical tracking systems, databases and persistent data storage, or Voice over Internet Protocol (VoIP) systems), and information exchange between remote locations. It also provides an interface for VR applications for seamless integration of corresponding data streams.

Chapter 4 – Flyables Toolkit In this chapter, we introduce the *Flyables* toolkit. With the help of this toolkit, we conducted research with drones used to provide haptic feedback in VR. The *Flyables* toolkit can help with integrating all kinds of drones and can steer them autonomously to locations in the room where VR users would expect haptic feedback of virtual objects.

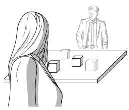
Prototype	Description	Chpt.
	The *I'm in Control* system connects remote locations in VR. Collaborators in each location can shape a collective solution to a task using haptic props. We developed a range of interaction techniques that allow for remote manipulation using local haptic props.	10
	The *Flyables* toolkit allows VR developers to integrate quadcopters with haptic attachments into their VR applications. The toolkit steers drones with 3D-printed attachments with respect to an associated virtual object's position. The VR user can reach out to the virtual object and use it for interaction while experiencing haptic feedback through the quadcopter attachment.	11
	We developed a framework that can *land drones* precisely on different parts of the *human body*. We used this framework to investigate which parts of the human body are suitable for drone landing.	11

Table 1.4: The prototypes of Part V that we have developed within the scope of this thesis.

Chapter 5 – VRception – Mixed Reality Prototyping In this chapter, we introduce *VRception*. With the help of this toolkit, we were able to prototype CR systems completely in VR. This gave us the opportunity to obtain first insights into our prototypes without having to build them first.

Chapter 6 – Enhancing Redirected Walking In this chapter, we introduce our research to improve redirected walking techniques for endless natural locomotion in VR. Here, we utilized EMS to actuate the human leg in such a way that the VR user walks in circles instead of in a straight line. We found that this can enhance redirected walking techniques that shift the vision of the user to the side in order to make them walk a circular path.

Chapter 7 – Enhancing Non-Euclidean Virtual Reality In this chapter, we introduce our research on non-Euclidean VEs. These environments overlap virtually to make VR users walk in a confined area that is smaller than the virtual one. We investigate this in two ways. First, we investigate how different levels of immersion affect the perception of virtual overlapping environments. Next, we employ a minimap in VR that indicates to the user that the environment is non-overlapping. With that, we distract the VR user from the overlapping architecture.

Chapter 8 – Haptics Through Real World Objects In this chapter, we integrate real-world objects into the VR experience. We approach this in two ways. First, we integrate a physical pen into VR. We then apply different levels of transparency to the virtual representations of the pen and hand of the VR user. We do so to investigate the influence on sketching accuracy. Next, we create illusions by manipulating the size of the integrated objects and displace the user's hands in order to align the real-world objects with the differently-sized virtual representations.

Chapter 9 – Beyond Default Sensing Capabilities of VR-HMDs In this chapter, we enhance the interaction via BCIs in VR. Therefore, we introduce a novel design of SSVEP stimuli for BCI-based interaction in VR that blend with the underlying VE. Thereby, we make SSVEP less disruptive to the virtual experience. We designed virtual butterflies that *flicker* or *flap* their wings to elicit SSVEP responses in the VR user's brain. Further, they vary in terms of their realism. With this, we propose an approach for SSVEP stimuli that blend into VEs.

Chapter 10 – Haptics for Remote Collaboration In this chapter, we research remote collaboration in VR. In particular, we employ haptic props for remote object manipulation. With the haptic props, we enable VR users to interact with remotely located objects in order to create a collective solution. The haptic props implement methods similar to *CUT* and *COPY*, which are known from standard desktop environments. During the collaboration, the VR user could take over control of remote objects. We found that our methods can enhance collaboration and reduce the need for verbal communication.

Chapter 11 – Haptics Through Flying User Interfaces In this chapter, we evaluate our *Flyables* toolkit. With our toolkit, we provide VR users with five well-known input devices mounted on quadcopters. Our participants used a flying *button*, *knob*, *slider*, *joystick*, and *3D mouse* in various VR scenarios. While the *Flyables* toolkit cannot outperform standard VR controllers in terms of precision, we could show that it provides matching haptic feedback as well as a playful and more active way to interact in VR. Further, we investigate landing drones on the human body. With this, we outline a novel research direction in the field of Human-Drone Interaction (HDI). Future VR systems that use drones can benefit from our insights in the context of mobile deployment.

Chapter 12 – Conclusion and Future Work In this chapter, we conclude this thesis. We summarize our research contributions and present the answers to our RQs. Furthermore, we outline promising future research directions and give our suggestions for important future research endeavors.

Chapter 2

Background

In this chapter, we introduce fundamental background knowledge that is related to VR. We start by briefly revisiting the history of VR. Then, we introduce the fundamentals of human perception as VR aims for the manipulation of the same. We continue with a scoping review on CR systems to understand the interplay of reality and virtuality. We conclude this chapter with visualization techniques for MR scenarios to foster the understanding of complex research scenarios.

This chapter is based on the following publications:

- **Jonas Auda**, Uwe Gruenefeld, Sarah Faltaous, Sven Mayer, and Stefan Schneegass. “A Scoping Survey on Cross-Reality Systems”. In: *Submitted to ACM Computing Surveys (CSUR)*. 2022.
- **Jonas Auda**, Uwe Gruenefeld, Sarah Faltaous, Sven Mayer, and Stefan Schneegass. “The Actuality-Time Continuum: Visualizing Interactions and Transitions Taking Place in Cross-Reality Systems”. In: *Submitted to MUM 2022*.

2.1 Brief History of Virtual Reality

The first VR devices were large and tailored to specific use cases. One of the oldest examples – *Sensorama* – was developed by Morton Heilig in the 1960s [194, 195]. Through *Sensorama* one could experience a side-by-side dual film of a dune buggy ride on a beach, a bicycle ride through New York, or a belly dancer, among other short films [554]. The device addressed various human senses with visual and auditory feedback but also used odor emitters and fans to stimulate the user in a more sophisticated way. As time passed, technology evolved from such large setups to more compact Head-Mounted Displays (HMDs) like the *Sword of Damocles* [326]. The rise of HMDs in the following years resulted in the diffusion of VR devices into the mass market. Although VR devices were popular in many professional contexts like education or training before [314], now they are also available for leisure activities like video gaming [451]. One major and prominent step in this process was the *Oculus* Kickstarter campaign in 2012, which raised $ 2.5 million and made VR devices accessible to the masses and thereby powered new applications in professional and private sectors and many research domains. Since then, these VR-HMDs went through a vast improvement process backed by the industry [13]. For instance, it took one year from the initial release of the *Oculus Go* which has no inside-out tracking nor hand-tracking capabilities, to the release of the *Oculus Quest*. This HMD can be operated without the need for stationary sensors as it uses camera-based inside-out tracking or cables that are connected to a PC. Further, the user can interact using controllers or the hands, which makes the *Oculus Quest* more versatile for many VR use cases like natural walking through VEs. Up to this date, the devices are not the limiting factor anymore, at least from a visual or auditory perspective. Now the physical environment poses limitations like walls that hinder the user from walking further. Also, it remains challenging to provide haptic feedback for all kinds of virtual objects. Here, modern VR systems fall short. When we develop VR experiences, we cannot neglect reality as its influence on the user is still there even if the user is fully immersed. Also, sometimes the user needs to interact with the real world while using a VR system. In this context, research in the field of Augmented Virtuality (AV) introduced new approaches to tackle some of the shortcomings of modern VR systems by mixing in parts of the real world into the virtual experience [317]. For example, to provide haptics for VEs [454]. Hence, reality has a lot of impact on virtual experiences as there is a constant interaction between reality and simulated environments. Through advancements in technology, this interaction can also be utilized to provide benefits to users. This research domain is called CR interaction, and systems that enable this kind of interaction are called CR systems. Research in the field of CR interaction and systems received a lot of attention lately [453, 453]. In the future, experts forecast that such systems blend between reality and virtuality and the remaining MR spectrum (e.g., AR) within the next five to ten years [464]. Such systems would provide the ultimate CR experience. Through the history of VR, we observed that the technology evolved from bulky devices and prototypes with specific use cases to flexible and mobile devices. In the future, these devices will provide experiences that go beyond one specific technology class like AR or VR, can be used anywhere (e.g., at work or outside) and allow multiple users to interact with each other across multiple manifestations within the MR spectrum.

2.2 Foundations

In the following, we introduce fundamental knowledge that is needed to understand how humans perceive virtual experiences. Here, we start with the basics of human perception. After that, we introduce fundamentals on VR and closely related technology classes like AR or AV.

2.2.1 Human Perception

Humans perceive an estimate of one Pebibyte (PiB, $2^{50} byte$) in a lifetime of 100 years through their eyes and ears [215]. This vast amount of data processed through the visual and auditory channels and afterward relayed to the brain to transform it into information shows the importance of visual and auditory input. This dominance is reflected in the current state-of-the-art MR technology. For instance, a wide array of technology was introduced over the years for AR and VR displays. The common goal of these displays is to provide suitable Field of Views (FoVs), render 3D imagery with matching depth, and sufficient high resolution [573]. Meeting these requirements is important to avoid discomfort in users. Here it is essential to consider the requirements of the visual system of humans. As VR aims to manipulate human perception, it is important to consider not only visual stimulation but also auditory and haptic perception, among others. For instance, auditory perception is also useful for object localization in VR, and therefore, important to consider for the interaction with VEs, but not in the focus of this thesis. We

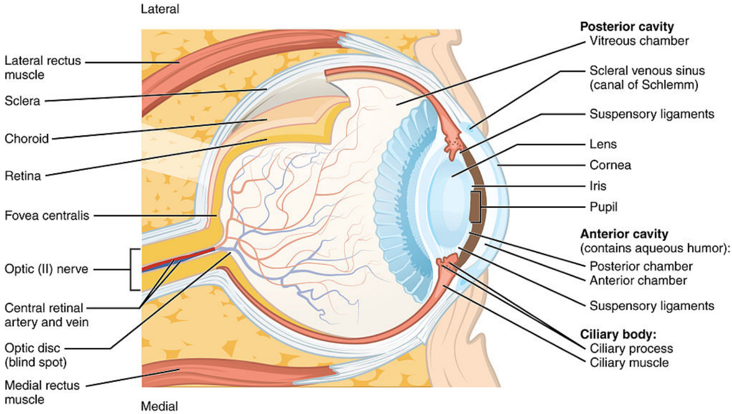


Figure 2.1: The anatomy of the human eye[6].

also neglect the remaining senses (i.e., taste and smell) as we have a strong focus on visual and haptic perception.

Visual Perception

Human perception is dominated by the visual sense. The FoVs of our eyes covers approximately 160° and 130° in the horizontal and vertical directions respectively [573]. Through our eyes, we can perceive light in the visible spectrum ranging from 310*nm* (ultraviolet) to 1100*nm* (near-infrared) and is dependent on the brightness [459]. The light enters the eye through the cornea (see Figure 2.1), passes the pupil, and then is refracted by the lens. The refractive power of the human eye or, in particular, its lens is measured in diopters [260]. This means to what degree the lens of the human eye can refract the light to keep the focus on an object. Eventually, the refracted light is picked up by the retina. The retina consists of millions of photoreceptors [548]. Approximately 5 million cones and 100 million rods. Cones process high light level vision, whereas rods are responsible for perceiving low light level vision. The perceived light is translated into electrical signals that are relayed to the brain via the optical nerve. The maximum resolution of the human eye is depended on the optical power of the lens and the size and spacing between the photoreceptors. For the human eye, this is 60 Cycles per Degree (CPD) with

[6] Structure of the Eye – Wikimedia Commons (CC BY 3.0), `https://commons.wikimedia.org/wiki/File:1413_Structure_of_the_Eye.jpg`, last retrieved on August 12, 2022

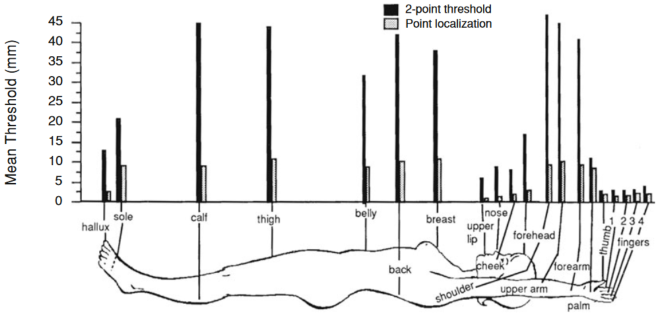


Figure 2.2: The haptic resolution of different parts of the human body [275].

an lens power of 60 diopters [548]. This is an important threshold as displays that offer a higher resolution can render spatial variations at a level that can not be further resolved by the human eye. Besides this spatial resolution, the temporal resolution of human perception is an important factor to consider for visual output. Humans can perceive around 10 to 12 individual static images per second [409]. Displays that render images with a higher frame rate allow us to perceive motion. Most modern VR systems offer sufficient high display refresh rates of around $80Hz$ or above [13]. Mobile VR-HMDs like the *Oculus Go* or *Oculus Quest* operate at slightly lower refresh rates – $60Hz$ or $72Hz$ respectively [244].

Haptic Perception

Through our skin, we can perceive haptic sensations in various forms. Responsible for this perception are a number of receptors in the skin layer each of which is associated with different primary functions [275]. *Merkel* receptors react to continuous pressure on the skin and are capable of recognizing haptic details like textures, patterns, or form. *Meissner* receptors allow for the detection of change and support handgrip control. *Ruffini* receptors detect stretching and support hand positioning. Finally, *Pacinian* receptors can detect vibrations and fine textures, for example, when we move our fingers. The human skin does not perceive haptics everywhere with the same spatiotactile resolution [519]. Two different tests can show how this resolution differs at different body sites. These tests are point localization [46] and two-point discrimination [298]. For point localization, two haptic stimuli are applied one after the other. The second stimulus is applied either to the same location or a different location. The stimulated subject should determine if both stimuli were located at the same body location. The test shows that the distance of the two stimuli influences the ability to distinguish their location on the human skin. For two-point discrimination, two stimuli are haptic stimuli applied to the skin at a specific distance from each other. The stimulated subject should determine if the two stimuli are perceived distinctly or not at the same time. The test shows that the distance between two stimulated points that allows for the distinction of the stimuli varies from body site to body site. Both tests show that the spatiotactile resolution differs significantly at various body parts (see Figure 2.2). This is an important factor to keep in mind when designing for haptic stimulation. A haptic system that stimulates the fingers must aim for a higher resolution than one that stimulates, for example, the thighs or the back. Otherwise, users might feel a mismatch between the haptic stimulus and, for example, the visual output of a VR system.

Proprioception

The human body has the ability to not only sense the environment but also make use of internal sensing to allow for movement and motor control [577, 510]. Proprioception can be seen as an additional sense that allows the human body to sense the position and orientation of different body parts to each other [226]. Proprioception does not dependent on-visual input [577], and thus, allows us to determine how the different body parts are located to each other without the need of our eyes. When we manipulate our senses through VR, we should consider that the internal sensing of the human body may indicate a different state to our brain than compared to the manipulated senses. For example, if we render the virtual hand of a VR user at a different position as the real hand, the proprioceptive sense can mismatch with visual perception.

2.2.2 Immersive Technologies

In the following, we introduce immersive technologies such as AR and VR in greater detail. Additionally, we introduce definitions for CR systems that help to structure this novel research domain. Here, we add new terms to the existing terminology that allow the classification of CR systems and their interactions.

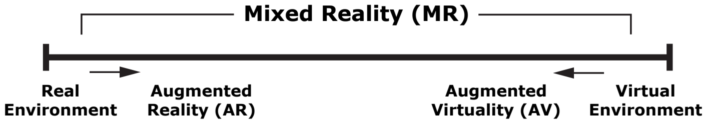


Figure 2.3: The Reality-Virtuality Continuum introduced by Milgram and Kishino in 1994 [328].

The Reality-Virtuality Continuum

At the time of writing, over 25 years have passed since Milgram and Kishino introduced the Reality-Virtuality Continuum in 1994 [328] (see Figure 2.3). Up to this point, the work has had a profound impact, coining terms that are frequently used in the field. According to *Google Scholar*[7] the work has over 6000 citations, which highlights its significant impact. During the last three years, the paper's citation increased by 2500, demonstrating the rapid growth of interest in the wide range of related research topics and applications that can be classified using this continuum.

The Reality-Virtuality Continuum that spans between *reality* or the *real environment* (on the left) and *virtuality* or the *virtual environment* (on the right) allows the classification of different degrees of virtuality. On this continuum, *reality* refers to the real world, in which every entity is real and subject to the laws of physics. On the other end, *virtuality* refers to VEs, in which every entity is digital and generated by a computer. Certain degrees of virtuality are often referred to as manifestations, such as AR and AV (see Figure 2.3). These manifestations allow one to refer to technology classes that have been frequently researched in previous work and implemented in consumer devices. Each point on this continuum between *reality* and *virtuality* refers to a degree of virtuality, which incorporates a different amount of virtuality depending on the position on the continuum. Milgram and Kishino refer to all degrees of virtuality that are not the two extremes as MR.

Manifestations of the Continuum

Along the continuum, there are different areas that represent concrete technology classes referred to as manifestations (e.g., AR [329]). Theoretically,

[7] List of citations of the Reality-Virtuality Continuum from Milgram and Kishino on Google Scholar, `https://scholar.google.com/scholar?cites=465000189172069232`, last retrieved on August 12, 2022

infinite manifestations could exist; however, only a few are distinctive enough to be frequently used in literature. In the following, we discuss these well-known manifestations. However, it should be noted that the Reality-Virtuality Continuum does not inherently define concrete locations or ranges to describe these manifestations. Instead, it specifies where they are positioned relative to one another [328, 329].

Augmented Reality (AR) The idea of AR is to alter the perceived reality by overlaying digital information. Superimposing digital information empowers users to see and interact with virtual objects within their real-world environment [329]. Thus, AR is the manifestation closest to *reality*, as it results in users perceiving the physical environment to a stronger degree than they do virtual aspects. According to Azuma et al., AR has three characteristics that need to be fulfilled: AR 1) combines real and virtual elements, 2) is interactive in real-time, and 3) is registered in 3D [38].

Augmented Virtuality (AV) In AV, users are immersed in a VE; however, parts of reality are incorporated into the digital experience [329, 317]. In comparison to AR, AV relates more to the VE, while AR relates more to the real environment. With the support of see-through modes in current VR devices, AV has recently gained popularity and is, for example, used to configure the play area for the latest VR devices[8].

Virtual Reality (VR) In VR, users experience an entirely VE similar to how one experiences reality or, in other words, VR enables one to enter a digital 3D environment (i.e., immersion) in which they can act similar to physical reality (i.e., presence). Immersion and presence are core aspects of VR [49]. The level of sensory fidelity of a VR system depicts how immersive it can render corresponding VEs [61]. Therefore, immersion is objective. Presence is the reaction to immersion [455]. It describes the involvement of VR users in the VE [49]. Hence, it is the subjective feeling of VR users of *"being there"* [61], being present in the VE. Users in VR can act similar to physical reality or even beyond. VR can bypass certain laws of physics, and therefore, can exceed certain boundaries from physical reality [328]. Although one could argue that VR represents virtuality on the continuum, current VR experiences do not completely immerse the user into a VE, and thus, do not represent *virtuality*. For example, users may bump into walls or get motion sickness if the real-world and VR experiences do not align. Hence, we understand current

[8] Oculus Guardian System,
`https://developer.oculus.com/documentation/native/android/mobile-guardian`, last retrieved on August 12, 2022

VR as a part of MR rather than pure virtuality. VR can be seen as a mode of reality that exists together with physical reality to provide its users with new forms of experiences [574].

Mixed Reality (MR) MR is not a term describing a particular manifestation on the continuum; instead, it represents all possible manifestations on the continuum that involve both *reality* and *virtuality* to some extent. In other words, every experience that lies between *reality* and *virtuality* is considered to be MR [329, 327]. In this context, Speicher et al. [464] published a paper addressing the following question: *"What is Mixed Reality?"* They conducted interviews with ten experts and analyzed 68 related papers, finding that different definitions of MR exist. Hence, we see MR as an umbrella term that represents all manifestations of the continuum such as AR, AV, and VR. Furthermore, four experts interviewed by Speicher, Hall, and Nebeling stated that "five or ten years from now, we will not distinguish between AR, MR, and VR anymore." In other words, the four experts believed that there will be one merged category of devices that supports different manifestations. In the future, this category of devices will form the ultimate *CR systems*.

Actualities

With CR systems, the ongoing trend towards systems supporting more than one manifestation continues. More than that, proposed systems can implement seamless transitions on the continuum, for example, to allow users to transition from the real world into VR [480, 229, 425] or to integrate parts of reality into their VR experience [317, 186, 106]. Here, the existing term *manifestation* is too inflexible to reflect such experiences and, more importantly, does not allow to describe changes in these experiences over time. Thus, we argue for using the term *"actuality"* to depict the current experience of a user. The term *actuality* goes back to the concept of *"potentiality and actuality"* introduced by Aristoteles [427]. In short, Aristoteles stated that potentiality is a not yet realized possibility of all possibilities that can happen and an actuality is the realization of a specific potentiality – the actual thing that became real. The English word *actuality* is derived from the Latin word *actualitas*, which translates to *"in existence"* or *"currently happening."* In other word, the state the world is in [460]. Thus, we could use the term actuality to describe the *"current reality"* of MR users – the things that currently seem to be facts for them. For example, we can consider two users – one using VR and one standing nearby. The actuality for the VR user would be a virtual, digital experience, while for the bystander, the actuality is reality. Moreover, when a user transitions, for example, from reality to VR, we can say that the actuality of that user changes over time. Our definition is in line with the suggestion of Eissele, Siemoneit, and Ertl who propose to use the word *actuality* for describing different virtual experiences [118].

Definition 1: Actuality

An **actuality** refers to the current experience of a user on the Reality-Virtuality Continuum. For each point in time, the **actuality** of a user can be represented by one point on the continuum. Moreover, the **actuality** of a user can change over time, allowing one to experience different degrees of virtuality.

Subjects and Objects

CR systems involve different entities: subjects and objects. The difference between both entities is that subjects have ways to perceive their environment, while objects have no perception. Hence, subjects can experience their environment and an actuality exists that describes their current experience. However, besides this difference, subjects and objects also have attributes in common. Primarily, both can either exist physically in the real environment, digitally in the VE, or in both environments simultaneously. Nevertheless, because subjects that would solely exist in the VE would refer to artificial intelligence without physical properties or transcended biological lifeforms, they will not be discussed further in the following.

$$subject = object + perception \tag{2.1}$$

In previous work, researchers focused mainly on the role of subjects in CR systems. Nevertheless, we think that objects also play an important role (see Section 2.2.2).

Definition 2: Subject and Object

Cross-reality systems can consist of two types of entities: **subjects** and **objects**. They differ in the sense that for **subjects** an actuality exists that describes their current experience while **objects** have no perception of their environments, and thus, no actuality is assigned.

Definition of Cross-Reality Systems

Simeone et al. categorized CR systems into two types that either involve (i) a smooth transition between systems using different degrees of virtuality or (ii) collaboration between users using different systems with different degrees of virtuality [453]. Following this definition, the role that objects can play in CR systems is somewhat neglected, as the definition focuses on the subjects' perspectives. Nevertheless, the interaction between subjects and objects should be considered in CR systems as well. Especially if the object is not intended purely for the subjects' actuality but instead was repurposed and integrated into the user's experience. For example, a haptic prop specifically designed for a VR experience should not be considered a CR system; however, if a real-world object such as a vacuum cleaner is repurposed for a VR experience, we consider it a CR system (e.g., [537]).

Definition 3: Cross-Reality Systems

We define three types of cross-reality systems:

Type 1: Subjects transitioning on the continuum experiencing a changing actuality.

Type 2: Subjects interacting with objects that are repurposed for the subject's actuality.

Type 3: Multiple subjects experiencing different actualities.

2.3 Cross-Reality Systems: A Scoping Literature Review

Today, we see a trend towards CR systems and research. While these systems provide great opportunities for novel experiences, they also introduce more complexity. The complexity of these systems does not only result from the number of users, their actualities, and possible bystanders but also depends on the different objects involved. For example, CR systems can integrate physical objects (e.g., keyboards in VR [441]) or the surrounding environment (e.g., walls in VR [292]). Furthermore, these systems can also include digital information such as notifications [426] or even physical forces such as motion induced by a driving car [204]. These examples highlight the uniqueness and complexity of CR systems, which makes them hard to describe and compare to each other. Here, a common language is not yet established; thus, it remains unclear how to formalize, interpret, and compare these systems.

To tackle this issue, we conducted a scoping literature review that investigates CR systems. We identified 185 papers as relevant and analyze them to provide insight into the current state of CR research. We analyzed the introduced systems, following our three types of CR systems; *Type 1:* subjects transitioning on the continuum experiencing a changing actuality, *Type 2:* subjects interacting with objects that are repurposed for the subject's actuality, and *Type 3:* multiple subjects experiencing different actualities. During our analysis, we found that the presented systems have become rather complex and frequently utilize implicit transitions that are difficult to grasp and hard to articulate. After our analysis, we present nine golden rules extracted from previous findings that can guide researchers and developers to built better CR systems. Finally, we conclude this review with research challenges and opportunities for future investigations of CR systems.

2.3.1 Review Methodology

As this scoping review [388] presents the first compilation of a literature corpus that analyzes CR systems and interactions, we considered literature that focused on research involving:

(i) A *subject* changes its actuality (e.g., a user transitions into VR [53, 54, 419]) – *Type 1*.

(ii) There is an interaction between at least one *subject* and at least one *object* that is repurposed for the current *actuality* (e.g., a physical keyboard brought into VR for typing [317]) – *Type 2*.

(iii) There is an interaction between at least one *subject* and at least one other *subject*, experiencing different actualities each (e.g., two users collaborate using AR and VR [85]) – *Type 3*.

An initial investigation revealed that a systematic search term-based literature review (e.g., PRISMA[9]) would not be possible as terms to describe CR systems

[9] PRISMA, `http://prisma-statement.org/PRISMAStatement/Checklist`, last retrieved on August 12, 2022

are not yet fully established. Furthermore, relevant aspects are often hidden within a research prototype or system, are a smaller part of a broader research agenda, or seemed too marginal for the scope of the corresponding publication to be described by the authors. An example would be the paper from Ruvimova et al. in which a user is distracted by the noise of an open office space, and therefore, transitions into VR for an isolated experience [425]. Here, the developed system was not explicitly described as a CR system; however, it is an intrinsic part of the approach. Hence, to present the most complete literature corpus, we individually screened our initial literature set manually.

For our literature review, we performed the following steps (see Figure 2.4):

1. We started by manually going through the proceedings from 2015 to 2020 of the five leading conferences in which related CR system papers were published (in parentheses: corresponding publication count): ACM CHI (3748), ACM UIST (575), ACM VRST (545), IEEE VR (1355), IEEE ISMAR (255). The corresponding digital libraries account for 6,478 entries for these venues in the given time frame. All authors together checked the title of each paper to identify off-topic research.

2. We then individually read the abstracts (and further sections if necessary) of all remaining publications to identify if the publications fit the scope of our literature review (meaning the three inclusion criteria hold; see Figure 2.4) and gathered them in a spreadsheet similar to Doherty and Doherty [109]. If the relevance of a publication was not clear to the screening author, it was discussed with all authors and a mutual decision was made. In total, we identified 105 papers that are relevant for this review.

3. After that, we looked at all references and all citing papers of the already gathered literature to identify further relevant papers, an approach which others have also applied, e.g., Katsini et al. [236]. We applied this process recursively, going through the references and citing papers of newly added ones until we could not find any more relevant publications. In this step, we went through 8,168 references and 15,324 citations and found 68 additional referenced papers and 12 additional cited papers (n=80).

4. In total, we found 185 relevant papers describing a CR system, which we further classified to extract their core features and identify common themes.

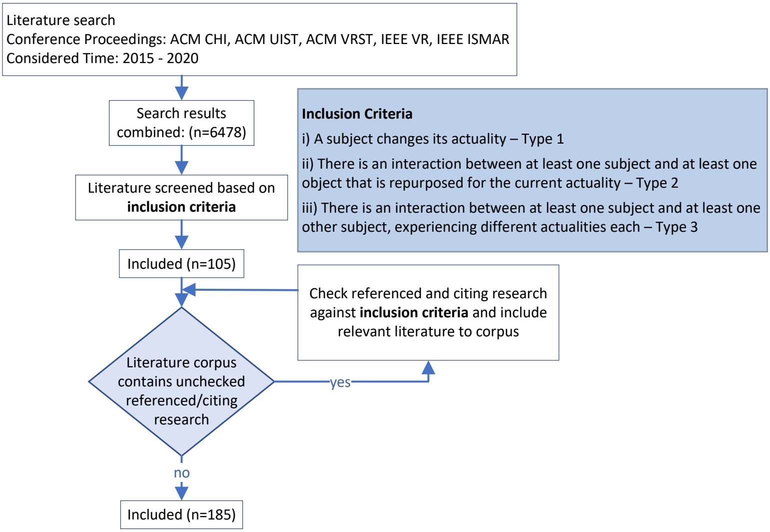


Figure 2.4: Literature selection process: The initial literature corpus from five leading conferences was screened based on our inclusion criteria. Then, referenced and citing literature was screened and added based on the same criteria. We repeated this process until we did not find more relevant literature.

The literature corpus was compiled from May to December 2020 using *Google Scholar* as the main search engine for citing papers while also relying heavily on the *IEEE DL* and *ACM DL*. At this point, it is worth mentioning that this strategy does not guarantee one will identify all relevant papers. As our research corpus is substantial in size, there is a chance that we have missed some relevant publications. However, strict database queries suffer from the same issue, especially when the terminology is unclear or not fully established. Therefore, we argue that our approach was able to identify more relevant research publications than an automatic approach.

The final publication corpus (n=185) served as the basis for understanding the interplay among different subjects and their actualities and corresponding objects that manifest across the Reality-Virtuality Continuum. For the publication corpus, we went through all publications and identified important features relevant to this survey to obtain a holistic view of the review corpus. Here, we identified features like the *research topic* and *keywords* that briefly

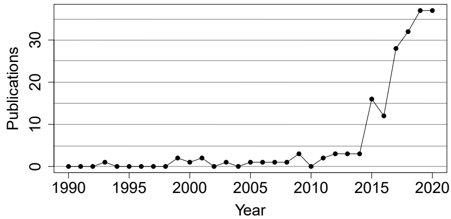


Figure 2.5: CR systems publication count of identified papers over the last 30 years.

describe the given research and involved scenarios as well as the purpose of the scenario (e.g., collaboration, leisure activity). Furthermore, we categorized the *scenario* together with involved *subjects* and *objects*. Therefore, we identified and quantified the involved *entities* (e.g., users, objects/artifacts) and how they were integrated into their *scenarios* (e.g., real-world objects brought into VR). Further, we extracted the *form-factors* (i.e., type of used devices) and *modalities* (i.e., visual, auditive, or haptic). We then identified how different entities relate to one another across the Reality-Virtuality Continuum and how they manifest on the continuum (e.g., VR, AV, AR).

2.3.2 Classification of Research Proposing Cross-Reality Systems

Over the last decade, we have seen a clear uptick of publications proposing CR systems (see Figure 2.5), indicating a growing interest in the research community. While the publication count before 2015 may be inaccurate because we did not screen conference proceedings before that year, a clear trend between 2015 and 2020 remains recognizable.

To understand and classify the gathered research which proposes CR systems, we in-depth analyzed our previously collected 185 papers. Each publication presents an artifact contribution (research prototype or system) that involves more than one manifestation of the Reality-Virtuality Continuum. In the following, we present the classification of our research corpus concerning the three types of CR systems and their research topics (see Section 2.3.2). Thereafter, we analyze the involved real and VEs (see Section 2.3.2). Finally, we examine the different transitions taking place in the identified CR systems (see Section 2.3.3).

Types of Cross-Reality Systems and Their Research Topics

We started analyzing all 185 papers by assigning categories to each paper, following an open-coding approach with all authors involved (e.g., we assigned the category "HMD user transitions into VR" to the following paper [480]). Thereafter, we applied the method of card sorting [466], clustering the identified categories and assigning a research topic to each cluster (e.g., we clustered "HMD user transitions into VR" into the research topic "transitional interface"). Then, we grouped the categories within each research topic into additional types to further classify the different papers (e.g., "HMD user transitions into VR" into the type "automatic transition"). Here, it is important to note that a paper can be sorted into multiple research topics and types if necessary. Finally, we assigned each research topic to one of the three CR systems types that we have defined in Section 2.2.2. In the following, we describe the research topics within the three CR systems types.

Type 1: Subjects Transitioning on the Continuum Experiencing a Changing Actuality

For the first type of CR systems, we identified one research topic as relevant: transitional interfaces. In sum, we identified 52 of 185 papers (28.11%) that investigate *Type 1* systems.

Transitional Interfaces A transitional interface is a system designed to empower users to transition on the Reality-Virtuality Continuum and experience its various manifestations, proposing a new way to interact and collaborate among these manifestations [158]. An early example is the *MagicBook* from Billinghurst, Kato, and Poupyrev [53, 54]. It is a book that one can read in reality, augmented with virtual objects in AR, or use as a companion in immersive VR. With AR- and VR-enabled devices becoming part of our everyday lives, it is imaginable that transitional interfaces will become a ubiquitous technology. In the past, two different categories of transitional interfaces have been explored (see Table 2.1): transitional interfaces controlled by the user (29) and interfaces with an automatic transition (22).

User-controlled transitional interfaces empower users to choose between different available manifestations. Different form factors of user-controlled transitional interfaces have been explored in the past, ranging from headset-

Research Topic	Type	Category	Count	Publications
Transitional interface	User-controlled	Headset-based	14	[419, 507, 532, 148, 186, 292, 248, 277, 441, 141, 261, 578, 571, 592]
		Combined form factors	9	[421, 422, 389, 157, 289, 420, 167, 106, 166]
		Handheld-based	3	[53, 54, 103]
		Projection-based	3	[257, 446, 187]
	Automatic	Headset-based	19	[480, 468, 514, 229, 249, 58, 317, 71, 202, 546, 147, 407, 558, 330, 485, 90, 9, 370, 557]
		Handheld-based	2	[231, 232]
		Projection-based	1	[6]

Table 2.1: Publications representing research that investigates transitional interfaces.

[419, 507, 532, 148], handheld- [53, 54, 103], and projection-based devices [257, 446] to a combination of various form factors [421, 422, 389, 157]. Different types of transitional interfaces are those that utilize an automatic transition between two manifestations on the continuum. So far, the investigated transitions are limited to those between reality and VR, investigating users transitioning into VR [480, 468, 514, 229] or out of the VR experience [249].

Type 2: Subjects Interacting with Objects That Are Repurposed for the Subject's Actuality

For the second type of CR systems, we found that 105 of 185 papers (56.76%) are relevant that are distributed over two different research topics: object integration (76) and collision avoidance (29). In the following, we present each of the research topics in detail.

Object Integration The 76 papers that address object integration investigated users experiencing a concrete manifestation (e.g., VR) in which they lacked relevant objects, for example, real-world objects. It is important that these objects are not components specifically designed for being used in VR such as VR controllers. These controllers have no real purpose in the real world because they are only used to interact with the VE. Hence, to fulfill our definition of *Type 2* CR systems, we focus on objects that have specific semantics in the real world (or VE) and are repurposed for the user's experience.

Research Topic	Type	Category	Count	Publications
Object integration	Integrate into VR	Environment scans	15	[357, 334, 469, 598, 558, 569, 504, 186, 90, 262, 138, 579, 498, 513, 391]
		Haptic real-world objects	13	[561, 454, 36, 75, 379, 420, 141, 86, 192, 182, 344, 289, 133]
		Nearby objects	7	[317, 58, 71, 407, 230, 237, 231]
		Keyboards	6	[529, 253, 159, 324, 441, 60]
		Notifications	6	[587, 152, 557, 426, 211, 370]
		Handheld devices	5	[106, 246, 487, 60, 9]
		Motion	3	[204, 318, 381]
		Food	3	[261, 358, 384]
		Robotic actuators	3	[191, 537, 170]
		Others	6	[277, 138, 310, 403, 149, 102]
	Integrate into AR	Environment scans	5	[368, 578, 292, 171, 240]
		Manipulate real-world obj.	2	[435, 491]
		Passive haptics	1	[202]
		Human body	1	[399]

Table 2.2: Publications representing research that investigates object integration.

A typical example of this category is a VR user who wants to use a physical keyboard within the VR environment (cf. [317, 529]). In this example, the keyboard is not designed for VR but instead is used to operate a computer in the real world. A counter-example are VR haptic props (cf. [22]). In all papers investigating object integration, real-world entities are integrated into either VR (67) or AR (9). An overview of all these papers and their categorization is shown in Table 2.2.

The integrated real-world objects include mostly physical objects from the real world or parts of the user's environment to create more realistic haptic sensations in VR. The approaches range from integrating specific real-world objects [561, 75] to annexing any kind of object automatically [454, 202] or with the help of another user [289]. A side effect of including physical objects is that users are more aware of their presence and are less likely to bump into them. Besides physical objects, previous work investigated the influence of other more abstract objects such as motion or notifications. Integrating real-world motion empowers users to experience VR in moving vehicles without getting motion sickness [204, 318, 381]. In addition, studies have shown that enjoyment and immersion significantly increase with included motion [204]. Finally, various studies have investigated how to integrate notifications without negatively affecting immersion [587, 152, 557, 426, 211, 370]. This can be

Research topic	Type	Category	Count	Publications
Collision avoidance	User manipulation	Redirected walking	11	[70, 311, 568, 30, 502, 390, 111, 330, 110, 39, 35]
		Resetting user position	1	[544]
	Collision Warning	Visual-based information	7	[232, 231, 593, 592, 558, 432, 557]
		Audio-based information	1	[6]
		Multi-modal information	1	[147]
	Experience manipulation	Adapting environment	8	[95, 230, 307, 237, 513, 469, 569, 268]

Table 2.3: Publications representing research that investigates collision avoidance.

accomplished, for example, by seamlessly integrating notifications into the VE as diegetic elements [426].

Collision Avoidance When users are immersed in VEs, obstacles in the real world are no longer visible. In order to solve this problem, various collision avoidance approaches have been explored. While these approaches have mostly investigated VR scenarios, the problem is not exclusive to immersive VEs [232, 231]. Overall, previous work presents three main strategies for avoiding collisions in VR and AR experiences: manipulating the user (12), providing warnings that alert users (9), or manipulating the experience (8). All approaches previously researched and found in our literature review can be seen in Table 2.3.

Unlike warnings, which are designed to gain the user's attention, approaches that manipulate the environment or user often incorporate unnoticeable changes into the experience, empowering users to walk around infinite VEs without being aware of it [568, 30]. These approaches currently have their limitations (e.g., mainly resulting from the induced illusions that only work to a certain degree), making collision warning approaches useful additions to VR scenarios or alternatives for non-VR scenarios (e.g., auditive warnings [6]).

Type 3: Multiple Subjects Experiencing Different Actualities

In total, we found that 103 of the 185 papers (55.68%) investigated *Type 3* CR systems. For these papers, we identified the following research topics (in descending order): collaboration (58), bystander inclusion (33), and isolated experiences (12). In the following, we present these topics.

Research Topic	Type	Category	Count	Publications
Collaboration	Remote	VR headset + AR headset	15	[12, 371, 85, 278, 76, 393, 125, 392, 498, 501, 394, 499, 240, 181, 576]
		AR headset + 2D display	5	[235, 397, 143, 84, 566]
		VR headset + 2D display	4	[495, 332, 565, 98]
		VR headset + AR handheld	3	[139, 305, 132]
		VR headset + telepresence robot	2	[102, 201]
		Transitional interfaces	2	[248, 503]
		Others	7	[68, 471, 472, 377, 391, 136, 191]
	Co-located	VR headset + 2D tabletop	3	[219, 483, 300]
		Transitional interfaces	3	[157, 289, 446]
		AR headset + projection	3	[533, 224, 187]
		VR headset + AR handheld	2	[74, 139]
		VR headset + projection	2	[422, 166]
		VR headset + 2D display	1	[281]
		Others	6	[330, 44, 346, 429, 360, 579]

Table 2.4: Publications representing research that investigates collaboration between users.

Collaboration The most frequently researched topic of *Type 3* CR systems is collaboration, with a total of 58 publications. Here, the collaboration between users experiencing the same manifestation on the Reality-Virtuality Continuum was not included in our literature review (as it does not fulfill the definition of *Type 3*). Thus, we only included publications involving two or more manifestations on the continuum, so-called asymmetric collaboration [483, 136]. We identified two types of asymmetric collaboration: remote (38) and co-located collaboration (20). In Table 2.4, all of these publications are listed in their respective categories.

Compared to co-located collaboration, remote collaboration is the more extensively researched topic, with a share of over 65.52%. Different remote collaboration approaches have been investigated, with collaboration between VR and AR headset users being the most frequent (39.47%). The reason for this is that expert-novice scenarios are explored frequently, with the expert in VR and the novice on-site in AR. Other approaches typically involve a headset in combination with another form factor. Here, the most frequently used form factor is a traditional 2D display involved in 23.68% of the remote collaboration approaches. Besides users experiencing concrete manifestations, transitional interfaces have been explored for collaboration as well. They allow users to switch between augmented and virtual views of one collaborator's space [248] or to use the transition to switch between the spaces of both collaborators [503]. Moreover, others have investigated various combinations that involve tabletops [471, 377, 472], handhelds [305, 139, 472, 132], or projections [377, 136] to enable remote collaboration.

For co-located collaboration, the most frequent combination of form factors is a VR headset combined with a tabletop device [219, 483, 300]. However, compared to remote collaboration, utilizing users that experience different actualities has been explored less frequently, with only 20 publications (34.48%). Furthermore, besides the combination of VR headset and tabletop, only a VR headset combined with an AR handheld [74, 139] and an AR headset combined with projections [533, 224] have been investigated more than once thus far. Other combinations appear only once in previous work. Some of these papers explore highly unique concepts that are difficult to group with other publications, such as work from Baudisch et al. [44]. Here, the authors investigate multiple users collaborating in the same real-world space; however, they play with a virtual ball that can only occasionally be perceived. We believe this work is relevant because, while the collaborators experience the same manifestation, the scenario still integrates an object that has a different manifestation. Especially interesting here is that the object exists in virtuality but not reality.

Bystander Inclusion In many publications, researchers investigated a range of approaches to include bystanders in the MR experience (oftentimes of an HMD-user). Unlike collaboration scenarios, a bystander is a real-world person who does not participate in all aspects of the experience but rather interacts with the user as needed. Overall, we identified 33 of 103 *Type 3* CR system publications as relevant (32.04%) to this research topic. These publications can be classified into three different approaches: bystanders contribute to the user's experience without a channel back to themselves – unidirectional (13), the user interacts with a bystander – bidirectional (12), or the user shares their experience with a bystander who does not interact with it – unidirectional (8). In Table 2.5, all publications researching bystander inclusion are listed with their respective categories.

For interaction between bystanders and users, all approaches describe the interaction between a head-mounted VR user and their bystanders, with two approaches being most frequent: adding a display on the VR headset that faces bystanders [168, 82, 169] or using projection and tracking on the bystander's side [123, 167, 166, 582]. When sharing an experience with bystanders in two cases, an augmented environment is shared [187, 564]. A VR user often

Research Topic	Type	Category	Count	Publications
Bystander inclusion	Bystander in MR	Awareness of bystander	9	[355, 301, 58, 192, 396, 317, 546, 485, 571]
		Bystander as support	4	[91, 87, 136, 483]
	Interacting with bystander	VR and projection	4	[123, 167, 166, 582]
		VR and HMD display	3	[168, 82, 169]
		VR and no technology	3	[596, 17, 300]
		VR and 2D display	2	[281, 75]
	Sharing with bystander	VR via HMD display	3	[398, 302, 532]
		AR via projection or handheld	3	[187, 564, 224]
		VR via CAVE	2	[221, 222]

Table 2.5: Publications representing research that investigates bystander inclusion.

Research Topic	Type	Category	Count	Publications
Isolated experience	Users in same space	VR + VR	8	[39, 35, 432, 268, 308, 111, 110]
		VR + Reality	3	[485, 571, 546]
	Away from reality	VR + Reality	1	[425]

Table 2.6: Publications representing research that investigates isolated experiences.

shares their experience using a CAVE [221, 222] or headset display facing bystanders [398, 302]. For scenarios in which bystanders are involved in the VR experience, it is always a VR user for whom the bystanders create haptic sensations [91, 87] or to whom bystanders are shown [355, 301].

Isolated Experiences Isolated experiences aim to separate two users on the Virtuality-Reality continuum as far as possible from each other. In total, we found 12 publications investigating one of two different scenarios: users share the same physical space while at least one is immersed in a specific manifestation of the continuum, for example, VR (11), or users are immersed into a manifestation to escape reality (1). All scenarios are listed in Table 2.6. In most cases, VR users share the same space and need to be redirected to avoid collisions between them. This is similar to collision avoidance, except that here two users are involved. For user isolation, an interesting idea has been presented by Ruvimova et al. [425]. They suggest using VR as a solution to evade a crowded office space.

Type	Involved entities	Entities Repel Each Other	Entities Attract Each Other
Type 2	Subject + Object	Collision avoidance	Object integration
Type 3	Subject + Subject	Isolated experience	Bystander inclusion/Collaboration

Table 2.7: Overview of all research topics involving multiple entities (subjects / objects) and their relationship on the Reality-Virtuality Continuum – covering both *Type 2* and *Type 3* CR systems.

Summary

When reflecting on all investigated 185 publications, we identified that different entities are involved in the explored research topics. To describe these entities, we employed a classification into two groups: subjects and objects. Subjects can be users or bystanders that perceive their environment and can have different manifestations. Their very own perspective on the scenario depends on these manifestations (e.g., AR or VR), and therefore, forms their actuality – that what is *"currently happening"* for them. This can be individual for each subject. In contrast, objects can be various things, such as real-world objects, information (e.g., notifications), or even motion. Essential for the classification as an object is that they do not have a perception of the environment. In the investigated publications, we found all three types of CR systems, however, with different frequencies. It is worth mentioning that a CR system does not have to be limited to one specific type but can be classified as multiple types at the same time (e.g., *ARchitect* [289], in which users can transition between AR and VR (*Type 1*), repurpose physical real-world objects for the VR experience (*Type 2*), and experience different actualities at the same time (*Type 3*)). In sum, we found 52 publications (28.11%) that investigated *Type 1* systems which involve subjects transitioning on the continuum and thereby experiencing different actualities. For *Type 2* and *Type 3*, we found 105 (56.76%) and 103 (55.68%) publications respectively. Both types involve multiple entities, with *Type 2* systems including at least one subject and one object, while *Type 3* systems involve more two or more subjects.

Furthermore, during our analysis, we observed that there are similarities between *Type 2* and *Type 3* CR systems. For both types, there are research topics that aim to increase the distance between the entities on the Reality-Virtuality continuum, while there are other research topics that investigate how to decrease the distance between different entities on the continuum (see Table 2.7). For the research topics collision avoidance and isolated experiences, the entities should repel each other, meaning that the interaction between the entities is decreasing, while in the topics object integration, bystander inclusion, and collaboration, the entities should attract each other on the continuum, and thereby, increasing their interaction. Interestingly, we observed that the majority of publications investigate aspects of entities attracting each other 143 of 185 (77.30%), while the minority looks at increasing the distance between entities 31 of 185 (16.76%) – entities that repel each other. Please note that we counted each publication here once; thus, adding up the numbers from the different research topics results in higher numbers as publications can exist within multiple topics. Furthermore, the publications that only belong to the topic of transitional interfaces are excluded here.

Combinations of Environments in Cross-Reality Systems

Experiences on the Reality-Virtuality Continuum involve different environments. Per definition, these include at least one real environment and one VE between which the continuum spans. They are entangled with each other, or otherwise, there would not be any influence from one into the other environment. The most simple example is a VR user who experiences some form of virtual world but still stands on the real, physical floor. Nevertheless, in a minority of publications, more than two environments are involved (e.g., two VR users in the same physical space that experience different VEs [35]). Overall, we found three different environment constellations: scenarios involving one reality and one virtuality (136), scenarios involving multiple real-world environments and one virtuality (40), and scenarios involving multiple virtualities and one real-world environment (9).

Multiple Real-World Environments Scenarios of this category involve at least two real-world locations (i.e., different geographical areas) between which physical entities do not move; for example, an expert user joining a novice user from a different real-world location [12]. Overall, we identified 40 publications as relevant for this category (21.6%). While reviewing publications involving multiple real-world environments, we found that they mainly address remote collaboration (35), followed by object integration (8), and one bystander inclusion [136] as the underlying research topics. Object integration investigated various approaches, including the integration of information from the real world, such as notifications or messages (4) [310, 211, 426, 587], or a video feed (1) [384] from another real-world environment.

Multiple Virtual Environments We found 9 publications involving multiple VEs (4.9%). The main research scenario in 8 of these publications involved multiple VR users who share the same physical space but not the same virtual experience [396, 39, 35, 432, 268, 308, 111, 110]. In this case, every user has a distinct actuality that differs from the actualities of the other users. Corresponding publications also focus on avoiding collisions between co-located VR users and assume that these users want to engage solely in their individual experiences. On the contrary, Wang et al. [532] recently proposed a transitional interface that allows a user to view other co-located VR players' experiences. Finally, the number of VEs can also be higher than two, for example, if more users are involved and need to share the same physical space [111].

Summary We identified the different environment constellations presented in the screened publications. The majority of 73.5% of the publications investigated scenarios with one real and one VE. When multiple environments are involved, these are often physical locations located apart from each other and are digitally connected mainly for collaboration. We also identified publications that aimed for isolated experiences of users with different virtual experiences. Here, these users were located in the same physical space. Hence, the research aimed to provide isolated experiences and closely related because of an inevitable interaction or influence, avoiding collisions. When multiple VEs were deployed, we found that most approaches aimed for providing users with isolated experiences that reduced the interaction with co-located users. Along with that, collision avoidance was investigated to reduce the number of encounters with other persons to preserve isolation. Eventually, we did not find any systems that use multiple real-world and multiple VEs.

2.3.3 Analyzing Changing Actualities in Cross-Reality Systems

When using a *Type 1* CR system, the actuality of a user changes over time due to transitions along the Reality-Virtuality continuum. However, numerous systems in the literature are not introduced as CR systems, nor are transitions highlighted in particular because the presented research did not investigate the CR aspects in itself but, for example, topics like user perception [420] or collision avoidance [6]. Therefore, we conducted an in-depth analysis of our literature corpus to find *Type 1* CR systems and corresponding transitions that are not obvious to readers. We identified 52 relevant publications that introduced systems that changed the actualities of their users. Continuing our overview presented in Section 2.3.2, we present our in-depth analysis of these transitions in the following. First, we analyzed the involved manifestations

Transitions			Count	Publications
RW	$\rightarrow (\leftrightarrow)$	VR	3	[514, 480, 468]
AR	$\rightarrow (\leftrightarrow)$	VR	7	[157, 420, 422, 419, 103, 248, 289]
RW	$\rightarrow (\leftrightarrow)$	AV	1	[532]
VR	$\rightarrow (\leftrightarrow)$	AV	26	[317, 106, 58, 186, 485, 71, 546, 167, 166, 330, 370, 571, 504, 592, 557, 231, 9, 90, 141, 558, 407, 441, 147, 277, 292, 6]
RW	$\rightarrow (\leftrightarrow)$	AR	3	[578, 202, 187]
AR	$\rightarrow (\leftrightarrow)$	RW	1	[232]
VR	$\rightarrow (\leftrightarrow)$	RW	2	[261, 249]
Multiple Manifestations			9	[446, 229, 389, 421, 53, 54, 148, 507, 257]

Table 2.8: Transitions of the subjects along the Reality-Virtuality Continuum. Involved Manifestations: Real World (RW), Augmented Reality (AR), Augmented Virtuality (AV), and Virtual Reality (VR).

in the described systems (see Section 2.3.3). Here, we limited ourselves to the distinct manifestation previously introduced: VR, AV, and AR, including transitions involving the Real World (RW). Thereafter, we identify the cause of these transitions (see Section 2.3.3). Finally, we conclude with a summary (see Section 2.3.3).

Transitions between Manifestations

As seen in Table 2.8, subjects transition along the Reality-Virtuality Continuum from and to various manifestations. Here, the perception of the transition is dependent on the perspective of a subject – the actuality (e.g., a VR user experiencing VR or a bystander experiencing reality). For example, a bystander could walk by a VR user and is shown to the VR user in the VE when being close [317]. The bystander's actuality does not change as the bystander still perceives the RW while crossing the area around the VR user. However, the VR user sees the bystander in the VE; therefore, the VR user's actuality changes with a transition from VR to AV. This is because the VE is augmented with objects from the real world and therefore is no longer purely virtual. In this case, with the bystander. In the following, we introduce the different manifestations involved in the transitions that we found in the literature.

Transitions to Virtual Reality In sum, we found 10 (19.23%) publications that involved transitions to VR. We identified 7 (13.46%) publications that investigate transitions from AR to VR. Users could start in AR and then, for example, decide to transition to VR [420, 422], to exchange information between the two manifestations [419], or to collaborate [157]. Further, we identified 3 publications (5.77%) involving a transition from RW to VR. For example, Steinicke et al. introduced an approach for transitioning into VR through a portal metaphor. They provided a portal from the real environment to VR to the user. The user could enter the portal to enter the VE [480]. Also, it could be shown that a smooth transition into VR helps the user to create awareness of the VE [514].

Transitions to Augmented Virtuality We found 27 (51.92%) publications that involved transitions to AV. We found 26 (50%) publications investigating transitions from VR to AV. Bringing in real objects like a cup for drinking, a keyboard for typing [317] or a smartphone [106] when needed depicts a transition from VR to AV. Also, integrating approaching bystanders into the virtual world in order to create awareness or foster interaction results in a transition from pure VR to AV [546] or when actively interacting with them [167]. Further, while in VR, partially showing the RW would result in a transition from VR to AV [186]. Further, transitions from VR to AV can occur in a non-obvious manner and often rely heavily on the visual sense. But, for example, two users that use redirected walking to meet each other for shaking hands while being immersed in VR [330]. As soon as they are redirected towards each other and shake hands, their VR is externally influenced through the handshake, which is part of the real world. In this case, they transition for a brief moment from VR to AV. Additionally, we found 1 (1.92%) that investigated transitions from the RW to AV [532]. Here, a bystander could enter a VR user's experience and thereby augment the virtual experiences with their appearance.

Transitions to Augmented Reality We identified 3 (5.77%) publications that investigate switches from the RW to AR. Editing the real world with AR's help can be seen as a transition from a real environment to AR [578]. Likewise, overlaying virtual objects onto real ones lets a user transition from RW to AR as soon as the overlays are brought into place [202]. Also, sharing content with a bystander can be seen as a transition from the RW to AR [187]. Here, the bystander is the transitioning subject.

Transitions to Real World We found 3 (5.77%) publications that involved a transition to the RW. Here, taking a glimpse at reality while being in VR results in a transition from VR to the real world [261]. This can be useful when immersed VR users want to interact with the surrounding physical

Transition Cause	Count	Publications
Interacting with Physical Objects	15	[317, 71, 261, 504, 106, 441, 9, 186, 578, 292, 407, 141, 507, 103, 202]
Interacting with Virtual Objects/Environments	10	[480, 420, 53, 54, 421, 468, 514, 419, 277, 229]
Collision Avoidance	8	[232, 6, 231, 557, 147, 592, 558, 90]
Bystander Inclusion	8	[167, 546, 187, 58, 370, 485, 166, 571]
Collaboration	6	[248, 389, 289, 422, 157, 330]
Exiting Experience	5	[249, 532, 446, 148, 257]

Table 2.9: Transition causes for transitions of subjects along the Reality-Virtuality Continuum.

environment for a brief moment. To avoid collisions when using AR obstacle detection and accompanying alerts that make users aware of these obstacles form a transition from AR to the RW [232]. When taking off the VR-HMD, and thereby transitioning to the RW, users report that they, for example, felt disoriented [249]. Therefore, gradual exit procedures could help VR users to exit their virtual experience more comfortably and safely.

Transitions to Multiple Manifestations We found 9 (17.31%) publications that focused on interfaces for transitions along the whole continuum from the RW to AR, then further to AV, and finally to VR [446, 229, 389, 421]. In these scenarios, a user transitioned step by step from the real world to the virtual. Each step involved different objects or actions taken by the user.

Summary We investigated 52 publications that introduce transitions on the continuum and identified involved manifestations. We found that most transitions (26) are from VR to AV, followed by transitions from and to multiple manifestations (9). Some transition categories are underrepresented, like transitions from AR to the RW or from the RW directly to AV. Moreover, the presented transitions can be very subtle and non-obvious at first (e.g., users that transition from VR to AV when they meet and shake hands [330]).

Causes of Transitions

Transitions on the Reality-Virtuality Continuum can have different causes. We identified several causes for transitions in our literature corpus (see Table 2.9). In the following, we introduce these causes in greater detail.

Interaction with Physical Objects We found that most transitions occur due to interactions with physical objects. Here, we found 15 (28.85%) publications. Interaction with the real world can cause transitions, for example, from VR to AV [317]. Users transition when they want to drink or eat something while experiencing VR [71, 261]. Further, we found the usage of an external device causes transitions [106]. A user could check a smartphone for messages [9]. This could be accomplished by capturing the smartphone in the RW by video. The smartphone can then be cropped out of the video feed and presented to the VR user. This augments the VR experience, making it AV. Similarly, when using a physical object such as a keyboard in VR constitutes a cause for a transition [441]. Here, the VR user is transitioning from VR to AV when using the keyboard.

Interacting Virtual Objects/Environments We identified 10 (19.23%) publications that introduce transitions on the continuum that are deliberately caused by the user to access virtual objects or to enter a VE. That can enhance, for example, presence [480]. Traversing on the continuum can be accomplished by different user actions [421]. These actions initiate a transition from one form of reality to another. Metaphors like a book can be used to give the user a token to access the different manifestations [53, 54]. When entering a VE causes a transition, designing the transition from the RW to VR in a gradual manner fosters, for example, presence [229]. This can be accomplished by gradually blending out real-world objects while blending in the VE.

Collision Avoidance We found 8 (15.39%) publications in which the avoidance of obstacles causes transitions of users. Providing such safety features can cause transitions of entities along the continuum, like creating awareness of obstacles in the VR user's proximity [231, 557]. Other modalities than the visual were also investigated, e.g., auditive feedback, which lets the user transition out of VR to AV as the VE is augmented with the auditive warning of real wold objects [6]. Another way to avoid collisions and at the same time enhance VR experiences can be accomplished by constantly scanning the real-world environment and adapting the virtual world accordingly to let the user walk in an automatically generated world [90]. Here, the user transitions from VR when not adapted to AV when the virtual world is adapted to the surrounding physical environment.

Bystander Inclusion Including bystanders can also be a cause for transition. We identified 8 (15.39%) publications that investigate transitions caused by bystanders. For example, a transition from the real world to AV can be caused if the bystander enters the tracking space of a VR user [546]. Here, the bystander is integrated visually into the VE. A bystander could also cause a transition from the real world to AR when projections are used to give access to the virtual content that a AR user experiences [187]. Breaking the VR isolation can be done by enabling bystanders to interact with the VR user [167, 166]. Here, the bystander can actively participate in the VR user's activity and influence the VE. In this scenario, the VR users transition from VR to AV when interacting physically with the bystander. From the perspective of the bystanders, they can see floor projections in the RW and can use a display to enter the virtual experience, which also can be seen as a transition from the RW to VR.

Collaboration We found 6 (11.54%) publications in which the cause for a transition was the collaboration among users. Often, collaborators transitions from AR to VR when creating a collaborative solution [248, 422, 157]. For instance, they shape a maze in AR and then use the created maze to play a game in VR [289].

Exiting Experiences We found 5 (9.62%) publications that let users exit experiences. Users may exit, for example, VR which causes a transition from VR to the real world. Here, Knibbe et al. investigated which factors influence transitions out of virtual experiences. The results pointed out that the virtual experiences influence the users beyond the point of exit and therefore need further consideration. To exit virtual experiences, metaphors like portals [532] or curtains [257] can be used to indicate the possibility of a transition between VR and the RW.

Summary We investigated 52 publications that introduce transitions on the continuum and identified their corresponding transition causes. We found that most transitions (15) happened when physical objects were included in virtual experiences. For example, a smartphone can be integrated into the virtual experience making the user transition from VR to AV. This is followed by 10 publications that introduced transitions that occurred when there was the need to access virtual objects or when entering VEs from, for example, the RW. The third most cause of transitions was collision avoidance and the inclusion of bystanders into the virtual experience with 8 publications, respectively. Here, users were made aware of physical obstacles by augmenting the virtual experience (e.g., through auditory feedback), and bystanders were brought into the virtual experience of, for example, a VR user to create awareness of their presence and thereby, making the VR experience a AV experience.

2.3.4 Nine Golden Rules of Cross-Reality Systems

Following our previous section that investigated and described current research on CR systems, we continue with the introduction of nine golden rules for designing and implementing such systems, which we derived from our analysis. We categorized the golden rules according to the three different CR system types introduced in Section 2.2.2.

Type 1: Subjects Transitioning on the Continuum

Rule 1: Allow for Smooth Transitions When Changing the User's Actuality Allowing users to slowly and gradually transition into a target manifestation can benefit their understanding of what is going on. For example, slowly transitioning into VR allows users to keep an awareness of their physical environment [514], improve the sense of body ownership [229], and increase presence [480] while slowly transitioning out of VR can mitigate disorientation [249]. A slow and gradual transition can, for example, be implemented by morphing real objects into virtual objects one after another in the target environment [514].

Rule 2: Use Suitable Metaphors to Make Transitions Intelligible and Believable A possibility to transition should be indicated by a metaphor to help users understand possible actuality changes (e.g., portals [148, 532]). This helps to peek into other manifestations and increases presence [480] and immersion. Also, tokens that allow for a transition can be employed as such metaphors (e.g., books [53, 54] or smartphones [148]). It is important that the employed metaphor communicates its affordance to users.

Rule 3: Give Users Control Over Transitions Transitions are a powerful technique of cross-reality systems as they enable users to change their actuality. However, they can result in severe issues for users if they are deployed wrong (e.g., a system that automatically transitions from AR to VR while the user navigates traffic would put its' users at risk). Following the golden rule "support internal locus of control" from Shneiderman et al. [452], designers and developers should consider three primary aspects to give users control over transitions: 1) users can initiate the transition (e.g., by following a metaphor [53, 54, 148, 532]), 2) users can control the transition (e.g., speed of transition adjusted by the user [514]), and 3) if multiple manifestations can be visited, the user should have the power to identify and choose the target manifestation (e.g., [421, 53, 54, 468]). If automatic transitions are deployed, ensure that users understand what triggers the transitions.

Type 2: Subjects Interacting with Objects Repurposed for the Subject's Actuality

Rule 4: Consider Surrounding Physical Objects to Avoid Collisions Every object physically existing in the user's environment should be considered in the experience to avoid collisions [231, 307, 569, 90]. Here, one can either bring over the physical object to the user's current actuality to raise awareness, for example, by substituting physical objects with feasible digital representations [454, 513] or one can use solutions that redirect users around the physical obstacles [30, 95, 502]. If immersion is not of high importance, designers and developers can also deploy warnings using various modalities to help users avoid collisions (e.g., visual, auditory, or multimodal alerts [6, 232, 147]).

Rule 5: Integrate Relevant Physical Objects to Enrich Experiences Every object that is relevant to the user should be integrated into the user's experience [317]. For example, one can enable users to enjoy a drink or use a keyboard without taking off the VR headset [529, 317, 71, 253, 246]. Here, it is relevant to reduce the mismatch between the real and virtual world by finding a suitable virtual representation of physical objects (e.g., not showing the correct amount of liquid in a glass can result in problems [71]). Furthermore, we consider relevant objects to be more than physical bodies. Objects are also abstract information like notifications [426] or physical phenomena like motion [170]. These objects surround us and thus, influence our perception in various ways. For example, if we experience VR inside a car as a passenger, we need to take the motion into account that is caused by the car driving [318, 204]. Similarly, for VR experienced on board of an airplane [545]. If physical phenomena are neglected, it can degrade the experience of users.

Rule 6: Provide Opportunities to Interact With Object in Every Possible Actuality When objects are present in the experience of users, there should be an interaction possibility for these objects. Furthermore, if the user's actuality changes throughout the experience, it is valuable to provide interaction possibilities with objects throughout all these actuality changes [53, 54, 421]. These interaction possibilities cannot necessarily remain the same across the changed actuality and therefore requires designers/developers to adapt them (e.g., a book that enables transitions changes its appearance in different manifestations [53, 54]).

Type 3: Multiple Subjects Experiencing Different Actualities

Rule 7: Allowing for Isolated Experiences If surrounding users should be excluded from the experience (e.g., for an isolated experience), one can utilize the different methods provided by collision avoidance research [396] and adapt them while keeping in mind that other users move and are not static. Overall three different approaches exist: manipulate the experience [425, 502, 268], manipulate the user [432], and give collision warnings [231, 147].

Rule 8: Include Bystanders in Closed Experiences Experiencing a manifestation of MR in a head-mounted device excludes bystanders from the experience [24, 168]. Hence, a cross-reality system should be capable of including bystanders in the HMD user's experience. Depending on the goal, cross-reality system can bridge the actualities of HMD user and bystander by either providing a representation of the bystander in the MR experience [355, 301, 58, 192, 396, 317, 546, 485, 571] or by sharing the MR experience with bystanders [187, 564, 224]. Here, allowing bidirectional communication is possible as well and offers the foundation for collaboration [168, 82, 169, 596, 17, 300].

Rule 9: Enable Collaborators to Understand Each Other's Actualities As cross-reality systems enable users with different actualities to collaborate, it is beneficial to communicate these actualities, helping collaborators to understand the individual perspectives involved. Designers and developers of cross-reality systems have three ways to apply this rule: 1) they can allow collaborators to switch into each other's perspectives [289], 2) they can allow collaborators to glimpse at each other's perspectives (e.g., in the form of portals [532]), or they can integrate the elements of each other's perspectives in their own actuality [565, 503, 85].

2.3.5 Research Challenges and Opportunities

Based on our literature review, it is evident that there has been an uptick in research around CR systems (see Figure 2.5). In recent years, we can see a strongly increasing interest in this topic, with a larger number of manifestations involved and a trend towards more dynamic actualities that frequently change over time. Our literature review revealed that it is difficult to identify relevant research, especially *Type 1* CR systems as occurring transitions on the continuum are often not in the focus of the work, and thus, are not prominently described (see Section 2.3.5). Further, we found that CR systems can become rather complex due to the different perspectives involved (see Section 2.3.5). Moreover, we identified that current CR systems partially neglect AR devices (see Section 2.3.5) and a trend towards AV solutions becomes visible (see Section 2.3.5). To address the increasing complexity of CR systems, we conclude this section by discussing novel prototyping methods of CR systems as an opportunity to make the field more inclusive and allow for quicker iterations (see Section 2.3.5).

Implicit Transitions

Many of the surveyed papers contain transitions on the continuum, meaning they change users' actuality over time. However, the presented evaluations did not or only vaguely investigate the transition, in particular, cf. [302, 147]. Often, authors do not explicitly describe the transition that takes place on the continuum, for example, when the underlying research instead focuses on haptic feedback through the inclusion of real-world objects [253, 454]. Nevertheless, these transitions can be manifold, as they potentially involve multiple actualities and can affect various subjects that interact with the CR system. We refer to these transitions as implicit transitions since they are a byproduct of the proposed system and not in the focus of the introduced research. As these implicit transitions between actualities are complex, we found that they are difficult to grasp and hard to articulate. But, due to their strong impact, they should be considered. Here, we found that common ground to describe these transitions has not yet been established. As a result, it is tough to extract the transitions' essence, making an evaluation and comparison non-trivial. To make implicit transitions comprehensible and comparable, we recommend investigating visualization methods that enable one to convey the transitions taking place within a CR system. Finally, CR systems often do not investigate the transitions of their proposed systems. For example, research evaluating different approaches to display a physical keyboard in VR assumes the keyboard is always present [253, 441]. Hence, they neglect the transition necessary to initially introduce the physical keyboard to VR users.

Multiple Actualities

We identified several research topics that involve multiple users and bystanders (see Section 2.3.2), which we refer to as *Type 3* CR systems. Here, both users and bystanders have different actualities and can transition along the continuum. Thereby, they can change their actuality, resulting in more complex interactions. For example, Willich et al. introduced a CR system in which from the VR user's perspective, a bystander enters VR and thereby, transitions closer to the VR user; however, from the bystander's perspective, there is no transition into VR, meaning the bystander still experiences the real world [546]. Thus, all perspectives need to be taken into account as they contribute to an all-encompassing understanding of the scenario. However, it remains challenging to grasp and convey users' and bystanders' perspectives and actualities to an audience that has not experienced the system itself. Again, we recommend investigating visualization methods; nevertheless, we emphasize that such visualizations need to consider the different actualities of the users involved in *Type 3* CR systems.

Missing Research on Augmented Reality

We revealed that current research investigations mainly focus on CR systems that shape around VR users. We found only a smaller number of systems that proposed CR experiences with AR users. We believe that the tendency of immersive VR to blend out the visual information from the real world while auditory or haptic sensations remain perceivable inherently offers more conflict potential, which previous work has aimed to address. Nonetheless, previous work has demonstrated that AR suffers from similar problems – just to a smaller degree [232, 231] Still, neglecting these problems can cause serve problems, especially when CR systems are operated in more dangerous environments (e.g., while navigating traffic [228]). Hence, more investigations into head-mounted AR systems are needed, especially as these systems already provide the possibility to communicate more easily with bystanders, but the digital content is hidden, similar to VR systems. However, especially for CR systems that allow users to transition on the continuum, more hardware is required as only very few devices allow transitioning between AR and VR. Currently, these devices are also limited to video see-through AR.

Trend Toward Augmented Virtuality

Current VR systems aim for immersive experiences; however, the physical environment of VR users continues to have an impact [307]. For example, VR users need to be careful not to bump into bystanders or furniture [317]. Thus, in recent years, research has shifted towards CR systems that include parts of the VR user's environment on demand, meaning they temporally or permanently transition users towards AV. In this work, we define such systems as *Type 2* CR systems (or *Type 3* if they include other users). Commercial products have followed this trend, for example, *Oculus* with the release of their Pass-through API[10]. Thereby, researchers have acknowledged the shortcomings of current VR systems and started embracing the opportunities CR systems do offer. In the future, more research is needed to systematically investigate which aspects of users' real environments need to be introduced to VR experiences and, more importantly, when and how users transition to AV with the goal to incorporate real-world aspects in their experiences.

Prototyping Cross-Reality Systems

Prototyping and developing CR systems can be a time-intensive process that requires software and hardware prototyping expertise. Especially, the creation of CR hardware prototypes (e.g., [317, 167, 90, 168]) has a high entry barrier and requires the use of various hardware components (e.g., displays, projectors, sensors), engineering skills (e.g., electrical engineering, software development), and design expertise (e.g., rapid prototyping). Enabling fast and low-effort prototyping of CR systems could support researchers, developers, and designers of CR systems to quickly iterate their ideas and designs without the need to fully implement the entire system in both software and hardware. We argue that more novel prototyping methods are required that help to develop CR systems. Therefore, we published *VRception* (see Chapter 5) a prototyping concept and toolkit that allows for rapid creation of CR systems entirely in VR [162]. With this system, multiple users can remotely join one VE. In this environment, they can use various pre-defined virtual components to build CR systems and prototype their functionality in VR. A useful addition to this would be a modular hardware system that allows users to create CR systems with less effort and without the need for extensive software and hardware experience. Such a system could include modular hardware components that can be easily integrated with each other (e.g., small projectors, displays, cameras) and software components that allow for easy integration into VEs.

2.3.6 Conclusion

Due to the increasing interest in CR systems, we conducted a scoping literature review, surveying existing publications that propose such systems. Here, we first conducted an in-depth literature review by surveying more than 6500

[10] Passthrough API, `https://developer.oculus.com/documentation/unity/unity-passthrough`, last retrieved on August 12, 2022

papers as an initial pool of papers in this domain, ranging from the year 2015 to 2020. By following their referenced papers and papers that cited them, we surveyed an additional 23,000 papers. In sum, we identified 185 papers that describe implementations of CR systems (e.g., [317, 421, 229]). These served as a corpus for classifying their research topics and identifying shared properties. While we see a growing interest in CR systems, we could not identify common terminology or a common language. However, to describe CR systems and the aforementioned interplay among different actualities, such a language should be established. Hence, in our work, we contribute a classification of CR systems into three different types: *Type 1:* Subjects transitioning on the continuum experiencing a changing actuality. *Type 2:* Subjects interacting with objects that are repurposed for the subject's actuality. *Type 3:* Multiple subjects experiencing different actualities. Furthermore, we contribute to a better understanding of these systems by identifying shared properties and providing nine golden rules that should be followed when implementing these systems. Finally, we conclude our work with research challenges and opportunities that can benefit the field of CR systems. Here, we address current shortcomings and propose future research perspectives, including visualization and prototyping methods for CR systems.

2.4 Visualizing Cross-Reality Interaction

As a result of the increasing complexity, it becomes hard for researchers to describe CR systems precisely or to communicate the interactions and transitions between actualities that take place. A helpful concept to describe and understand CR systems is the Reality-Virtuality Continuum introduced by Milgram and Kishino (see Section 2.2.2). However, while this continuum can clarify one particular experience for a user at a defined point in time, it remains challenging to depict transitions between different actualities over time (see Section 2.3.3). For example, a user transitioning from reality into a VR experience [468]). Therefore, we added a time dimension to the Reality-Virtuality Continuum. This allows one to visualize how entities transition between different actualities along the continuum. We argue that visualizing transitions along the continuum over time offers several benefits, including structuring and communicating novel CR prototypes and visualizing CR experiences. We named the resulting continuum the *"Actuality-Time Continuum."*

Our goal is to synthesize a way for the community to describe CR systems and experiences. Therefore, we first argue for the term *"actualities"* (see Section

2.2.2) to depict one specific experience along the continuum from Milgram. Next, we describe ways to advance the continuum to visualize transitions over time. Fundamentally, we suggest adding a time dimension to the original continuum. This can help one to understand how users' perceived realities change over time. However, we do not limit ourselves to this; we suggest including multiple users in the continuum to describe mutual influences among them.

We implemented our extension of the Reality-Virtuality continuum as a web-based visualization application. To prove its effectiveness, we invited 16 VR/AR experts to apply the Actuality-Time Continuum to a set of scenarios. Through their feedback, we found that the Actuality-Time continuum can help to structure thoughts during the development process of CR systems, helps to communicate and discuss ideas with others, and fosters an understanding of the interplay among users. Further, experts stated that the Actuality-Time Continuum could be used to distill regions on the Reality-Virtuality continuum, such as areas that define AR or AV. Such areas could foster the comparability of CR systems. We used the experts' feedback to optimize our extension and outline future use and improvement possibilities (e.g., visualize the interplay of multiple VEs and visualize different modalities (especially beyond the visual) separately from each other).

2.4.1 Actuality-Time Continuum Visualization

The Reality-Virtuality continuum helps one to classify not only the actuality of a single user but also multiple interacting users. For example, a single user is completely in VR. This user would be somewhere on the right-hand side of the continuum. When two users collaborate in AR and VR [85], we would add the AR user somewhere on the left-hand side of the continuum. A bystander just watching the AR and VR user remains in the real world. The bystander would be shown on the far left of the continuum. However, the current research and technology trend leads to investigating possibilities to change the actuality and thereby transitioning on the Reality-Virtuality continuum on the fly. For instance, when the world around the user influences the experience, there is a short period during which, the user's actuality can no longer be described as a single position on the Reality-Virtuality continuum. An example of such a scenario would be a bystander interacting with a VR user, causing the real world to fuse with the virtual world (e.g., collision prevention [396, 557, 30]).

To empower researchers and designers to quantify their scenarios fully, we set out to establish a new concept for visualizing how people switch between actualities throughout an interaction. Thus, in the following, we present an extended continuum in which we argue that it is necessary to add a time dimension to quantify what a user might experience throughout an interaction. We then use this concept to implement a tool that allows others to generate their scenarios' visualizations easily. We envision that this will help to better develop scenarios, to foster discussion of possible alternative options, to share ideas with others, and to create novel experiences.

Concept

In the following, we introduce three questions that guided our concept, discuss their implications, and introduce our approach to tackle accompanying research challenges.

How can one manage the complexity of scenarios involving multiple actualities? The key for researchers, designers, and developers is to manage the complexity of their Reality-Virtuality scenarios to understand the impacts on the user. Therefore, an abstraction that fits various scenarios and their dynamic behavior is needed. This abstraction must take into account involved entities, objects, and environments. In particular, the perspectives of users or bystanders might differ enormously while experiencing different realities and involving different actualities [167]. The perceived influences on a user can even come from more than one form of reality, inevitably leading to increased complexity. This makes it difficult to comprehend individual experiences and their impacts on the perceiving person (e.g. communication between VR and the real world [82, 168, 169, 152, 426]). Further, depicting dynamic changes within these scenarios is vital to managing complexity and understanding the interplay between users, objects, and the environment.

We envision that a visualization tool would help people to better understand the complex nature of these scenarios, especially those that involve multiple users, objects, and actuality changes over time. Further, this will help designers and developers identify effects and relationships that arise from design decisions, technology, their users, and involved context.

How can one compare and articulate research or experiences involving multiple actualities? Comparing novel experiences to previously introduced research from the literature can be cumbersome due to complexity or a difference in the underlying hypotheses or RQs. Furthermore, relevant aspects can often be hidden inside the research prototypes. Transitions along the continuum over time add yet another layer of complexity. To approach these issues, we suggest visualizing experiences along the Reality-Virtuality Continuum to gain insight into involved users' experiences, where they manifest on the continuum, and how transitions can occur (i.e., when and how transitions affect the user's experience). This can help researchers to better understand the influences on the user and to articulate new ideas to others in order to obtain feedback on future design decisions that incorporate some form of interplay among multiple actualities.

How can the Reality-Virtuality Continuum be utilized to analyze scenarios involving multiple actualities? Currently, it is not entirely clear where on the continuum specific research projects of systems are located. For example, two VR systems could be classified close to the VR side of the continuum. It remains unclear to what extent, for example, the enrichment of a VR experience through a real-world object shifts it on the continuum towards AV. Quantifying ranges on the continuum might help with comparing and classifying future experiences, systems, or research prototypes, making them more comparable and easier to understand. Knowing how far a transition on the continuum goes might help in understanding its impact on transitioning users and their experiences and perceptions.

Components of the Visualization

The concept's general structure consists of three elements: the actuality someone experiences (e.g., reality, AR, or VR), the time, and the entities (e.g., users, objects, or environments). Here, the actuality is represented on the x-axis and the time on the y-axis. As a result, we obtain the *Actuality-Time Continuum*. Here, two or more entities on the *Actuality-Time Continuum* stand in a specific relationship to each other. This then allows one to represent various interactions between entities on the continuum over time. Now, we can visualize the interplay of entities experiencing different actualities or switches between them (see Figure 2.6).

Actualities on the Continuum To describe the actuality that an entity experiences or in which actuality certain objects are present, we use the Reality-Virtuality Continuum. We placed this continuum on the x-axis to depict the actuality of entities. The actuality of entities that are positioned furthest on the left is reality, whereas the actuality of entities furthest on the right is the purely virtual world.

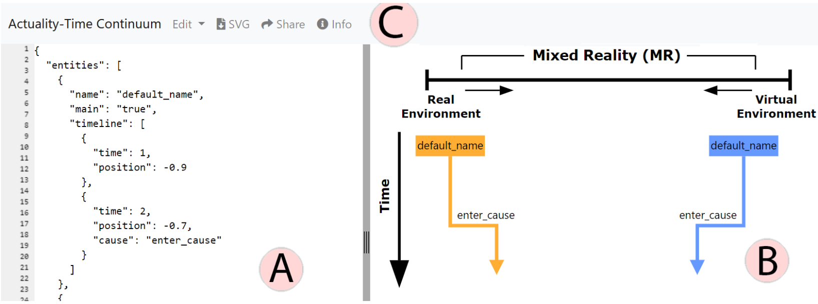


Figure 2.6: A screenshot of the Actuality-Time Continuum visualization tool. On the left side, (A) the tool shows the JSON structure with all necessary information of present entities, such as time position and position on the continuum, to generate the visualization. On the right side, (B) the tool shows a live visualization of the input from (A). On the top, (C) the tool offers various quick functions in a menu.

Time Exploring previous literature, we realized that the use of the Reality-Virtuality Continuum poses challenges when expressing the mix of elements from Reality and Virtuality over time. Therefore, we added a y-axis to our visualization that runs from top to bottom, representing time. Here, we took great inspiration from sequence diagrams that are part of the Unified Modeling Language (UML) [424]. We did not specify a definitive time measurement unit for this axis to avoid restrictions regarding specific scenarios. Hence, the time was specified in steps rather than hours, minutes, or seconds. This provides more flexibility and the ability to visualize various scenarios with the Actuality-Time Continuum. This allows us to change the actuality dynamically by moving along the continuum at different times.

Entities We have identified two types of entities that can temporarily influence the experience: *Subjects* and *Objects* (see Section 2.2.2). Subjects can be users or bystanders. Bystanders can engage with the user, but their presence alone can already impact the perceived actuality. Objects can impact or enrich the interaction or may be important for the user's safety (e.g., visualizing walls around the user). Both physical and digital objects can be presented in VR to further foster a feeling of a connection to the real world (e.g., displaying notifications for emails). All are ephemeral in nature; thus, they only impact the actuality for a short period. However, they are essential for allowing interaction with the world around the user.

Implementation of the Visualization Tool

With the general idea of the visualization concept, we set out to implement it in a software tool. This allowed us to evaluate the concept and others to access it. We opted to write the first version as a web app for easy deployment and use, using only HTML5, JavaScript, and CSS. See Figure 2.6 for a screenshot of the current version of the tool.

The tool itself provides an editing area on the left side (see Figure 2.6A) in which the structure, entries, and transitions can be defined using a simple JSON structure. Quick edit and reset buttons are in the top menu (see Figure 2.6C) to provide immediate access to common functionalities, such as adding a new entity. The structure is then rendered on the client-side, which allows for a real-time update of the visualization on the right side (see Figure 2.6B) and makes it easy to iterate through different designs. Finally, the tool allows one to share or save the visualization as a render or JSON for later use.

The *Actuality-Time Continuum* visualization source code is available under MIT license on GitHub[11]. This allows users to host on their own servers and enables the community to use the tool more effectively. An interactive version of the tool can be found online[12].

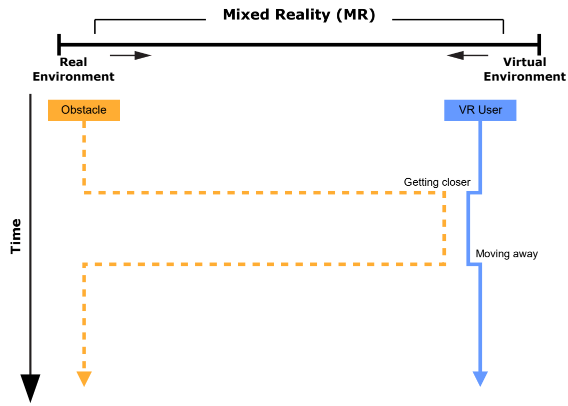
Example Scenarios

To illustrate our abstract visualization concept, we highlight four different example scenarios (see Figure 2.7 and Figure 2.8). The first two are single-user scenarios in which the main influence is due to the environment or remote people. The other two are co-located multi-user scenarios in which a bystander influences the AR or VR user. Later on, we use these scenarios in our expert interview.

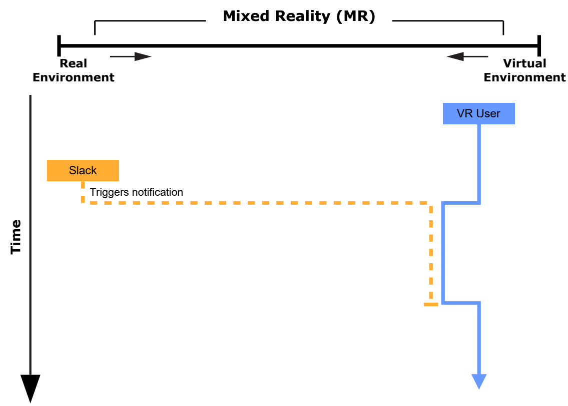
Obstacle Awareness in Mobile VR The first scenario was extracted from *SafeXR* by Kang et al. [231]. To make a mobile VR user aware of obstacles, they used built-in smartphone sensors to extract features from real-world objects and alert the user. The system was tested using a mobile VR game (see Figure 2.7(a)).

[11] GitHub Repository, `https://github.com/jonasauda/Actuality-Time-Continuum`, last retrieved on August 12, 2022

[12] Interactive Online Tool, `https://jonasauda.de/visualization.htm`, last retrieved on August 12, 2022



(a) Obstacle Awareness in Mobile VR [231].



(b) Receiving a Message in VR [152].

Figure 2.7: The first two of our four exemplary visualizations of the chosen scenarios using the Actuality-Time Continuum.

Receiving a Message in VR The second scenario was from Ghosh et al. [152]. Here, a Slack message was presented visually in VR. The message was presented on existing surfaces based on the user's location and viewing direction. We counterbalanced these two scenarios. For further details, see Figure 2.7(b).

Bystander Joins an AR Experience We extracted the third scenario from the work of Xu et al. [564]. In this scenario, a non-HMD user could use a smartphone to join the same AR experience as an HMD user experiencing virtual content in AR. The virtual AR content was synchronized between the HMD and the smartphone to present a joint experience in AR and enable interaction (see Figure 2.8(a)).

Bystander Approaching a VR User The fourth scenario was from McGill et al. [317]. In this scenario, a bystander approaches a VR user. When the bystander enters the same tracking space as the VR user, the former fades into the virtual view. When the VR user chooses to engage with them, they are rendered fully opaque (see Figure 2.8(b)).

2.4.2 Visualization Evaluation with Experts

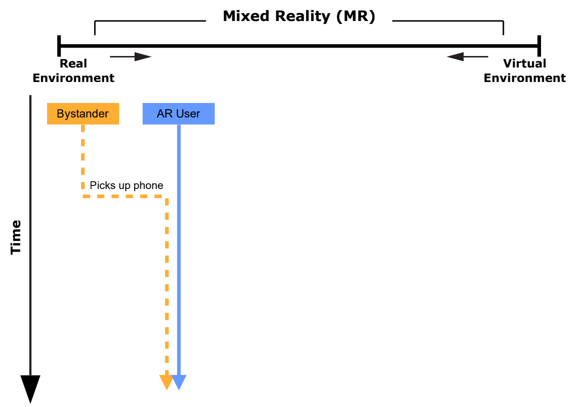
The Actuality-Time Continuum does not only allow others to classify and understand interactions but also serves as an exploration tool for new possibilities. With this in mind, we set up online interviews to understand how experts in the field would understand and value the presented visualization for future research and exploration.

Participants

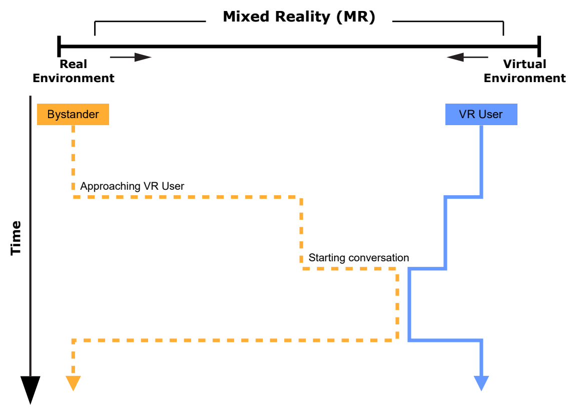
We recruited 16 experts from the AR/MR/VR domain who previously authored research papers in the domain. Two of our participants are identified as female and 14 as male, with an average age of 31.9 (SD=4.3, min=24, max=43). On average, they had 5.6 years of experience ($SD = 2.0$) in the field. They rated their overall experience with mixed reality on average as 6.2 on a 7-point Likert scale ($SD = 0.9$); their experience with AR as 5.8 ($SD = 1.1$), with AV as 3.7 ($SD = 1.7$), and with VR as 6.2 ($SD = 0.9$).

Apparatus

We conducted the expert interviews via the video conferencing service *Zoom*. For the interview, we used the same four scenarios that were presented to showcase our visualization in Section 2.4.1. All four examples are based on prior research and cover the concept space. For two of the four scenarios, namely "Receiving a Message in VR" and "Bystander Approaching a VR User," we created visualizations and showed them to the participants (see



(a) Bystander Joins an AR Experience [564].



(b) Bystander Approaches a VR User [317].

Figure 2.8: The last two of our four exemplary visualizations of the chosen scenarios using the Actuality-Time Continuum.

Figure 2.7(b) and 2.8(b)) via screen sharing. Then we asked them to summarize the given scenario. From the remaining two, namely "Obstacle Awareness in Mobile VR" and "Bystander Joins an AR Experience," we extracted details for synopses, which we gave to the participants. The participants were then asked to create a visualization from the synopses while sharing their screens with the interviewer (see Figure 2.7(a) and 2.8(a)). We counterbalanced the order in which we presented the scenarios.

Procedure

First, we contacted experts from the domain, asking them to fill out a screening questionnaire. This allowed us to then invite the participants who had self-identified as experts.

After welcoming the participants, we gave them an introduction to the topic. We then answered all the remaining questions and asked for their informed consent. After obtaining their consent, we started the core interview, which we recorded from this point onward. In the first step, we asked participants to describe their scientific work and asked if they generally identify with the topic. We then explained the visualization and its purpose in detail. Furthermore, we showed them how the visualization tool works, as we planned to have them create visualizations later on.

Next, we walked the participants through two visualizations in detail. Here, we showed them one after the other and asked them what they could extract from the visualization about the scenario using the think-aloud protocol [402]. No further information was given to them at this time. After they concluded their assessment, we explained the actual context. Participants were then asked to rate the following statement on a 7-point Likert scale (strongly disagree / strongly agree): *"I completely understood the scenario based on the visualization"* (Q1).

After completing two visualization analysis tasks, we reversed the task. Instead of giving them a visualization, we gave them a text to create visualizations using our tool. Before they started to create the visualization, again using the think-aloud protocol [402], we asked them to rate their agreement with the statement *"I think this is a very complex scenario"* (Q2). After the creation, we asked the same question again (Q3). Additionally, we asked them to rate their agreement with the statement *"I think the visualization tool empowered me to visualize the scenario"* (Q4). Here, we also asked them for the reasons behind their given ratings.

We then walked the participants through all four scenarios and asked some final questions regarding the tool's usability and helpfulness. We also had them rate two more statements: *"The visualization tool empowered me to visualize the scenarios"* (Q5) and *"The visualizations enabled me to understand the scenarios better"* (Q6). We ended the interview by inviting them to leave final remarks and reimbursed them 15 Euros for their participation.

2.4.3 Results

First, we transcribed all 16 interviews without summarizing them. In the next step, we extracted all participants' statements, resulting in an initial 843 statements. Afterward, three researchers excluded all statements that a) involved the interviewee explaining their prior work in the domain, b) only contained ratings for our questions (e.g., *"I rate this question as a six"*), c) were off-topic comments, d) were incomplete, or e) were a false start. After this reduction step, we had 410 statements concerning the task and tool. We then established a coding tree based on the first 10% of the remaining statements. Three researchers then coded the remaining 90% independently and added codes for all new aspects. To resolve conflicts and precisely merge codes, we employed affinity diagramming to sort and categorize atomic statements [183]. Starting the affinity diagramming with already pre-coded statements allowed us to confirm the coding quality and find common themes more efficiently.

On a high abstraction level, our affinity diagramming revealed that the experts commented on three major areas: the concept of the visualization (197 statements, 48%), the implementation of the visualization (152 statements, 37%), and the scenarios that they discussed (61 statements, 15%).

Concept

Within the 197 statements concerning the concepts, we could identify seven groups: positive (113 statements, 57%), negative (5 statements 3%), confusion (14 statements, 8%), problem identification (23 statements, 12%), additional features (15 statements, 8%), future work (9 statements, 5%), and usage (18 statements, 9%). While the feedback was overall positive, we also identified how we could further improve the diagram. In the following, we will present insights into the findings of the concept.

Positive The positive feedback discussed the general understandability of the visualization (62 statements). Here, each expert expressed at least once that the concept is clear, easy, helpful, simple, useful, or new. For instance, P4 stated "*I think you get a quick grasp on what it does and how it does it*."

Additionally, 51 positive statements concerned specific aspects of the concept of the visualization. Here, participants highlighted the great abstraction level (P10, P12, P14) and how it almost works like a UML diagram (P11, P12, P13). This then gives them a good overview of the scenario (P6, P8), helping them to grasp it in more detail (P1, P4, P9, P12, P15), which in turn allows them to better understand the interplay among the users (P3, P4, P7, P12). The detailed visualization (P2, P7, P8, P13, P14, P16) with its multi-user scalability (P13, P15) allowed them to better understand the time dimension. Most importantly, 9 experts (P5, P7, P9, P11-P16) specifically valued the added time dimension. For instance, P16 said *“The main thing is that you can specify the time slots and say what happens and when.”*

Negative and Confusion The experts mentioned only three negative aspects. Six experts (P4, P5, P7, P11, P14, P15) pointed out that it is confusing to them that the diagram has a perspective. For instance, P15 highlighted that “all the actions were on the bystander, that made me think more from the bystander’s perspective,” and P11 noted that “when you look at the VR user only, it’s true. [...] That makes sense if you only look at this.” Further, P3 and P16 were not sure about the degree to which interactions would affect users on the continuum: P16 stated *“actually what wonders me is [...] the VR user is somehow affected by this real-world information.”* However, both comments only occurred at the beginning of the interview. Finally, we uncovered a fundamental understanding problem with the fact that today we see mainly steps on the continuum (AR, AV, and VR). P14 and P15 pointed this out as negative, stating they would like to have a specific scale and not just steps.

Problem Identification We asked the experts whether they thought they could identify problems in a given design, and we got 23 statements discussing this specific topic. While P1 and P4 stated they are currently unsure and would need to explore the tool with more scenarios, all other experts were sure that the tool could help them to identify design problems.

Additional Features and Future Work While we got an overwhelming amount of positive feedback, ten experts also had comments to further improve the concept. Here, we found that they asked for additional features that are easy to implement (18 statements) and future work beyond the current concept (6 statements).

P2, P3, and P7 would like to have a feature to present different modalities and technologies. P1, P3, and P5 mentioned even better multi-user scalability as an addition. Further, six experts (P1, P4, P5, P9, P12, P13) asked for diagonal line support, which would allow for gradual transitions on the continuum over time.

In the future, some of the experts would like to see the concept of deploying teams and evaluating it in the wild (P3, P5, P11). Finally, P3 suggested overcoming the problem of the discrete steps on the continuum raised by P14 and P5 by quantifying the continuum itself.

Usage During the interview, the experts came up with a large number of use cases. Five experts (P2, P4, P5, P7, P13) stated that this concept is extremely helpful for discussing ideas with others. P14 and P15 added that this tool is suitable as an ideation tool for patterns in the first place. P1 and P8 envisioned that this concept allows the establishment of best practice patterns that could guide the use of an overall interaction concept. Here, P8 commented *"I could imagine making different parts of the diagram reusable as a pattern."* Finally, P3, P6, and P8 could even see this as a form to measure an implementation's quality.

Tool

Statements concerning the tool can be categorized into positive (50 statements) and negative (17 statements) aspects, as well as wishes for additional features (85 statements).

Positive and Negative The experts found the tool to be overall easy to use (P4, P6, P7, P10, P13 - P16), efficient (P2, P3, P7, P13), and helpful P5 - P7, P9 - P11, P15, P16). They highlighted that they liked that the visualization updates in real-time (P4 - P6, P12 - P15) and that it gives a side-by-side view (P9, P10). They also liked the use of JSON (P7 - P9, P14).

However, they found it difficult to set specific times in the timeline (P4, P8, P9), and they criticized the default example as not rich enough (P4, P8). Lastly, eight experts (P5, P6, P9, P10, P12, P13, P15, P16) stated that the links could result in visual clutter.

Additional Features As expected, we received a large number of comments on possible improvements. The clearest request was for an enhanced Graphical User Interface (GUI) (34 statements) with support for drag and drop and right-click for options. Additionally, they wanted more options to customize the diagram (26 statements), e.g., easier color selection or change line width and text size. While four participants liked the use of JSON, we also got statements from six experts (P2 - P4, P6, P7, P15) that they would prefer a more advanced editor.

We found that the tool should better support and highlight different entities (e.g., bystanders) (P9, P11, P16). As in the general concept statements, the experts asked for support to select specific actuality on the continuum (P3, P5, P6, P8, P9). Finally, they envisioned the tool could support switching the perspective (P7, P9), as well as possibly generate programming code for the interaction (P5, P8 P9).

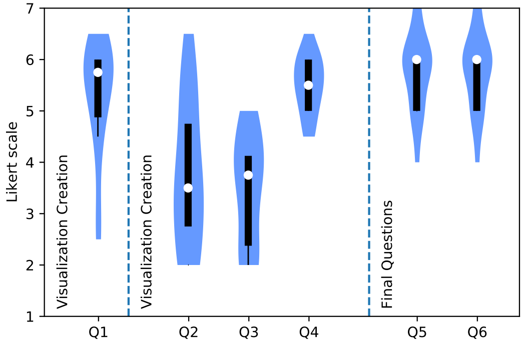


Figure 2.9: Likert results of the interview. Q1: I completely understood the scenario based on the visualization, Q2 (before): I think this is a very complex scenario, Q3 (after): I think this is a very complex scenario, Q4: I think the visualization tool empowered me to visualize the scenario, Q5: The visualization tool empowered me to visualize the scenarios' (concluding interview), Q6: The visualizations enabled me to understand the scenarios better (concluding interview).

Scenario

Lastly, we got 61 comments concerning the used scenarios. Twenty of these were positive (P1-P8, P10, P13 - P15), stating that the scenario was generally clear; for instance, P3 stated *"What I actually understand is where the person interacts and how it is happening all the time."* On the other hand, the remaining 41 comments asked for more details about the general scenario (P1, P2, P4 - P8, P11, P12, P14, P15), transition (P7, P9, P10, P16), and actuality (P4 - P7, P9, P12, P13).

Question Ratings

Q1 confirms that the visualization helps to understand the scenarios with a mean rating of 5.3 ($SD = 1.5$). We found similar confirming results that the visualization is empowering to visualize each scenario (Q4) with a mean of 5.5 ($SD = 0.8$). In the concluding interview after using the visualization twice, the experts rated the empowerment provided by the tool (Q5) with a mean of 5.8 ($SD = 0.8$), and that the visualizations enable one to better understand the scenario (Q6) with a mean of 5.8 ($SD = 0.8$) (see Figure 2.9).

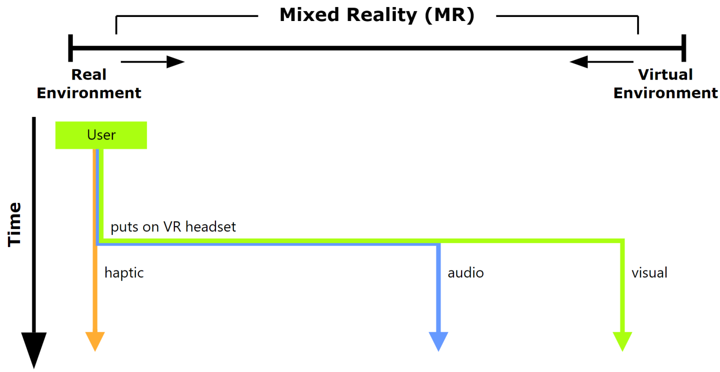
We performed a Wilcoxon Signed-Ranks Test to see if creating the visualization significantly changed participants' views on the complexity of a scenario using Q2 and Q3. However, the test indicated no statistically significant differences $Z = 1.0$, $p > .204$ (see Figure 2.9).

2.4.4 Discussion

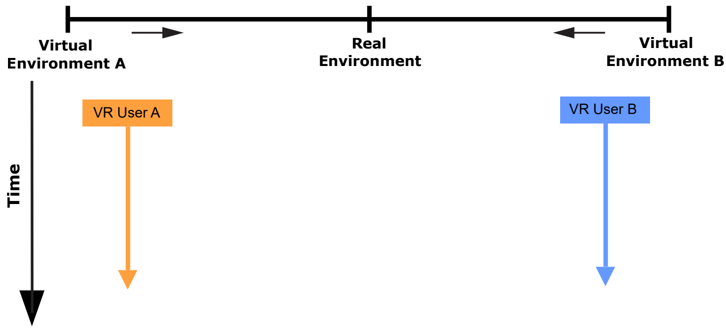
While we see a growing interest in CR systems research, that involves multiple users who can have their own actuality, we observe that further complexity is introduced through the interplay of one actuality with the other. To describe and abstract the interplay among different actualities, we propose the *Actuality-Time Continuum*. The *Actuality-Time Continuum* extends the Reality-Virtuality Continuum from Milgram and Kishino [328] with a time domain. This enables one to visualize the interplay of CR systems that change during the interaction. With our work, we aim to better support research that mixes elements from *Reality* and *Virtuality*. We contribute an initial step towards a common visualization concept that makes the interplay of different actualities on the Reality-Virtuality Continuum more understandable. Further, it helps one to describe and communicate transitions of entities between actualities.

Structure, Compare, and Communicate Research To truly structure, compare and communicate research in the field of CR interactions, existing terms, taxonomies, or the language used to describe different actualities of reality and virtuality should be unified. This could make future research more structured, more comparable, and most importantly more understandable. In other words, a common language must be established. With this work, we hope to take a step towards this common language by introducing a visualization concept that helps one to better understand the interplay of different actualities.

Extending the Continuum by a Time Dimension To better grasp the complex interplay of different actualities and possible transitions along the Reality-Virtuality Continuum, we developed a general visualization concept. We aimed to incorporate all important aspects into one single chart while maintaining a reasonable level of abstraction and flexibility. The key element for presenting various scenarios on a high level was the time dimension. We added this dimension as a y-axis to the Reality-Virtuality Continuum. This allows the communication of switches between actualities over time, giving researchers and designers the flexibility to express their scenarios while keeping the option space within confined boundaries. To further support them, we implement the general visualization concept in a web-based tool, allowing them to create



(a) Visualizing different modalities.



(b) Presenting scenarios with multiple environments.

Figure 2.10: Different ideas for an extension of our Actuality-Time Continuum visualization to support different modalities or environments.

scenarios as they please. On the one hand, we received a large amount of positive feedback on the visualization concept; we argue that it indeed supports researchers and designers in creating and researching scenarios. Further, we could not identify any drawback in terms of understandability, expressiveness, or complexity. On the other hand, as the tool itself is in the early stages of development, we received a lot of feedback to improve our web-based implementation. The feedback was mainly intended to allow easier use, using features like drag and drop and What You See Is What You Get (WYSIWYG) instead of or in addition to our current JSON editor. Hence, we argue that our visualization concept is suited to foster understanding of experiences that involve multiple actualities and thereby introduce a complex interplay of the same. A future version of the tool that implements all the improvement suggestions we gathered could be used to analyze the interplay of different actualities before their actual development. This could help researchers to avoid bad design decisions, better structure the development process, or better outline and investigate the underlying RQs of future research prototypes. Our extension of the Reality-Virtuality Continuum could assist in shaping a common language that is needed to describe complex interactions across actualities and could function as a general discussion tool to provide more insight into the interplay of actualities present along the Reality-Virtuality Continuum.

Refining the Reality-Virtuality Continuum Referring to the original continuum, experts who used our tool stated that it is unclear where actualities are located on the continuum. While Milgram and Kishino [328] added indicators for AR and AV to their continuum, they do not show precisely which ranges of the continuum represent specific actualities (e.g., specific implementations of AR or AV). This makes it challenging to use the Reality-Virtuality Continuum to compare two different experiences to each other or to depict how strong a transition from one actuality to another influences the perception of the transitioning entity. Our experts suggested that we could support users with predefined areas on the continuum for well-known actualities. For example, where exactly is the range of AR located, or to what degree does the augmentation of virtuality pulls an entity towards the real world? According to our experts, these areas could be sourced from various research prototypes or systems that implement a specific experience. Moreover, it was suggested that one could use our visualization tool to ask researchers to visualize different scenarios. From the results, we could extract the commonly used areas for various actualities and use them as guidelines for the future. Defining these areas by sourcing them with the help of our tool means that we would quantify them. This quantification could also make it easier to compare different research prototypes. We argue that this could help to research future prototypes and systems and the interplay of the different actualities in a structured manner. Additionally, we think that transitions across actualities could be described more accurately if one can precisely define the current actuality from which a transition starts and to which it goes.

Finally, the tool can be used to quantify numerous scenarios along the continuum to understand at which points humans perceive switches between the different "realities." In other words, it could be used to discern when a person perceives the experiences as AR, AV, or VR when transitioning between them.

Future Work

During the expert interviews, we received valuable feedback to further develop our Actuality-Time Continuum. It was suggested that we visualize the user's different modalities, overcoming the limitation of the original continuum, to classify mainly visual experiences. In Figure 2.10a, we implemented this idea with our visualization tool.

2.4.5 Conclusion

We developed the concept of the Actuality-Time Continuum. This extended continuum allows one to position multiple entities on the Reality-Virtuality axis and the new time axis. The position of entities now allows one to visualize the actuality of them and their relationships. As we envision this idea not solely as a theoretical concept, we implemented a tool to allow others to use it. Furthermore, our tool can be used to explore alternatives in the development process, discuss with others, or form new ideas. Finally, we conducted interviews with 16 experts in the field. Our findings confirmed many of our expectations about the Actuality-Time Continuum and the adjunct tool. We hope that our work sparks discussion on how to describe complex CR systems intuitively. We used the term *"actuality"* – Latin for *"in existence"* or *"currently happening"* – to name our extension of the Reality-Virtuality Continuum [328]. We argue one again, similar to previous literature [574] for the term *actuality* to describe a specific experience of users like the reality, AR, or VR [118].

Summary

In this part, we briefly introduced the history of VR. We followed up with the fundamentals of human perception. We focused on the senses that are addressed in the scope of this thesis, namely the visual sense, the haptic sense, and the proprioceptive sense. After that, we introduced fundamental knowledge on immersive technologies such as AR, VR as well as CR systems. In addition, we introduced our CR system definitions that help to structure the young field of CR systems. To better understand the interplay of reality and virtuality, we continued with a scoping review on CR systems. Here, we classified a large body of literature and, based on that, distilled golden rules that can inform future CR design and development. Afterward, we introduced visualization techniques for CR interaction to foster the understanding of complex research scenarios and prototypes.

II

Tools and Frameworks

In the following part, we introduce the tools and frameworks we have developed in the scope of this thesis. These systems served as the infrastructure that accelerated the development of a wide range of research prototypes. Therefore, we implemented an ecosystem of different artifacts that supported us with specific tasks during our research. In the following, we introduce these artifacts in great detail and show how we achieved rapid deployment of complex systems through their interconnectivity. We aimed for this approach because technical advancements act as a key driver for VR research. In this context, we decided on a modular infrastructure that allows for rapid adaption of novel technology while maintaining a limited integration effort.

First, we implemented the *VinteR* middleware. This middleware unifies sensing data originating in the real world with data from VEs within one canonical data format. This data format can be transferred to receiving endpoints (e.g., VR applications or databases). These endpoints can be distributed across multiple physical locations. We integrated various sensing technologies like optical marker tracking (e.g., *OptiTrack*), camera-based full body tracking (e.g., *Microsoft Kinect*), and on-body worn hand-tracking (e.g., *Leap Motion*). This approach allowed us to implement interactive VR applications that incorporate a wide range of our users' properties and properties of the surrounding environment along with the present physical objects. Through that, for example, *VinteR* can help to provide haptic feedback. As *VinteR* allows for remote interaction, our system allowed us to span our infrastructure beyond individual labs. In the background, *VinteR* records the data that emerges from the connected endpoints persistently. That allowed us to analyze all recorded sessions and the corresponding VR scenarios [7].

Supported by *VinteR*, we implemented the *Flyables* toolkit. Our toolkit allows for autonomous drone control within an optical tracking space. We used the tracking capabilities of *VinteR* to track drones and receive input data from VR applications. We combined these two data streams to steer drones to a physical location with respect to the VR environment using Proportional-Integral-Derivative (PID) controller algorithms. This allows, for instance, to automatically position haptic props via drones around a VR user. Further, we implemented techniques that allow for input via *Flyables*. For example, a VR user could grab a drone and use it to control certain elements within the VE. We designed and built various haptic UI devices that can be 3D-printed and attached to our drones like buttons, knobs, or joysticks. These physical elements and their virtual representations allow the user to interact with virtual content while the *Flyables* toolkit handles their positioning autonomously.

Lastly, we present *VRception*, our concept and toolkit for rapid prototyping of complex CR systems entirely in VR. Through the simulation of the entire Reality-Virtuality Continuum in VR, we eliminate real-world restrictions like technical integration challenges. This allows one to use the *VRception Toolkit* for building virtual CR systems and virtually experience their virtual look from all continuum levels. Additionally, our toolkit allows for collaboration in a VE from remote locations and work on prototypes together.

We open sourced the code of all these systems and frameworks along with detailed deployment documentation and instructions on the creation of corresponding hardware artifacts (e.g., model files for 3D-printing) for other researchers and developers[13]. In the following, we introduce our systems and frameworks in great detail.

[13] GitHub – Jonas Auda, `https://jonasauda.de/forward.html?res_id=code`, last retrieved on August 12, 2022

Chapter 3

VinteR

Interactive Virtual Realities

Code Repository
(QR Codes are clickable in PDF)

With *VinteR* which is short for *Interactive Virtual Realities*, we developed a system that accelerates the integration of data sources into our applications. *VinteR* integrates a variety of different tracking devices (e.g., *OptiTrack*, *Microsoft Kinect*, or *Leap Motion*) and streams the data to various endpoints like VR applications, databases, or to any endpoint that implements the underlying data model. *VinteR* transforms the data of its input sources into one canonical data format with one Global Coordinate System (GCS). Through that, we accelerated our research prototype development through a standardized device and application communication platform. The data sources that serve *VinteR* as input are not limited to hardware devices. Every software application can be integrated over the network through adapters. Through that, we were able to develop two modes in which we can run *VinteR*: The *single location mode* and the *Distributed Location Mode*. The single location mode allows to run *VinteR* in one location (e.g., a research lab). The distributed location model allows one *VinteR* instance to communicate with other *VinteR* instances that run distributed, for example, at remote locations. Through that, we could synchronize devices and applications across multiple locations, for example, to implement remote, multi-user VR experiences. Hence, *VinteR* acts as a middleware for most of our research prototypes and artifacts.

Figure 3.1: A VR user interacting with a stick of dynamite. The physical counterpart of the virtual dynamite is optically tracked in real-time through *VinteR*. Through that, the user is capable of catching the dynamite.

3.1 Single Location Mode

In this mode, *VinteR* serves with streaming data at one particular location. For example, to track physical objects within one tracking space (see Figure 3.1). Therefore, *VinteR* acquires data from its input sources (e.g., *OptiTrack*) and streams it to all registered endpoints within the local network. To easily integrate the data sources and endpoints, we designed *VinteR* in a modular way. The *VinteR* system consist of different layers that handle the incoming and outgoing data (see Figure 3.2). We implemented three layers - an input layer, a merge and transform, and an output layer. These layers make up the entire architecture of one *VinteR* instance. In the following, we describe the different parts of this architecture.

3.1.1 Input Adapters

VinteR's input layer allows to interface with sensory devices (see Figure 3.2, *Input Adapters*). Within the input layer, we can implement $1-N$ input adapters. Each adapter communicates with one data source (e.g., *OptiTrack*). The adapters are loosely coupled with the *VinteR* system in order to accelerate the integration of new data sources. For *VinteR* to function correctly, we must implement at least one adapter – the *OptiTrack* adapter (see Figure 3.2, upper left). As *VinteR* relies on a GCS, we chose the *OptiTrack* coordinate system to serve as the basis for all other coordinate systems of additional data sources. All other data of additional data sources that are integrated will be transformed

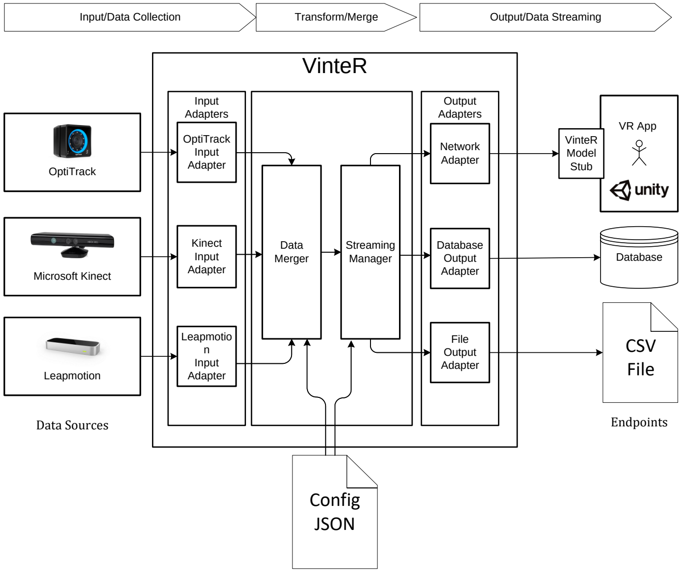


Figure 3.2: The *VinteR* Software Architecture for a single instance: Left, the input data sources for each of which *VinteR* provides a dedicated input adapter that implements the corresponding communication protocol to a specific data source. Middle, the *Data Merger* that merges the acquired data into one GCS. The transformed data is then merged into one canonical data format. The data is forwarded to the *Streaming Manager* at which the output adapters are registered. Right, the data from the streaming manager is relayed to the registered endpoints through output adapters that implement the corresponding communication protocol.

into this coordinate system. In the current version of *VinteR*, we included two more devices, i.e., the *Microsoft Kinect* and the *Leap Motion*. In the following, we describe how *VinteR* transforms and merges the data from its data sources. To register and configure the input adapters, we can use a configuration file that provides corresponding settings (see Section 3.1.5). For example, *enabling* or *disabling* a particular input adapter or specifying the sampling rate.

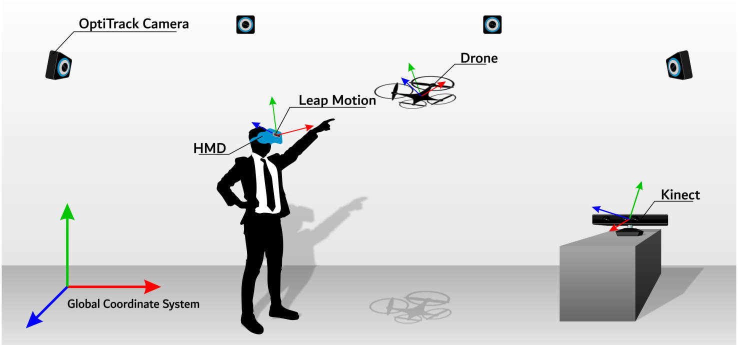


Figure 3.3: An exemplary tracking space in which *VinteR* unifies the data of three data sources – *OptiTrack*, *Kinect*, and *Leap Motion*. Therefore, all data points are transformed from the local coordinate system of *Kinect* and *Leap Motion* to *OptiTrack* coordinate system which serves as the *Global Coordinate System* (GCS). In this scenario, a VR user is present in the tracking space and interacts with a drone. Both are tracked by *VinteR*.

3.1.2 Data Merger

The *Data Merger* forms, together with the *Streaming Manager* the middle layer of *VinteR* (see Figure 3.2, middle). After the data is acquired by the available data sources, it is forwarded to the *Data Merger*. Within the *Data Merger*, the data is combined into one canonical data format with a GCS. Therefore, *VinteR* tracks the position and orientation of the additional data sources (e.g., the *Kinect*) via the *OptiTrack* and uses this information to transform their coordinates correctly into the GCS. For example, when *VinteR* acquires data from the *OptiTrack*, the *Kinect* at the same time (see Figure 3.3), *VinteR* users the position and orientation of the *Kinect* to transform its data to the GCS (i.e., the *OptiTrack* coordinate system). Then, the *Data Merger* merges coordinates of all tracked objects into the GCS and provides the collected data as unified samples in the canonical data format. These samples are forwarded to the *Streaming Manager*.

Canonical Data Format

VinteR's canonical data format[14] is used to unify the data from different data sources. This has the advantage that we can integrate one stub in a receiving endpoint like a VR application instead of multiple input adapters, one for each data source. The canonical data format contains the name, the position and orientation of each tracked object. This allows the receiving endpoint to filter the data stream to objects of interest. We modeled the canonical data format using *Protocol Buffers*[15]. Thus, we can compile the model to a specific programming and integrate the generated *VinteR Model Stub* into the receiving endpoint (see Figure 3.2, right). The stub can parse the data stream from *VinteR*, and thereby, provides the application with data that is understood by the corresponding programming language.

3.1.3 Streaming Manager

The *Streaming Manager* is used to register output adapters that serve as connectors to the final endpoints to which *VinteR* streams the recorded data. Data from the *Data Merger* is relayed to these output adapters. Then, the adapters handle the communication to the endpoints. We can implement $0-N$ output adapters. Each adapter communicates with one particular endpoint (e.g., a VR application or a database). Similar to the input layer, we aimed for a loosely coupled and modular architecture to allow for accelerated integration of new endpoints.

3.1.4 Output Adapters

The output adapters form the last layer of *VinteR*. Currently, we implemented three output adapters.

[14] VinteR – Canonical Data Format, `https://github.com/jonasauda/VinteR/blob/main/vinter/model.proto`, last retrieved on August 12, 2022

[15] Protocol Buffers by Google, `https://developers.google.com/protocol-buffers/`, last retrieved on August 12, 2022

Network Adapter

The *Network Adapter* streams the recorded data via the local network to registered endpoints. Therefore, it uses Unified Datagram Protocol (UDP) for best performance and real-time capabilities. To specify an network endpoint, we can use a configuration file (see Section 3.1.5). This file contains a list of endpoints together with their Internet Protocol (IP) addresses and corresponding ports. The outgoing data stream is serialized using *Protocol Buffers*. Thereby, we can compress the recorded data, which makes the streaming more efficient. The receiving network endpoint can use the compiled *VinteR Model Stub* to parse and process the received data. Therefore, it can implement a UDP receiver and then can use the *VinteR Model Stub* to parse the received data. We provide a demo *Unity3D* application that implements this functionality in our *GitHub* repository[16].

Database Output Adapter

The *Database Output Adapter* implements a connection to a database. In our case, we implemented a connection to a locally installed *MongoDB*[17]. The adapter handles the database session in the background. As soon as the *Streaming Manager* sends data to the *Database Output Adapter*, it stores the data within the database.

File Output Adapter

The *File Output Adapter* lets *VinteR* write data to a persistent file. Thereby, we can output the recorded data into files that can be used for later analysis. Currently, *VinteR* can write the recorded data to JSON files. If another file format is desired, one can integrate an additional file adapter that can handle different file formats, for example, Comma-separated values (CSV) files.

3.1.5 Configuration

VinteR is configures through a JSON file. Here, a user can specify which input adapters or output adapters are enabled. For example, if no database or file is

[16] VinteR Unity Demo, `https://github.com/jonasauda/VinteR/tree/main/Demo%20Projects/BasicDemo`, last retrieved on August 12, 2022

[17] MongoDB, `https://www.mongodb.com/`, last retrieved on August 12, 2022

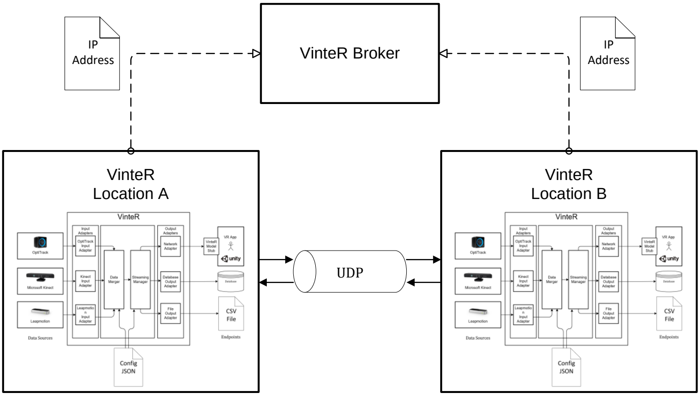


Figure 3.4: The VinteR Software Architecture for Multi-Location Support: Left, the *VinteR* instance in Location A. Middle, we the broker that mediates the IP address between registered *VinteR* instances. Right, the *VinteR* instance in Location B. For details see Figure 3.2.

needed, one can disable these adapters to save resources. Further, the configuration file contains all the IP addresses and ports of all network endpoints to which *VinteR* streams data. This allows multiple users or applications within one local network to interface with *VinteR* at the same time. One exemplary configuration file can be found in the GitHub *VinteR* repository[18].

3.2 Distributed Location Mode

In a second iteration, we added new functionality to the *VinteR* middleware. To collaborate beyond one single location, we added multi-location streaming support to support remote VR applications. In the following, we describe the enhancements which we integrated into the previously introduced *VinteR* system. Through the resulting system, we could synchronize streaming data across multiple physical locations. In each location, *VinteR* allowed for the integration of the available data sources and endpoints. Eventually, we

[18] VinteR – Configuration File, `https://github.com/jonasauda/VinteR/blob/main/vinter/vinter.config.default.json`, last retrieved on August 12, 2022

would run one *VinteR* instance in each location which communicates to other instances over the Internet.

3.2.1 Broker

In order to establish a connection between two physical locations, we deployed a broker on a server reachable via a publicly available Uniform Resource Locator (URL) (see Figure 3.4). When a *VinteR* instance in one location starts, it registers with the broker and publishes its IP address. Other *VinteR* instances that register with the broker also publish their addresses. The broker sends the IP addresses of registered instances to all other instances. Hence, all instances can establish a direct UDP communication channel between each other.

3.2.2 Data Synchronization

The *Streaming Manager* can use the previously established UDP channel to forward locally originating data to remote *VinteR* instances (see Figure 3.4). Therefore, it implements an output adapter that communicates with remote *VinteR* instances. Further, it implements a novel input adapter that receives data from remote *VinteR* instances. Each location has a unique identifier, for example, *Location-A*. This identifier is encoded into a VinteR Resource Identifier (VRI). Through that, all *VinteR* instances can identify to which location the streamed data belongs when it is streamed across different locations. The VRI also encodes to which objects the current data belongs. For example, when one *VinteR* instance streams spatial data of a VR-HMD user, a corresponding VRI can look like the following: *Location-A/ User-1/VR-HMD*. Thereby, each application that receives the data can identify the originating location, the user, and the HMD that is worn by the user. This hierarchy can be used to specify a wide variety of streamed objects, for example, nested objects that belong together but must be processed individually.

3.2.3 Configuration

For *VinteR* to communicate with remote locations, we must specify a variety of new parameters. First, we must specify the URL of the broker in order to allow distributed instances to find each other. Each location must specify a unique identifier that is incorporated in the VRI of the streaming data of the corresponding locations. Last, we must enable the adapters that allow for the communication to remote *VinteR* instances. We provide a exemplary configuration file on GitHub *VinteR* repository[19]. Further, we provide detailed deployment descriptions in the same repository[20].

[19] VinteR – Configuration File, `https://github.com/jonasauda/VinteR/blob/main/vinter/vinter.config.default.json`, last retrieved on August 12, 2022

[20] VinteR, `https://github.com/jonasauda/VinteR`, last retrieved on August 12, 2022

Chapter 4

Flyables Toolkit

This chapter is based on the following publication:

- **Jonas Auda**, Nils Verheynen, Sven Mayer, and Stefan Schneegass. "Flyables: Haptic Input Devices for Virtual Reality using Quadcopters". In: *Proceedings of the 27th ACM Symposium on Virtual Reality Software and Technology*. Osaka, Japan, 2021.

Code Repository
(QR Codes are clickable in PDF)

To utilize drones as haptic end effectors using well-known haptic UI elements to serve a wide range of VR environments, we developed the *Flyables* toolkit. Through our toolkit, we allow for haptic interaction that provides not only matching haptic feedback but also input capabilities to control the VR narrative. The toolkit controls a set of drones equipped with customized 3D-printed UI elements. These elements serve as physical proxies for virtual UI elements with which VR users can interact. This works as follows: As soon as a virtual UI element is visible in VR, a quadcopter equipped with a matching physical UI element – which we call a *Flyable* – is steered to the location where a VR user expects to touch or grab it (see Figure 4.1). During our design process, we developed five 3D-printed UI elements derived from classical input devices: a *button*, a *knob*, a *joystick*, a *slider*, and a *3D mouse*. This enables users to experience haptic feedback that matches the shape of the virtual UI element. Additionally, the *Flyable* acts as an input device, fostering a similar experience as using a UI element in the real world (e.g., a real button, joystick,

Figure 4.1: Left: A user piloting an aircraft in VR. The user has a slider in his right hand to control the speed. With the joystick in his left hand, the aircraft can be steered sideways. Right: A user is rotating an object in VR using a knob.

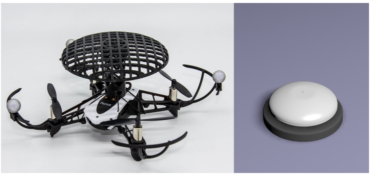
or slider). Moreover, *Flyables* have the advantage over VR controllers that the user does not need to carry them all the time, which leaves their hands free. In the future, this could enable a more natural gestural interaction [313, 331, 520]. In the following, we present the design and implementation of the *Flyables* toolkit. In Chapter 11, we present an evaluation of the *Flyables* toolkit.

4.1 Flyables Toolkit

With Shneiderman's eight golden rules [452] in mind, the *Flyables* toolkit provides a consistent set of input devices across arbitrary VR scenarios: a *button*, *knob*, *joystick*, *slider*, and *3D mouse* (see Figure 4.2). In the following, we describe the design process of the five input devices. Further, we introduce the *Flyables* control system and explain how it recognizes input from the flying UI elements.

4.1.1 Design Process

Our design process for creating *Flyables* involved multiple stages. We started with the goal of designing physical haptic counterparts for possible virtual UI elements. However, at this stage of the process, we did not know how the physical objects would look nor which virtual UI elements they should resemble.



(a) Button

(b) Knob

(c) Joystick

(d) Slider

(e) 3D mouse

Figure 4.2: The five *Flyables*. Each *Flyable* consists of a 3D-printed haptic interface element that is mounted on a quadcopter and a corresponding virtual representation in VR. The quadcopter is equipped with markers for optical tracking.

We started our design process by gathering a large number of interactive items. We looked not only at on-screen elements from GUIs but also at everyday physical objects. During our process, both virtual and physical objects served as an inspiration for the next step. The virtual UI elements helped us to understand what type of UI elements we use daily and how they look and react in the virtual domain. The physical character of the objects helped us to design appropriate counterparts for the virtual UI elements. The goal was for people to immediately feel comfortable when using them.

We started with a wide range of physical (e.g., crossbars latches, volume knobs, and stove control knobs) and virtual objects (e.g., buttons, sliders, and drop-down menus). We narrowed down our search to five interactive elements that can be directly manipulated (e.g., translated or re-orientated) in a specific way: a *button*, *knob*, *joystick*, *slider*, and *3D mouse*. Each element serves a particular purpose. The *button* can be used for discrete input events. The *knob* enables rotary input in one dimension, while the *joystick* offers three-dimensional rotation (yaw, pitch, roll). The *slider* can be adjusted along one dimension. Finally, the *3D mouse* enables 3D translation. After extracting the basic interactions, our next step was to design the virtual representations of the input devices as well as their physical forms. Here, we began by choosing real-world objects to serve as templates for the virtual and physical representations. For the virtual representations, we wanted them to have an overall coherent *"look and feel"* and to be noticeable, but not to distract from the VR experience. The button was derived from a traditional *"kill switch"*, the knob from volume control knobs, the joystick from a manual gear stick, the slider from an industrial machine, and the *3D mouse* from a free-floating ball like a balloon. This gave us an overall *"look and feel"* for our *Flyables*. With the first version of *Flyables*, we tested their dimensions and ability to fly. For each *Flyable*, we tested if the drone, together with the attachment, could lift off on its own and stabilize itself in the air. Over a number of iterations, we remodeled the *Flyables* to improve their flying capabilities. At the same time, we tested them in VR to see if they would meet our expectations. During this process, we asked people from our institution with a design background for informal feedback. After weeks of prototyping, remodeling, and redesigning, we present our five *Flyables* (see Figure 4.2).

Button The *button* (see Figure 4.2a) allows the user to trigger discrete events. As soon as the user touches the button, the toolkit triggers an input event. At the same time, the physical *button* allows the user to feel the matching haptic feedback.

Knob The *knob* (see Figure 4.2b) can be rotated by the user to adjust a specific value. A visual marker on the top of the *knob* indicates its orientation. The *knob* is located on top of a round base to communicate its affordance (i.e., turning left or right). Its physical counterpart mounted on a quadcopter allows the user to feel the round structure of the knob. When the physical knob is turned, the rotation of the quadcopter is applied to objects or values that should be manipulated in VR.

Joystick The *joystick* (see Figure 4.2c) provides a means of input for yaw, pitch, and roll (3 Degrees of freedom (DOF)). It consists of a base and a spherical part at the top. The values for yaw, pitch, and roll are measured in degrees and can be applied to any virtual object in VR.

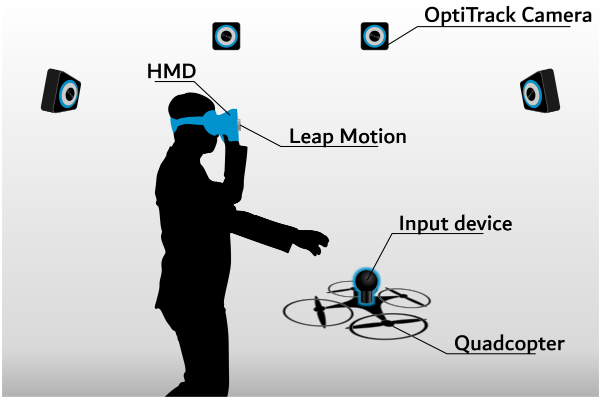


Figure 4.3: An HMD user reaching out for a *Flyable*. The user's hands are detected via a *Leap Motion* (attached to the user's HMD). The quadcopter is tracked by an *OptiTrack* system. After grabbing the *Flyable*, the user can use it to control elements in VR. We aligned the coordinate systems of the HMD, the *Leap Motion*, and the *OptiTrack* system to allow users natural interaction using their hands.

Slider The *slider* (see Figure 4.2d) can be used to specify a value within a specific range. It can be moved in the 3D VE, but only the translation along one specific axis is considered for changing the target value. Arrows at the base of the *slider* indicate the directions the *slider* can be moved to adjust this value.

3D mouse The *3D mouse* (see Figure 4.2e) allows the user to translate objects in 3D space, cf. [353]. If an object is linked to the *3D mouse*, the user can translate it by grabbing the *3D mouse* and moving it around. It can be used to position objects without directly touching them. Objects in VR often have no physical representation, so the *3D mouse* can act as a proxy, enabling haptic feedback. Further, as the object is not directly held by the user, the virtual representation of the hand does not occlude the object. This means that the *3D mouse* can be used to move distant objects.

4.1.2 Toolkit Functionality

The *Flyables* toolkit consists of a set of quadcopters with haptic UI attachments and a control application that interfaces with an optical tracking system and the

VR application. With respect to the position and orientation of a UI element in VR, our toolkit steers a quadcopter mounted with the physical counterpart of the UI element to the physical location where a VR user would expect the haptic feedback of virtual objects (see Figure 4.3). Users can touch and hold the physical object. While in VR, they see a virtual representation of their hands and the virtual input device.

The *Flyables* toolkit uses PID controllers [380] to steer the quadcopters. The PID controllers constantly track the target location of the virtual UI element and the physical position of the quadcopter. They then use this data to calculate the commands necessary to steer the quadcopter to the location of the virtual element in 3D tracking space. Tracking the position can be accomplished by various means, such as optical marker tracking, indoor localization systems, or even through utilizing tracked components of modern VR systems (e.g., a *VIVE* Tracker) [209]. The PID controllers can be tuned to the desired flying behavior, e.g., desired acceleration, maximum velocity, or spatial precision, similar to [153]. The steering is executed by the control application without human intervention.

We open-sourced the *Flyables* toolkit [21] together with the model files of the 3D-printed quadcopter attachments. We included the control application that steers the quadcopters and provided a *Unity3D* plugin to integrate *Flyables* into arbitrary VR scenarios. We included a showcase application for *Unity3D* that uses the plugin to interface with *Flyables*. Further, we published instructions for integrating *Flyables* into other applications or game engines. We also provided guidelines and instructions on how to integrate any drones into the toolkit. This will enable other researchers and designers to build upon the presented research.

[21] Toolkit and PID configurations of the drones: `https://github.com/jonasauda/flyables`, last retrieved on August 12, 2022

Chapter 5

VRception

Rapid Prototyping of Cross-Reality Systems in VR

This chapter is based on the following publication:

- Uwe Gruenefeld, **Jonas Auda**, Florian Mathis, Stefan Schneegass, Mohamed Khamis, Jan Gugenheimer, and Sven Mayer. "VRception: Rapid Prototyping of Cross-Reality Systems in Virtual Reality". In: *CHI Conference on Human Factors in Computing Systems.* New Orleans, LA, USA, 2022.

Teaser Video

Code Repository

(QR Codes are clickable in PDF)

In this chapter, we introduce a concept and toolkit for prototyping CR systems. As we saw earlier, these systems can be complex and involve multiple users and manifestations such as AR or VR. Furthermore, users can transition between these manifestations (see Section 2.2.2). All this adds to the complexity of the system and the scenario. Developing prototypes to enable immersive CR systems is often time-consuming and requires both software and hardware prototyping expertise as well as the hardware itself. In particular, CR hardware prototypes (e.g., [317, 167, 169, 90]) have a high entry barrier as they require technology

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

Figure 5.1: The *VRception Toolkit* allows users to transition on the reality-virtuality continuum [328], 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.

(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 CR 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 allow for rapid prototyping of CR systems, we present *VRception*: the concept of simulating CR systems entirely in VR and thereby allowing researchers and practitioners to prototype these systems rapidly. 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 remix and blend the simulated real and virtual worlds instantly. Moreover, it reduces the need for strong engineering skills, as it is a software-only approach, allowing to prototype CR systems that typically require hardware setups.

Based on our concept, we developed the *VRception Toolkit*, a multi-user toolkit for quickly and easily prototyping CR 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 editor and 2) *Unity3D*. In VR, users are immersed in a simulation of the reality-virtuality continuum (see Figure 5.1), in which they can combine and configure predefined objects to prototype CR 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 losing the ability for more advanced customization.

In this chapter, we introduce the concept of *VRception* and the implementation of the *VRception Toolkit* as a WYSIWYG application inside a VR headset, enabling novice users to collaboratively and rapidly prototype CR systems without coding or hardware building expertise.

5.1 Related work

In 1994, Slater et al. [457] presented the idea of nested virtual realities and investigated their influence on presence. In this work, we use this idea as nested realities inside of VR. We propose to apply the idea to the domain of CR systems, which we will review first. We will then review literature proposing VR as a research and prototyping tool.

5.1.1 Cross-Reality Interaction and Systems

Several researchers have pointed out the disconnect between the real world and the digital world [448, 545, 146]. This disconnect is particularly present when the user engaging with the digital world is not alone [303] and when collaboration between users is important [24]. 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., [317, 533]). These systems are referred to as CR 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 [453]. Today, different research prototypes focus on users transitioning on the continuum, such as by transitioning into VR [480, 514] or back into the real world [249]. 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 [9], projecting VR into the real world [167, 221, 222, 123], or attaching projectors [224, 533, 187] and displays [169] 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. [533] used a taut strap to distribute the weight of the device, and Jansen et al. [224] outlined that one of their future aims is to reduce their prototype’s weight.

5.1.2 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 [335], for the evaluation of user behavior in front of public displays [304], as a test bed for the evaluation of real-world security systems [309], and as an implementation and evaluation method of situated visualization [539], among other uses. Rebelo et al. [410] even argued that VR enables one to develop realistic VEs 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. [15] 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 [11] and that such controlled VEs can provide users with rich contextual experiences [217]. 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 [104, 447] or using VR as a training platform for underground coal miners [156]. 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 [400, 253]. 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 [523, 539]. The final component for using VR as an effective research platform is to enable remote studies. Rivu et al. [405], for example, present a framework for remote VR studies and guidelines for best practices of such studies. Saffo et al. [428] went one step further and conducted remote collaborative VR studies and presented their findings. However, Ratcliffe et al. [406] found that safety and hardware variability issues have to be overcome in order to run remote studies effectively.

5.1.3 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 [55]. 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 Unity3D or Unreal engine. For these environments, toolkits and programming interfaces exist that help practitioners implementing typical user interactions (e.g., Mixed Reality Toolkit[22]) or integrate the real-world environment (e.g., Oculus Passthrough API[23]). However, technical barriers such as programming skills and a steep learning curve make it difficult for non-experts to quickly build CR prototypes [21, 360, 363]. Therefore, researchers have started to explore new tools that allow non-experts to quickly prototype AR [362, 465, 128] and VR [361, 360] applications without the need for programming or 3D modeling. Nebeling et al. presented 360proto [361], a toolkit that allows designers to create complex 3D environments using sketches on a piece of paper. They then presented ProtoAR [362], a toolkit focused on optimizing the workflow in AR. 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 CR 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

[22] Mixed Reality Toolkit, `https://github.com/microsoft/MixedRealityToolkit-Unity`, last retrieved on August 12, 2022

[23] Oculus Passthrough API, `https://developer.oculus.com/blog/mixed-reality-with-passthrough`, last retrieved on August 12, 2022

non-experts to build and experience CR systems without the need for hardware prototyping and programming.

5.2 *VRception* - Concept

We propose *VRception*, a concept to simulate different realities in VR. Thereby, we enable users to prototype experiences rapidly 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 CR 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 [532]. Moreover, when users collaborate remotely, they share the virtuality, but two realities exist in the sense that each has its distinct physical space [394]. 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 [457].

Characteristic 2: Enabling Transition between Realities. Supporting multiple realities requires a mechanism to switch between these 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 5.1b). In general, we expect different types of transitions to be possible, as shown in previous work [514]. 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 prototype rapidly. Apart from the HMD worn by the user, every part of the simulated realities is software-based and does 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 [90] or the limited fields of view of AR-HMDs [161]). 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 CR 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) that 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 (less often used in CR 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.

5.3 *VRception* - Toolkit

Based on our concept, we developed the *VRception Toolkit*, a multi-user toolkit for quickly and easily prototyping CR 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*.

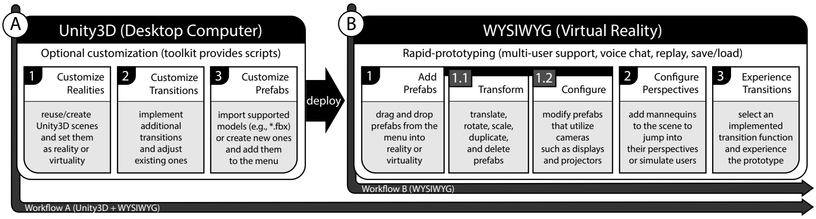


Figure 5.2: Workflows and Environments of the VRception toolkit. The Unity3D option is designed to maximize expert developers' ability to customize the toolkit. The WYSIWYG mode allows developers that are not experts in Unity to experiment with CR systems; thereby lowering the barrier to entry.

5.3.1 Prototyping with the *VRception Toolkit*

Essentially, the *VRception Toolkit* provides two different environments to rapidly prototype CR systems: 1) VR with a WYSIWYG editor and 2) Unity3D (see Figure 5.2). 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 create additional resources, while designers can utilize the VR environment to quickly try out different ideas.

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 5.3a). 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 CR systems (see Figure 5.3c). The corresponding workflow is demonstrated in Figure 5.2. While this is most certainly the quickest way to prototype CR 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).

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. Similarly, our toolkit allows experienced developers to extend our scripts, enabling them to build richer interactions using the editor and C#. In Unity3D, 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.

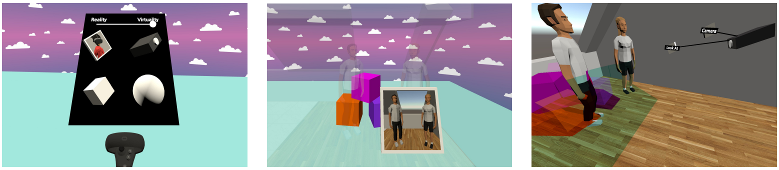
5.3.2 Implementation of the *VRception Toolkit*

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 Software Developer Kit (SDK)[24]. Our implementation has two goals. First, we wanted to create a VR application that allows users to experience *VRception*, thus enabling quick prototyping of CR 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[25] 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.

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

[24] Oculus Developer, `http://developer.oculus.com`, last retrieved on August 12, 2022.

[25] *VRception Toolkit*, `https://github.com/UweGruenefeld/VRception`, last retrieved on August 12, 2022



(a) Virtual menu attached to a controller.

(b) Example of a display showing reality.

(c) Example of a projector showing virtuality.

Figure 5.3: 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.

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 (see Figure 5.3a). Additionally, it contains a set of predefined objects. The users can drag these objects into the scene, attach them to each other, 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 [328]. 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 (see Figure 5.1). Each user has a slider to independently switch between realities and different glasses (i.e., HMDs) on their avatars indicate 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 CR 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. 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[26]). Both objects can be manipulated and combined to represent more complex objects. For example, users can connect objects to form more complex structures. Therefore, they can intersect two or more objects to group them together. When objects are grouped, users can move them as a whole.

Besides these two primitive shapes, we implemented a display that allows one to bridge realities. While it exists in one reality, it shows the other (see Figure 5.3b), 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 [168, 167, 302].

Also, 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 (see Figure 5.3c). Projectors also allow the user to adapt the position and direction of the camera. We selected projectors because they are found in many prototypes [224, 533, 187].

[26] Game Minecraft, `https://www.minecraft.net`, last retrieved on August 12, 2022

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[27] 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[28] (see Figure 5.1). 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[29] that implements a variety of IK solvers such as Cyclic Coordinate Descent (CCD) [239] and FABRIK [18] 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[30]. 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 Light Detection and Ranging (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 a state-based replay. Here, we were inspired by previous work on analyzing user sessions in mixed reality [7]. The feature supports viewing within VR or the Unity3D editor and uses a self-hosted database to store all changes that occur during a recording.

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[27] PhotonEngine, `https://photonengine.com`, last retrieved on August 12, 2022

[28] Liam, `https://assetstore.unity.com/packages/3d/characters/humanoids/humans/liam-lowpoly-character-100007`, last retrieved on August 12, 2022

[29] FinalIK, `http://root-motion.com`, last retrieved on August 12, 2022.

[30] Chalet in France, `https://skfb.ly/6ZynL`, last retrieved on August 12, 2022

5.4 Conclusion

We presented *VRception*, a concept and toolkit for rapid prototyping of CR systems. We highlighted the great potential of *VRception* to not only overcome hardware limitations but also to enable remote collaboration and studies in the context of CR systems and interactions, thereby allowing broader research on the subject. The corresponding *VRception Toolkit* provides two different environments for prototyping CR systems – a VR application with a WYSIWYG editor and within Unity3D. We integrated a wide array of features, for example, primitive shapes or common objects that are often used in CR interaction research (e.g., displays and projectors). Further, we integrated avatars and corresponding IK as well as networking capabilities to allow for collaborative prototyping from remote locations. We argue that CR systems and interactions should be addressed further in future prototyping tools since they are becoming a fundamental type of interaction for AR and VR applications.

Summary of Key Functionalities

In this part, we introduced the tools and frameworks that make up our research infrastructure. In particular, we developed one middleware and two frameworks. In the following, we summarize the key functionalities for each of them:

***Key Functionality – VinteR*:** *VinteR* forms the streaming middleware that allows us to integrate data sources like optical tracking systems, databases, or applications. The acquired data is transformed into a canonical data format. The data is then streamed over the network to registered endpoints. Endpoints like VR applications can connect to *VinteR* and thereby can access the data stream in real-time. This allowed us to integrate novel sensors or applications with limited effort. We designed *VinteR* with two modes – a *Single Location Mode* and a *Distributed Location Mode*. Thereby, *VinteR* allows for the integration of various data sources and endpoints that are located in one or multiple locations.

***Key Functionality – Flyables Toolkit*:** We developed the *Flyables Toolkit* to position drones as haptic end effectors and input devices around a VR user. Therefore, the *Flyables Toolkit* steers a drone that is equipped with a haptic UI element to the location where a VR user expects to touch or grab the corresponding virtual UI element. We designed and developed five UI elements which can be 3D-printed and mounted on drones. In particular, we designed a *button*, a *knob*, a *joystick*, a *slider*, and a *3D mouse*. With that, *Flyables* have the advantage over VR controllers. For example, the user does not need to carry them all the time, which leaves their hands free. Further, *Flyables* communicate their affordance through their appearance and shape as they resemble well-known input devices.

***Key Functionality – VRception*:** With *VRception*, we presented a concept and toolkit for quick and easy prototyping of CR systems. By entirely simulating all levels of the reality-virtuality continuum in VR, our concept overcomes the asynchronicity of realities and eliminates technical hurdles. Our *VRception Toolkit* implements this concept to allow rapid prototyping of CR systems and easy remixing of elements from all continuum levels. We implemented a wide array of functionality to allow for the development of CR prototypes in Unity3D or directly in VR. We designed the *VRception Toolkit* with networking capabilities to allow for remote collaboration.

III

Avoiding Conflicts with the Real World

VR technology enables users to immerse themselves into digital worlds and experience them similar to being there. Recent technology improvements allow for higher display resolutions [467], more precise tracking [40], and low latency [160], while current VR devices, such as the *Oculus Quest*, can be operated standalone, enabling more mobility. As a result, the immersion into VR increases, and the real world receives less attention from VR users. In general, a high level of immersion is desired for VR experiences. However, neglecting the real world can lead to serious ramifications. When VR users' eyes and ears are occupied, for example, by HMDs, they get less aware of their surroundings. This can lead to unsafe situations such as VR users bumping into obstacles like walls. Especially, the visual mismatch between the virtual and the real world can lead to motion sickness [81]. This phenomenon makes users uncomfortable, similar to car- or seasickness. Additionally, the real world hinders users from traversing vast virtual worlds because their movement is blocked by physical obstacles like walls. Thus, allowing for natural locomotion can lead to conflicts between the real and the virtual world.

Prior work evaluated how users can move around in VR, similar to video games, typically with joysticks, controllers, or gamepads [59]. However, these approaches often result in motion sickness [269]. Therefore, point and teleport locomotion emerged as an alternative approach [135]. Yet, studies showed that such techniques limit immersion and potentially result in the disorientation of VR users [512, 310], and thus, reduce immersion.

Natural locomotion like walking has the potential to preserve the immersion of VR users [479]. On the one hand, exploring virtual worlds similar to the real world allows for high-quality virtual experiences familiar to most users. On the other hand, conflicts between the virtual and the real world are currently inevitable due to limited physical space. To tackle this, research has investigated natural locomotion approaches like redirected walking [408, 477]. These approaches deviate the user's physical walking path from the virtual one, thereby evading physical obstacles like walls. Further, the literature introduced approaches that utilize non-Euclidean spaces to utilize the physical space more effectively through virtual overlapping architectures [486, 516].

In this part, we extend this work by approaching these research topics from two directions – manipulating the user and manipulating the VE. First, we introduce our approach to enhance natural locomotion through redirected walking via EMS-based actuation of the VR user and answer the following RQ: **How can we reduce the physical space needed for natural locomotion in VR? (RQ 1)**

Second, we tend to the VE and investigate limiting factors of non-Euclidean architectures and corresponding illusions in VR. Specifically, we fit a large VE into a smaller physical space through a virtual overlap. As long as this overlap is not recognized by the VR user, we can utilize the physical space more efficiently. To make this illusion more convincing, we propose a distractor that shifts the attention of the user away from the VE. Here, we answer the following RQ: **How can we use the available physical space more efficiently for natural locomotion in VR? (RQ 2)**

This part includes the following two chapters:

- **Chapter 6:** In this chapter, we introduce an EMS actuation-based approach to decrease the physical space needed for redirected walking. Specifically, we actuate the user's leg with every step and thereby turn the leg. As a result, the user walks on a cyclic physical walking path while in VR the user walks straight. This approach is similar to previous approaches that shifted the vision of the VR users to the side to make them walk on a cyclic path [408, 477]. Our results show that combining EMS actuation with these vision shift approaches yielded less demand for physical space that is needed to realize infinite natural walking in VR. Precisely, we confined the space needed to a circle with an average radius of $5.48m$.
- **Chapter 7:** In this chapter, we investigate the influence of immersion on the perception of non-Euclidean spaces in VR. Therefore, we compared how users perceive the underlying overlapping architecture when being immersed in VR or when using traditional desktop PCs. Thereby, we discovered limiting factors that make users uncover the illusion. Our results show that a higher immersion lets participants recognize the virtual overlap more frequently. To counteract this, we propose a distractor in the form of a virtual minimap that can be used as a navigation aid in VEs. The minimap shows a non-overlapping environment, although it actually overlaps to a certain degree. Our evaluation showed that VR users recognized the overlapping environment after an overlap of 100% or when the environment exceeded the overlap further. Here, we outperformed previous approaches [486, 96].

Chapter 6

Reducing Physical Space Requirements Using Actuated Walking

This chapter is based on the following publication:

- **Jonas Auda**, Max Pascher, and Stefan Schneegass. "Around the (Virtual) World: Infinite Walking in Virtual Reality Using Electrical Muscle Stimulation". In: *Proceedings of the 2019 CHI Conference on Human Factors in Computing Systems*. Glasgow, UK, 2019.

Teaser Video | Presentation Video

(QR Codes are clickable in PDF)

Possible infinite VEs can be accomplished through actuated walking. Simply translating the position of a user based on controller input without the user moving in the real world often results in motion sickness [243]. Therefore, numerous approaches aimed at convenient locomotion methods ranging from jump-based locomotion [555], teleportation [135] that can even be triggered by foot [547], over adapting the VR narrative to the available physical space [307], to natural locomotion like walking in place [129], subtle reorientation during opportune moments [271] and redirected walking to steer the user away from obstacles like walls [477, 267, 270]. This further confines the physical space needed to traverse infinite VEs by natural locomotion. The illusion which is created by redirection techniques allows to decrease the physical space needed for natural walking but if applied too strongly the users' immersion breaks [436].

Previous research showed that redirected walking approaches reduce the physical space needed to a large extent by deviating the physical walking path of a VR user [479, 477, 484]. This is accomplished by shifting the user's view subtly to guide the user on a physical path that differs from that in the virtual world [37, 484]. By steering the user away from obstacles like walls, conflicts between the physical and the virtual world can be reduced.

Our work builds upon redirected walking techniques and previous research endeavors which effectively actuated the user's legs using EMS. For example, Pfeiffer et al. used EMS to actuate the legs of a user for navigation [386]. Through this actuation, they could navigate the user to a specific destination. To improve the running style, Hassan et al. used EMS to actuate the legs and thereby mitigated adverse effects when the foot strikes the ground [188]. Building upon this work, we built a system that actuates the leg muscles of a user in a way that the user's movement in the virtual world is decoupled from the movement in the real world. This allows the user to walk an infinite distance in the VR without requiring infinite physical space. With that, we answer the following RQ: **How can we reduce the physical space needed for natural locomotion in VR? (RQ 1)**

In this sense, we introduce an approach that combines vision-shifting techniques [408, 477] with EMS-based actuation to further decrease the physical space needed to walk endlessly in VR. First, we report on the design and implementation of our infinite walker system using EMS actuation to provide an infinite walking experience in VR. Second, we report on a user study in which we evaluated our system. Therefore, we combined EMS with the vision shift approach from the literature. We show that particularly the combination of shifting the vision and EMS outperforms both individual approaches, allowing users to walk in circles with an average radius of $5.48m$.

Figure 6.1: Left, the user walking in VR on a straight path. Right, the user's leg is rotated via EMS to the left. Through this actuation, the user walks in a circle (staged scene).

6.1 Related Work

In this chapter, we combine two related research areas for our actuated walking approach. First, we introduce approaches that allow for locomotion in VR. Second, we present work that employs electrical muscle actuation to create interactive systems.

6.1.1 Locomotion in Virtual Reality

Previous work introduced a wide array of approaches that support locomotion in VR. Virtual walking experiences were created using active re-positioning via treadmills, motorized floor tiles, or human-sized hamster balls [367, 322]. Further approaches for navigating through VR were based on the user's arm movement [378]. For instance, *ArmSwing* controls the movement of a user by the swing of their arms. The system navigates in the direction where the arms are swung, without any feet or head movement.

In contrast to approaches like walking in place [496] or teleportation [135], our approach focuses on natural walking. As physical space is a limitation for walking around freely in VR, different approaches were explored to tackle the issue. One of these approaches is vision shift. Vision shift is a method that shifts the user's virtual view by a certain number of degrees [37]. As a result, as soon as the users compensate for the shift by following the shifted view, they start to slightly redirect their walking direction in the real world. This technique of redirected walking enables natural locomotion through a VE which can be larger than the available real-world walking space. In general, vision shift plans a walking path through a VE and calculates the parameters for combining translation, rotation, and curvature gains of the walking redirection. To optimize the walking space, this technique changes the user's orientation in a way that the user is steered away from the boundaries of the physical space. Suma et al. found that employing subtle techniques for continuous or discrete reorientation results in fewer reported breaks of the participants' feeling of presence when the technique was applied optimally [484]. Ideally, the user would not notice the employment of redirection techniques. That would make the VR experience as immersive as possible. Steinicke et al. investigated the thresholds that make users detect the vision shift [477]. They found that a shift of 13° when walking 5 meters remains undetected by VR users.

6.1.2 Electrical Muscle Stimulation

EMS received an increased amount of attention from the HCI community [439]. EMS delivers a weak electrical signal to the muscles. The electrical signal elicits action potentials on motor nerves, which control muscle fibers. Stimulating these motor nerves leads to a contraction of the muscle fibers. This can be used in a variety of different research scenarios. For example, EMS was used in several applications such as supporting the user while drawing graphs [297], communicating the affordance of objects [295], or sharing emotions with a remote partner [190].

Additionally, EMS has been used to augment users while walking. Pfeiffer et al. showed the feasibility of manipulating the direction of a walking pedestrian by using non-invasive electrical muscle stimulation [386]. Two self-adhesive electrodes were attached to the participant's sartorius muscle. Other muscles of the human leg are inaccessible for electrode pads, because they are deeply embedded in tissue, or are partially located in intimate zones of the body. The contraction of the sartorius leads to the flexion of the hip and the knee joints. Based on their results of a possible direction change of the human leg up to an average of 15.9°/m, we developed an actuation system for a slight change of the direction the human is not recognizing. In the *FootStriker* project, Hassan et al. and Wiehr et al. also researched in the area of locomotion combined with EMS [188, 542]. They provide corrections to the user's gait while running.

To foster immersion in VR, EMS has been used to provide haptic feedback. Lopes, Ion, and Baudisch realized different virtual objects using EMS feedback [294]. Particularly, the system could increase realism in VR scenarios by providing an experience of impacting objects to its users.

6.2 Actuated Walking using EMS

The core idea in this chapter is to use EMS to create an unlimited walking experience in VR. While current methods either use room-sized setups (e.g., Cakmak and Hager [77]) or modify visual perception (e.g., vision shift [477]), we propose a partly on-body system that actuates the legs of the user. In particular, we slightly twist the legs outwards by actuating the *sartorius muscle*. This actuation causes the user to walk in circles instead of a straight line, similar to the approach of Pfeiffer et al. [386]. Such an actuation can be realized with one pair of electrodes per leg. We conducted a user study using this actuation approach for natural walking in VR. In our study, we solely actuated the left leg, but one could mirror our system and use it on both legs. In the following, we introduce the technical implementation of our infinite walker system that served as the prototype for our user study.

6.2.1 Infinite Walker System

Our system consists of the following components (see Figure 6.2): an *EMS Control Unit*, a *Step Detector*, an *optical tracking system* (see Figure 6.4), and a *VR scene* (see Figure 6.5).

Step Detector To apply EMS and turn the leg while in the air, we had to detect when the user lifts the left leg. Therefore, we developed the *Step Detector*. We used an *Interlink FSR 400 Short* force sensor which we placed underneath the user's left shoe (see Figure 6.2, *Step Detector*). We connected the force sensor to an *Arduino Pro Mini* and *SparkFun Bluetooth Mate Gold* board. The board was connected wirelessly via Bluetooth to a smartphone (i.e., *Samsung Galaxy S7*). The *Step Detector* sends an actuation command to the *EMS Control Unit* as soon as the leg of the user is in the air. The *EMS Control*

Figure 6.2: The *Infinite Walking* setup includes cameras and markers for optical tracking, an EMS Control Unit and Electrodes for actuating, a Step Detector for properly timed actuation, and an *Oculus Go* for displaying the VR scene (staged scene).

Unit then actuates the *Sartorius muscle*, and the leg is turned outwards. As soon as the foot hits the ground, the *Step Detector* sends a stop signal to the *EMS Control Unit*. We observed no human-detectable delay between the step detection and triggering of the actuation signal.

EMS Control Unit To actuate the leg of the user, we built an *EMS Control Unit* (see Figure 6.2, *EMS Control Unit*). We used a *STIM-PRO T-800* EMS device and the *Let-Your-Body-Move* toolkit [385] from Pfeiffer, Duente, and Rohs as the core element of the *EMS Control Unit*. We connected the control unit via Bluetooth to a smartphone (i.e., the same *Samsung Galaxy S7* as used

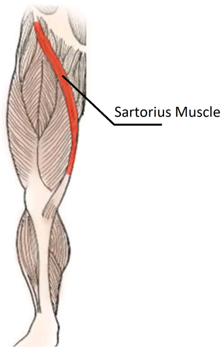


Figure 6.3: We use the sartorius muscle[32] which is the longest muscle in the human body. This muscle rotates the leg outwards.

by the *Step Detector*). When the *Step Detector* sends an activation signal to the smartphone, the signal is forwarded to the *EMS Control Unit* which actuates the leg. In particular, the electrical current is sent through two self-adhesive electrodes that we attached to the *Sartorius muscle* (see Figure 6.3) of the user and eventually leads to an outwards rotation of the leg (see Figure 6.1, right).

User Tracking To track the user in the entire tracking are (see Figure 6.4) and to transfer real-world motion into VR, we used seven *OptiTrack Prime 13* infrared cameras (see Figure 6.2, *OptiTrack Camera*) and *19 mm (3/4") M4 Markers* (see Figure 6.2, *OptiTrack Marker*) in a specific arrangement. The tracking data was streamed using our *VinteR* middleware (see Chapter 3). We took an off-the-shelf backpack and attached a rigid body consisting of tracking markers to determine the position and orientation of the user. We used the X and Z coordinates to track the position, as the X-axis and Z-axis built up the ground plane in most computer games. Furthermore, we used the rotation around the Y-Axis as the body orientation of the user. The position and rotation data is streamed by a tracking server to the *Oculus Go* (see Figure 6.2, *Oculus Go*) which runs the VR application (see Figure 6.5).

Virtual Reality Application For our evaluation, we developed a VR application using *Unity3D*. This application lets the user walk down a path between two rows of trees (see Figure 6.5). The user could only move forward

[32] Sartorius Muscle, Wikimedia (Public Domain), `https://commons.wikimedia.org/wiki/File:Sartorius.png`, last retrieved on August 12, 2022

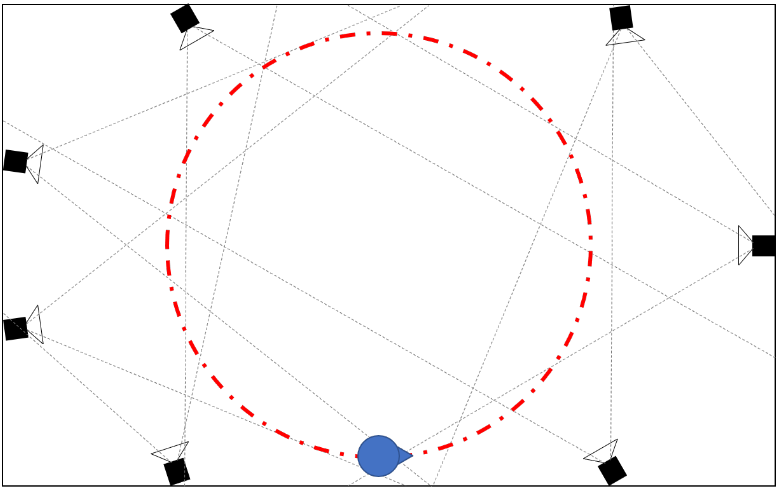


Figure 6.4: Overview of the *Infinite Walking* setup including the tracking cameras, the ideal walking path (red), and the participant (blue).

or back but not sideways. When the user was walking in the real world, the position data was streamed by *VinteR* to the VR application using WiFi. The position data was used to calculate how much a user moved forward to apply this translation to the position in the VE. Here, we transformed the circular movement of the user in the real world into a linear movement in VR. Because a turn in the real world would lead to a turn in the VE, we used the body orientation to re-adjust the viewing angle of the user. The rotation of the user in the real world was subtracted from the viewing rotation in the VE. This was necessary; otherwise, the user could not walk straight in VR while walking in a circle in the real world. As the *Oculus Go* has built-in sensors that enable the user to freely look around, it is still possible to look around in VR, but the body rotation of the user in the virtual world remains the same all the time.

6.3 Evaluation

To evaluate our infinite walker system, we conducted a user study. In this study, we compared our EMS-based approach to the vision shift approach from the literature [477]. We also evaluated a combination of both approaches (*Shift + EMS*). In the *EMS* condition, we used the infinite walker system to

Figure 6.5: VR scene with trees. This scene is shown on the *Oculus Go*. Movement of the real world is transformed to either forward or backward movement in VR.

actuate the left leg of our participants to make them rotate to the left while walking. In the *Shift* and the *Shift + EMS* condition, we shifted the view of the participants always to the left to make them walk a circle. We applied a vision shift with an angle of 8° to the left. This results in an arc that fits into the study room following the findings of Steinicke et al. [477]. Using the taxonomy from Suma et al., this redirection technique can be classified as a subtle, continuous reorientation [484]. In the last condition, we applied both – shifting the vision of our participants and actuating their left legs.

6.3.1 Study Setup

We conducted the study in an empty room with a tracking space of approximately $8m \times 8m$. We tracked the user's movement using an *OptiTrack Prime 13* tracking system. We attached tracking markers to a backpack worn by our participants (see Figure 6.2).

6.3.2 Participant and Procedure

We invited 12 participants to take part in our study (10 male, 2 female, and none other). Our participants were aged between 20 and 32 years ($M =$

$25.92, SD = 3.55$). All participants were either students or employees of the university. First, we informed each participant about the procedure of the study in both written material and personal instructions. In particular, we ensured that every participant met the requirements of using an EMS device, such as not being subject to high fever, having cardiac arrhythmia, or other heart conditions [439]. The participants ensured that they understood the procedure by signing a consent form. Next, we attached electrodes to the *sartorius muscle* (see Figure 6.3). For each participant, we individually calibrated the EMS signal to get a strong muscle actuation while not inducing pain or discomfort. After the preparation, each participant walked in each condition (*Shift*, *EMS*, and *Shift + EMS*) for 5 minutes in VR. We counterbalanced the three conditions using Latin square. Throughout the study, an experimenter made sure that the participants did not collide with any obstacles such as walls. After walking for 5 minutes in one condition, we asked the participants to stop walking and to fill out the User Experience Questionnaire (UEQ) [272] and the Simulator Sickness Questionnaire (SSQ) [238]. After filling out the questionnaires, we continued with the next condition. After each participant walked in each condition, we conducted semi-structured interviews.

6.3.3 Results

In the following, we present the results of our evaluation.

Data Preparation

Since we captured the movement data of each participant, we first prepared the data for further analysis. First, we smoothed the recorded data. As we attached the markers for the tracking system to a backpack, the markers were shaking while the participants were walking. To properly analyze the data, we smoothed the data by applying a sliding window mean filter. Sometimes, our participants reached the boundaries of our tracking system, we stopped them and manually turned them around. We excluded these turns from our data set. As a result, our participants' walking paths were divided into several slices. For each slice, we fit a circle into every 100 samples of the recorded data. We chose 100 samples as the sampling rate of the tracking system was $100Hz$ too. Hence, we obtained one-second intervals of data. This corresponds to around 1-2 steps of our participants. If there were less than 100 samples left, we did not further consider these samples for further analysis. Finally, we averaged

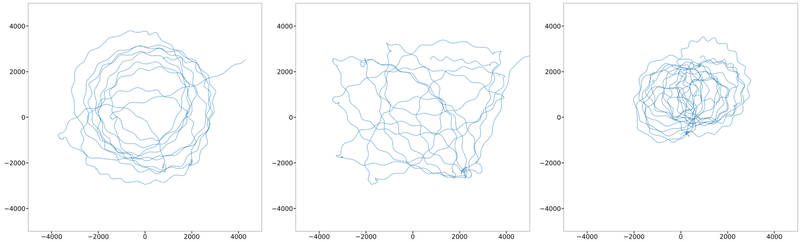
Participant	Shift		EMS		Shift + EMS	
P1	14.98	11.40	11.57	10.39	7.65	7.85
P2	3.49	5.22	12.13	12.11	4.52	4.09
P3	1.37	1.19	1.53	3.92	1.24	1.16
P4	3.90	3.73	10.26	12.65	5.99	6.55
P5	1.64	1.17	2.87	3.05	1.54	1.68
P6	2.22	3.37	11.28	11.34	1.39	0.35
P7	3.02	3.52	6.66	8.87	1.34	0.55
P8	11.12	10.31	12.61	11.84	11.05	9.46
P9	17.07	11.95	15.42	12.88	16.50	10.13
P10	0.46	0.16	3.80	5.20	0.59	1.69
P11	7.22	7.94	8.45	10.97	5.88	7.56
P12	9.89	10.22	7.86	9.28	8.03	7.44
M SD	6.37	5.39	8.70	4.12	5.48	4.62

Table 6.1: Mean walking radii (and the corresponding *SD*) in *m* for each participant in all three conditions.

the resulting circles for each participant in each condition to obtain individual radii.

Movement Radii

First, we compared the different movement radii of the three conditions (see Table 6.1). The results show that *Shift + EMS* ($M = 5.48m$, $SD = 4.62$) outperformed *EMS* ($M = 8.70m$, $SD = 4.12$) and *Shift* ($M = 6.37m$, $SD = 5.39$) when we applied these techniques individually. A repeated measures ANOVA revealed statistically significant differences, $F(2,22) = 6.223, p = .007$. Follow up Bonferroni-corrected post-hoc tests showed that *Shift + EMS* results in statistically significant smaller radii compared to *EMS*, $t(11) = 3.456, p = .015$. All other comparisons could not reveal statistically significant differences. In Figure 6.6, we plotted the walking paths for one particular participant (P7) in all three conditions.



(a) P7, Vision Shift (b) P7, EMS (c) P7, Vision Shift + EMS

Figure 6.6: The walking paths of one exemplary participant (P7) while walking in VR using *Vision Shift* (left), *EMS* (center), and *Vision Shift + EMS* (right). The plotted area covers $10m \times 10m$.

User Experience

The UEQ revealed that the overall user experience was highest for the *Shift + EMS* condition ($M = 1.25$, $SD = 1.06$) followed by *EMS* ($M = 1.24$, $SD = 0.93$). The *Shift* condition received the overall lowest ratings ($M = 0.96$, $SD = 0.98$). Given the small sample size due to one sample per condition and twelve participants in total, we did not assume normal distribution of our data and hence, applied non-parametric tests. A Friedman test could not show statistically significant differences between these conditions, $\chi^2(2) = 1.756$, $p = .416$. Looking at the hedonic quality, *Shift + EMS* ($M = 1.54$, $SD = 1.30$) outperformed both, *EMS* ($M = 1.22$, $SD = 1.56$) and *Shift* ($M = 0.98$, $SD = 1.55$). A Friedman test showed statistically significant differences between these conditions, $\chi^2(2) = 6.513$, $p = .039$. Post-hoc Bonferroni-corrected Wilcoxon Signed Rank tests showed that *Shift + EMS* was rated statistically significantly better than *Shift*, $Z = 2.448$, $p = .042$. All other comparisons could not show any statistically significant differences ($p > .05$). For the pragmatic quality, *EMS* performed better ($M = 1.25$, $SD = 0.83$) compared to *Shift + EMS* ($M = 0.96$, $SD = 1.10$) and *Shift* ($M = 0.94$, $SD = 1.02$). A Friedman test did not show any statistically significant differences, $\chi^2(2) = 0.439$, $p = .803$.

Simulator Sickness

The SSQ revealed the effects of our conditions on oculomotor sickness and nausea. For nausea, the *Shift* condition performed worst ($M = 2.08$, $SD = 2.15$) followed by *Shift + EMS* ($M = 1.83$, $SD = 2.79$). Here, the *EMS* condition performed best ($M = 1.50$, $SD = 1.31$). A Friedman test could not show any statistically significant differences, $\chi^2(2) = 1.000$, $p = .607$. The results of the oculomotor sickness part showed that *Shift* performed worst ($M = 3.75$, $SD = 2.63$), followed by *Shift + EMS* ($M = 3.17$, $SD = 3.81$) and *EMS* ($M = 2.33$, $SD = 1.92$). Again, a Friedman test could not show any statistically significant differences, $\chi^2(2) = 4.974$, $p = .083$.

Participants Feedback

We conducted semi-structured interviews after our participants finished walking in all three conditions. We asked the participants about their walking experience in VR and their general perception of the different walking experiences.

Immersion For the two conditions – *Shift* and *Shift + EMS* – in which the view was shifted, 8 out of 12 participants reported that they recognized the shift ("*I felt that the vision was shifted to the left.*" (P1). Further, one of them commented that it "*felt unsafe and shaky with the vision shift*" (P8). Another participant complained about the intensity of the vision shift and stated that "*the image shifted really strong - it was difficult to walk*" (P10). In contrast, other participants stated that they "*did not really feel the EMS*" (P8) and that "*walking with only EMS was pretty normal, straight, and easy to follow*" (P2).

Cognitive Demand For *Shift + EMS*, 4 participants reported that they received the best support during walking and that the demanded focus on the walking path was the lowest. "*While walking with shifted vision and EMS, I recognized that I was walking in a circle because no one stopped me. It was less challenging than in the other conditions.*" (P6). Our participants also mentioned that "*EMS was supportive during walking*" (P3) and "*helped walking in a circle*" (P4). They further added that they "*had not to focus all the time while [...] walking*" (P6). This indicates that EMS induced a lower cognitive load. When the vision was shifted, more focus was demanded by the participants; "*Shifting the view was somehow disturbing because one had to adjust to the view and walk the circle. One had to focus on that*" (P6). Using *Shift + EMS* further helped to reduce the demand for focusing on the path; "*With [vision] shift only, I had to focus to follow the path. I could never relax. With EMS I had not to focus that much. With Shift and EMS I was not re-adjusted once*" (P7). Contrary, EMS can be disturbing or tedious. P7 stated that "*at the beginning EMS was a little bit unpleasant. Not painful but inconvenient. You know that it is triggered when you lift the leg. But it is still* *surprising.*" In this sense, P8 mentioned that "*walking [with EMS] became more and more uncomfortable because I got tired.*"

6.4 Discussion

Further decreasing the physical space needed to walk infinite in VR is still one key challenge when developing highly immersive VR applications. With the combination of shifting the view of the user and actuating the leg during walking, we could decrease the space needed for redirected walking. This yielded an infinite walking experience in VR (see Figure 6.6). Although the difference in the radii seems not too impressive, it can make a difference regarding the deployment of a VR system in certain areas. For example, a room could be on average around $33m^2$ smaller for *Shift* + *EMS* ($\pi * (5.48m)^2 = 94.3m^2$) compared to only *Shift* ($\pi * (6.37m)^2 = 127.5m^2$) in the case of our setup.

Looking at the different average radii of each participant, we observed variations in size. One reason is that not all users respond the same way to an EMS signal. This is common in EMS studies (e.g., due to different muscle strength or skin thickness [108]). Also, some participants reacted to the vision shift stronger than others. Some of them stated that they did not really recognize the shift, whereas others suspected that the vision was slightly shifted. P10, for example, stated during the interview that it was difficult to walk with a shifted vision. Hence, P10 walked slowly and in a very small area resulting in smaller radii.

Our participants stated that they focused less on how they walk in VR when *EMS* was used in addition to the vision shift. Thus, we can derive several application scenarios. For example, *EMS* could be dynamically applied on-demand with respect to the virtual world. Here, we could guide the user back to the middle of the room if the bounds are reached.

When looking at the mean radii of all three conditions, the results show that the combination of *Shift* and *EMS* outperforms the two single approaches. This was also supported by the results of the UEQ. When we compared EMS to the vision shift approach, the results were mixed. While the overall radius was lower in the *Shift* condition compared to the *EMS* condition, our participants mentioned throughout the interviews that shifting the vision was quite conspicuous. Here, a more subtle vision shift would result in a larger average radius but also in a higher UX. Therefore, we state that both approaches are highly dependent on the chosen intensity. In future locomotion systems, both approaches need to be adjusted to the available room size.

6.5 Conclusion

In this chapter, we explored a novel way of providing an infinite walking experience for VR users. We showed that by applying EMS to the *Sartorius muscle*, we can actuate the leg in a way that the movement in the real world is decoupled from the movement in the virtual world. Thus, a user can walk straight in the virtual world but walks in circles in the real world. Comparing the results with a vision shift approach, as well as a combination of both, we found that the combination yields advantages for the user. While we focused on walking straight, future work could investigate how EMS can be used to enable users to freely walk in VR. As soon as users approach obstacles (e.g., walls), EMS could actuate the users in a way that they start walking in a circle and thereby do not encounter limiting obstacles that impact their experience negatively.

Chapter 7

Improving Space Utilization Through Non-Euclidean VR

This chapter is based on the following publications:

- **Jonas Auda**, Uwe Gruenefeld, and Stefan Schneegass. "If The Map Fits! Exploring Minimaps as Distractors from Non-Euclidean Spaces in Virtual Reality". In: *Extended Abstracts of the 2022 CHI Conference on Human Factors in Computing Systems*. New Orleans, LA, USA, 2022.

Presentation Video
(QR Codes are clickable in PDF)

In the previous chapter, we enhanced redirected walking by manipulating the VR user. Thereby, we reduced the space needed for natural locomotion. We did this by employing additional hardware to actuate the user's leg via EMS. Now we tend to approaches that manipulate the VE. Here, our approach does not rely on hardware additions. In this chapter, we confine the physical space needed for locomotion through non-Euclidean spaces or in other words, VEs that can not exist in reality as they violate the Euclidean laws of 3D space. First, we investigate different levels of immersion and their effect on the perception of non-Euclidean VEs. Next, we employ a virtual minimap as a distraction from the non-Euclidean VEs. As our approach can be implemented solely in software and therefore works on any VR device.

Non-Euclidean spaces offer great potential for natural locomotion in VR [486, 516, 517]. To further confine the physical space needed for exploring large VEs, previous approaches employed overlapping virtual spaces to fit large VEs into a smaller physical space. In this context, Suma et al. introduced the term *"impossible spaces"* to reflect the fact that such overlapping architectures are impossible to realize in the physical world [486]. These spaces and the combination with other means such as distractions (i.e., distractions that help to hide clues that would make VR users recognize that there is an overlap) enable interesting approaches to further reduce the need for physical space for natural walking in VR [96]. Hence, we employ such means to answer the following RQ: **How can we use the available physical space more efficiently for natural locomotion in VR? (RQ 2)**

In this chapter, we investigate how a higher level of immersion can lead to the uncovering of the underlying non-Euclidean architecture of a given VE. Further, we propose possible means to distract the user from the non-Euclidean architecture, and thus, preserve immersion by strengthening the recognition threshold of the illusion. To investigate the effects of different levels of immersion on the perception of non-Euclidean VEs, we compare locomotion in immersive VR to locomotion on desktop PC-based setups. We found that a higher immersion helps users to uncover the overlapping architecture of the VE more quickly due to the mismatch between the visual and the motor-sensory perception. For example, when the number of steps does not match the size of the VE, the non-Euclidean environment is recognized. To counteract this, we employed a minimap as a distractor from the non-Euclidean VR environments or as a reassurance of the same. Our minimap shows a non-overlapping VR environment, while in fact, it overlaps to a certain degree. We opted for a minimap as it is easy to implement and can be used in any VR experience but at the same time is not fully researched. To explore our approach, we conducted a user study with twelve participants. Our participants traversed virtual rooms using a VR-HMD, natural walking, and our minimap. We increased the overlap of our rooms in five different levels (i.e., virtual rooms) to uncover the threshold until the overlap was recognized. Our results show that our participants uncovered the overlap of the virtual rooms when it was at 100% or extended even further. Our findings can support designers and developers in implementing more convincing non-Euclidean spaces in VR, and thus, further reduce the physical space needed for natural locomotion.

7.1 Related Work

Non-Euclidean spaces – often referred to as *“impossible spaces”* in the context of VR [486] – are virtual worlds that cannot exist in reality as they violate the Euclidean geometry of 3D space. First explorations of such impossible spaces demonstrated that virtual rooms could overlap to a certain degree (e.g., see Figure 7.5a) and thereby enlarge the usable virtual space without users noticing [486, 516, 517]. This has an impact on immersion and presence. If the illusion is believable, immersion is preserved. If the illusion breaks, immersion is reduced.

7.1.1 Immersion and Presence

Immersion describes the sensory fidelity a VR system provides and therefore, is dependent on the underlying VR technology [61]. Thus, immersion is objective as it is dependent on the technology. Presence describes the subjective psychological response of a user to a VR system. Often, presence is described as the feeling of *"being there"*. It is dependent on the user’s perception and therefore, is subjective. Hence, immersion and presence should be maximized to provide users with a sophisticated VR experience. We introduced further details on these fundamentals in Section 2.2.2.

The holy grail of VR is to provide both, a high immersion and a high presence. In the context of natural locomotion, we face a constant conflict between immersion and restrictions induced by the real world. Natural locomotion increases immersion and presence [458] but at the same time is limited by the available physical space. Various approaches from previous research enable VR users to perceive endless worlds in limited physical space by natural walking using illusions and distractions [477, 267, 270, 30]. However, when these illusions break the immersion is reduced [436]. When presence is limited due to conflicts with the real world, interaction possibilities shrink. Therefore, it is important to employ illusions that improve immersion and presence in all kinds of physical environments. This research gap is constantly filled with new approaches that employ non-Euclidean architectures in VR. In the following, we introduce these approaches and position our research accordingly.

7.1.2 Impossible Spaces

The term *"impossible spaces"* in the context of VR was introduced by Suma et al. in 2012 [486]. In their pioneer work, they maximized the exploration of VEs by natural walking through self-overlapping virtual rooms. As an example, one can consider two rooms in VR connected through a corridor. We can create a virtual overlap of these rooms without the two rooms visually intersecting in VR, but in reality, these rooms share parts or the physical space available depending on how much they overlap virtually. Suma et al. investigated different levels of overlapping virtual rooms (0%-75%). Their evaluation showed that the rooms were judged as being impossible above an overlap of 55.57%. In particular, they showed that small virtual rooms ($3.66m \times 7.32m$) can overlap by around 56% until users recognize the overlapping, and for larger virtual rooms ($9.14m \times 9.14m$) by up to 31%.

Rothman and Warren used a similar approach to investigate how humans gain spatial knowledge [423]. They created two virtual maze environments. One contained wormholes that teleported users between different locations while the other did not. They compared how users build spatial knowledge of these environments after they have traversed them. Rothman and Warren found that users tend to develop a labeled graph of the environment rather than a global Euclidean map. Such graphs contain approximate local metric information but are geometrically inconsistent. This emphasizes the inability of humans to keep track of the exact Euclidean structure of space, and thus, it can be used to fit large virtual worlds into limited physical space.

Vasylevska and Kaufmann investigated the impact of various layouts of self-overlapping rooms in VR on the perception of VR users [516]. Different sequences of self-overlapping rooms with a different number of turns, varying door positions, and symmetric or asymmetric walking paths. They designed different layouts of virtual rooms and let participants explore them using natural walking. They found that the overlap of rooms was stronger perceived in right-angled layouts than in curved layouts. Based on the combination of impossible spaces and change blindness, Vasylevska et al. introduced a redirection technique called flexible spaces [517]. Dynamic layout generation enables unrestricted natural walking in large VE through the procedural generation of room layouts that fit into the tracking space. Thereby, they abandoned detailed spatial knowledge and extended the possible overlap of up to 100%. To maintain the integrity of Euclidean geometry, Vasylevska et al. used change blindness. They changed the layout of the VE depending on the user's position and rotation to prevent the user from noticing.

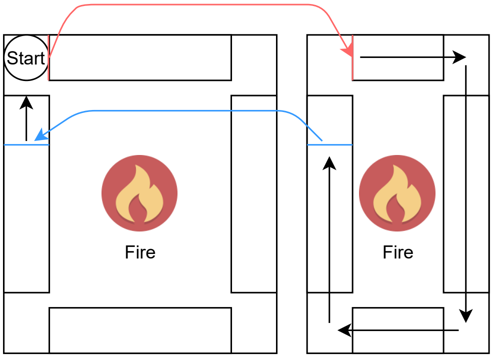


Figure 7.1: Layout of the rooms used in our study. The left room is the start room of the study. The room on the right is the first room the user gets teleported to in our study. The red or blue lines are the positions of the portals and their corresponding counterpart in the other room.

Ciumedean et al. used a task as a distraction incorporated into the VR narrative to hide its overlapping architecture [96]. Through the distraction, an overlap of up to 60% remained undetected. Without the distraction, the overlap was discovered at 40%. This shows the potential of distractions to further hide the overlapping architecture from the VR user, and thus, enhancing natural locomotion.

In the following sections, we introduce our approach to enhancing non-Euclidean VR using a distractor. But first, we take a step back and investigate how different levels of immersion influence the perception of non-Euclidean VEs. This is important to identify which factors lead to the recognition of non-Euclidean VE through the user and how we can counteract this.

Then, we introduce and evaluate our approach to a distractor similar to approaches that use a task-driven distraction [96]. Therefore, we developed a visual distractor in the form of a minimap. This minimap renders a non-overlapping environment to its users while, in fact, the environment overlaps to a certain degree.

7.2 Influence of Different Levels of Immersion

To investigate the effects of different levels of immersion on the perception of non-Euclidean spaces in VR, we implemented a self-overlapping VE in *Unity3D*. We compiled two versions of the same environment, one deployed for a desktop PC and one that we deployed on a VR-HMD. We used these VR applications to conduct a user study with 24 participants. In the following, we introduce our implementation in greater detail.

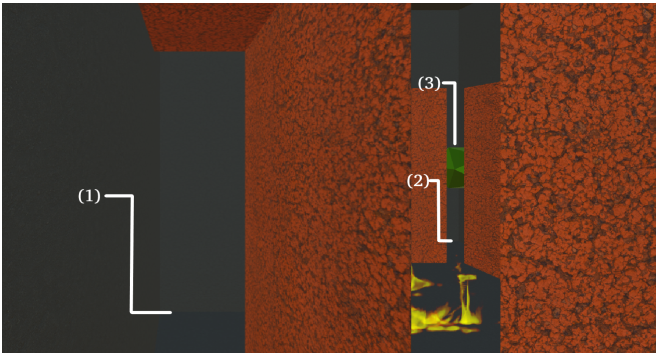
7.2.1 Implementation of the Non-Euclidean Space

We built a virtual rectangular room that measured $5m \times 4.5m$ (see Figure 7.1). We choose this size as it fits into our lab. At the borders, we placed tunnels with a width of $0.75m$ that align with the outside walls. In the middle, we placed a fire. The fire prevents the user from walking across the room. The red or respectively blue arrows in Figure 7.1 indicate portals. The users start in the left corner of the room, facing the first portal (see Figure 7.1, start). By entering the first portal, the user is teleported to the right room (see Figure 7.1, red arrow). This room is constructed exactly like the first room but has a smaller width. The user can continue to walk through the tunnels. When reaching the blue portal, the user is teleported back to the first room (see Figure 7.1, blue arrow). Simply translating the user into the other room would lead to immediate recognition of the differently sized second room and therefore, the portal renders the view into the second room on top of its surface to hide the fact that teleportation occurred. In Figure 7.2a, the view through the portal is shown. One can see the different lengths of the tunnels from the top view (see Figure 7.2b).

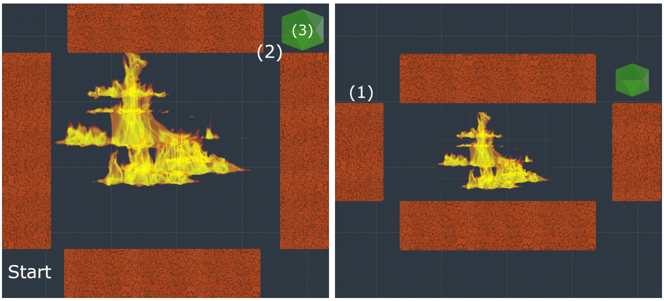
7.2.2 Evaluation

In the following, we introduce the study design, task, procedure, apparatus, and participants of our user study.

Study Design For our investigation, we decided to form two groups of participants. Each group traversed either the immersive VR environment or



(a) View from the start in the first room.



(b) Top View: First room and second room with shorter tunnels.

Figure 7.2: The VR environment which is viewed from the start in the first room (a) and from above (b). The user faces towards a portal. The portal renders the view into the second (shorter) room. (1) The edge of the wall to the floor at the end of the shorter tunnel. (2) The edge of the end of the tunnel in the current room. Comparing (1) and (2) shows that the edges do not align and suggest a violation of Euclidean geometry. (3) A green item on the other side of the room is visible across the diagonal.

the Desktop Environment (DE). We opted for a between-subject design to prevent participants from potentially uncovering the non-Euclidean space in one condition and then would be aware that they are facing an illusion in the other condition. We call these two groups the *VR group* and the *DE group*, respectively. We configured our application for both the VR and the *DE group* to have nine levels of ever-decreasing tunnel-length (independent variable, see Table 7.1).

Room No.	Width	Length	Length of Tunnel
Start	5 m	4.5 m	3 m
1	5 m	3 m	3 m
2	4.75 m	3 m	2.75 m
3	4.5 m	3 m	2.5 m
4	4.25 m	3 m	2.25 m
5	4 m	3 m	2 m
6	3.75 m	3 m	1.75 m
7	3.5 m	3 m	1.5 m
8	3.25 m	3 m	1.25 m
9	3 m	3 m	1 m

Table 7.1: Independent variable: The dimensions of the rooms and the length of tunnels (in meters) used in the study.

Task To motivate walking through the VE, we developed a task for our participants to fulfill. They had to extinguish the fire that was placed in the middle of the virtual room (see Figure 7.2). Therefore, they had to collect 18 items which we placed across the rooms. When the participants collected all the items, the fire was extinguished, and the task was fulfilled. To elicit walking through the tunnels, we placed items diagonally on the other side of the room (see Figure 7.2, green item (3)). These items were visible to the participants from the start position, but the fire prohibited them from walking across the room. Using the tunnels was the only option to get to the item. When the participants reached the item, another one appeared diagonally on the other side of the room, at the position where the participants started. Hence, they must return to the start to pick up the next item. Then they could look across the room and see the next item for the next lap. These steps were repeated to make them walk nine laps in total. When they collected all items, a sprinkler was activated that extinguished the fire.

Procedure At the beginning of the study, we informed the participants about the study procedure, and they gave us informed consent. We recorded demographic data and introduced them to the task. After we confirmed that they understood the task, we immersed them in VR or situated them in front of a PC, depending on their study group. When the participants found themselves at the start of the VE, we told them to look across the room to spot the first item they should collect. Then they were free to begin traversing the VE to fulfill the task. After the participants completed the task, they filled out the SSQ [238] and the PQ [549]. We concluded the study with semi-structured interviews. Each participant took approximately 20 minutes to complete the study.

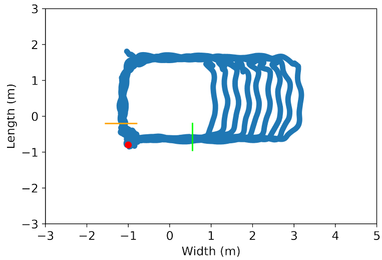
Apparatus We reserved an empty room at our lab measuring $6m \times 3.5m$ for the *VR group*. We deployed our non-Euclidean VR application on a mobile VR-HMD (*Oculus Go*). We used an *OptiTrack 13W* to track the participants' movement across the room and to move them in the virtual world. This was necessary because the *Oculus Go* has no inside-out tracking capabilities. The movement data was streamed to the *Oculus Go* using our *VinteR* middleware (see Chapter 3). For the *DE group*, we prepared a PC with an *Intel i7* CPU, an *Nvidia 1080Ti* GPU, and 32 GB RAM running our non-Euclidean *Unity3D* application. The monitor is a $24in$ display with a resolution of 1920×1080 at $60Hz$. The participants used a standard keyboard and mouse to interact with our application. We also used this PC to render the VR environment and streamed it using *AL VR*[33] on the *Oculus Go* to ensure a similar graphical experience on both the VR-HMD and the PC.

Participants We recruited 24 participants in total (female=6, male=18, other=0). Because we conducted a between-subject study with 12 participants in the *VR group* and 12 in the *DE group*. The *VR group* consisted of four females and eight males with an age span between 22 and 57 years ($M = 27.33$, $SD = 9.34$, $IQR = 6.0$). The *DE group* consisted of ten males and two females with an age span between 19 and 37 years ($M = 23.75$, $SD = 4.25$, $IQR = 2.0$). We aimed for age-balanced groups.

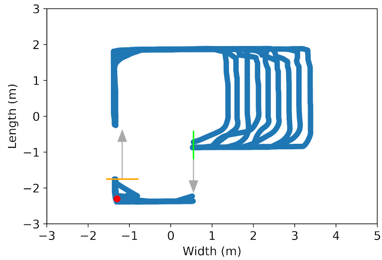
7.2.3 Results

In the following, we present our results. First, we report an overview of the recorded movement data together with the qualitative feedback we gathered from the semi-structured interviews at the end of the study. We report descriptive statistics, i.e., mean (M), standard deviation (SD), and interquartile range (IQR). Given the smaller sample size, we assumed non-normal distribution of our data and performed non-parametric tests.

[33] ALVR on GitHub, `https://github.com/polygraphene/ALVR`, last retrieved on August 12, 2022



(a) Virtual Reality (VR)



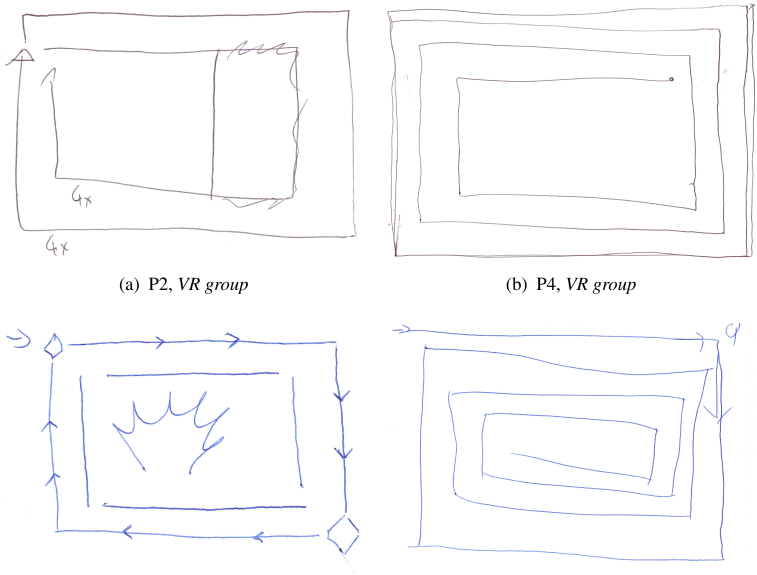
(b) Desktop Environment (DE)

Figure 7.3: Example plots (top view) of the participants walking in our VE. (a) The walking path of a participant of the *VR group*. Each lap, the route lengths decreased due to the teleportation between the original room and 9 additional rooms that decreased in size. (b) The walking path of a participant of the *DE group*. There is a gap in the walking path due to teleportation because we solely recorded the virtual movement.

Walking Paths We recorded movement data of our participants in the VE and plotted an exemplary trajectory view of the walking path of one participant [7] (see Figure 7.3). Here, we can observe how the walking distance shrinks each lap due to the consecutive teleportation into 9 smaller rooms. The orange and green lines indicate the positions of the first and the second portal, respectively. We calculated the distance traveled by the participants based on the recorded movement data and let the participants estimate the covered distance.

Distance traveled The *VR group* covered an average distance of 101.56m ($SD = 6.60, Med = 100.22, IQR = 9.25$). Similar the *DE group* covered a distance of 104.57m ($SD = 6.73, Med = 103.91, IQR = 8.23$). We let the participants estimate their covered distance. The *VR group* estimated the average distance to be 74.08m ($SD = 43.55, Med = 55.00, IQR = 42.50$) and the *DE group* estimated an average distance of 127.92m ($SD = 108.54, Med = 65.00, IQR = 177.50$). A Mann-Whitney test did not reveal a significant difference between both groups for the estimated walking distance ($W = 63.5, p = 0.639$).

Naturalness of Locomotion We asked both groups to rate the naturalness of locomotion inside the VE on a seven-point Likert scale, where 1 was totally unnatural and 7 totally natural. The *VR group* rated the naturalness



(a) P2, *VR group* (b) P4, *VR group*

(c) P21, *DE group* (d) P18, *DE group*

Figure 7.4: Drawings of the VE from the *VR group* and the *DE group*.

of locomotion on average with 5.42 ($SD = 1.04, Med = 6.00, IQR = 1.00$). They all emphasized that locomotion felt natural and did not mention any negative influencing factors. We also let the *DE group* rate the locomotion although they have used a PC. The *DE group* rated locomotion with 3.58 ($SD = 1.32, Med = 3.50, IQR = 1.25$). A Mann-Whitney test did reveal a significant difference between both groups for the naturalness of walking ($W = 122.5, p = 0.003$).

Participants from the *DE group* stated that the movement felt unreal because one does not move in front of the display and that they were missing vibrations or other haptic feedback.

Perception of the Virtual Environment We asked the participants to draw the path they had walked in the VE on a blank paper (e.g., Figure 7.4).

In the *VR group*, eight out of twelve participants did not notice that the size of the VE changed. One participant mentioned that it felt like the fire got bigger when looking across the room while collecting the items. The remaining participants noticed that the size of the room changed during walking. One participant mentioned that after four laps, the room got smaller once and then was square (see Figure 7.4a). Several additional participants said that after four to five laps, the room size changed. Further, participants stated that the size of the world shrunk in a spiral-like way (e.g., see Figure 7.4b). The participants stated that they visually perceived that the room got smaller. Besides the visual perception, the number of steps the participants took hinted at the room getting smaller. Through the interviews, we also confirmed that none of the participants in the *VR group* recognized being teleported.

Nine out of the twelve participants from the *DE group* did not notice the resized room. Eight participants perceived the room as rectangular (e.g., see Figure 7.4c). Three stated that the environment was square. Only one participant noticed that the size of the room changed each axis resulting in a spiral-like walking path (see Figure 7.4d) while another noticed that the fire seemed to get larger during the study. Several participants felt disturbed and claimed that the inner and outer walls of the tunnel did not seem to be parallel and that something about the environment felt wrong, but they could not identify the cause. Furthermore, they reported being distracted without specifying a reason or they stated that the proportions of the rooms felt wrong and created strange impressions. One participant recognized the differently sized rooms by traversing the VE sideways. Thereby, the participant faced the middle of the room at all times. During the teleport, the participant could see the environment changing. This participant was one of two participants in this group who noticed the teleportation. The other participant who noticed the teleportation stated that something was wrong with the rooms and mentioned that a teleport could be a possible explanation.

Presence After exiting the VE, both groups filled out the PQ [549]. We calculated the scores for each group. The *VR group* overall scored a higher presence than the *DE group*. Specifically, for *Realism*, the mean for the VR group was 36 ($SD = 5.58, Med = 36.50, IQR = 6.25$) while for the *DE group* the mean was 26.08 ($SD = 7.46, Med = 26.50, IQR = 10.25$). The *Possibility to act*) was rated with a mean of 24.25 ($SD = 2.22, Med = 24.50, IQR = 4.00$) for VR and 20.58 ($SD = 4.54, Med = 22.00, IQR = 6.25$) for DE. For *Quality of the Interface*, we observed for the *VR group* a mean of 15.58 ($SD = 5.00, Med = 16.50, IQR = 7.00$) and for the *DE group* a mean of 15.00 ($SD = 3.33, Med = 15.50, IQR = 3.25$). The *Possibility to Examine* was rated higher by the *VR group* ($M = 18.00, SD = 1.76, Med = 18.00, IQR = 2.25$) than the *DE group* ($M = 15.08, SD = 3.18, Med = 15.50, IQR = 3.25$). For *Self Evaluation of Performance* the mean score of the *VR group* was 11.92

($SD = 1.73, Med = 12.00, IQR = 2.00$). For the *DE group*, we observed a mean of 10.42 ($SD = 2.81, Med = 10.00, IQR = 3.25$). Overall the evaluation of the PQ shows that the level of presence was rated higher by the *VR group* than by the *DE group*. But in some categories, the ratings of the *DE group* were marginally lower than the *VR group*.

Simulator Sickness Questionnaire In the following, we present the scores of the SSQ [238] for our two groups. For *nausea*, the *VR group* scored on average $M = 2.08$ ($SD = 2.60, Med = 1.00, IQR = 2.25$) while the *DE group* showed marginal signs of *nausea* ($M = 0.75, SD = 1.01, Med = 0.00, IQR = 1.25$). For *oculomotor*, the SSQ also revealed a higher value for the *VR group* ($M = 2.00, SD = 2.68, Med = 2.00, IQR = 2.25$) while the *DE group* scored for *oculomotor* ($M = 1.42, SD = 1.61, Med = 1.00, IQR = 0.50$). Mann-Whitney tests did not reveal significant differences between both groups for *nausea* ($W = 93.5, p = 0.198$) or *oculomotor* ($W = 78.5, p = 0.720$).

7.2.4 Discussion

We compared walking in non-Euclidean VEs, which were traversed by our participants on either a DE using a mouse and keyboard or by natural walking in VR. This allowed us to assess the influence of different levels of immersion on the perception of the non-Euclidean VE.

We invited 24 participants to our study. We split them into two groups of 12 people. The first group, we called the *VR group*, traversed the VE by natural walking wearing an HMD. The second group used a DE with a mouse and keyboard. The VE consisted of a room with tunnels aligned to the walls and an impenetrable fire in the middle. The tunnels formed a lap around the fire. This ensured that the participants could only traverse the environment using the tunnels. The objective for the participants was to walk several laps through the tunnels to collect a certain number of items. Each lap, we teleported the participants into smaller virtual rooms with shorter tunnels without their knowledge. The tunnels were shorter from the inside than they were looking from the outside. This made the environment non-Euclidean and therefore shrunk the distance to cover with each lap. After they had traversed 9 laps and collected all items, the fire was extinguished, and the task was fulfilled.

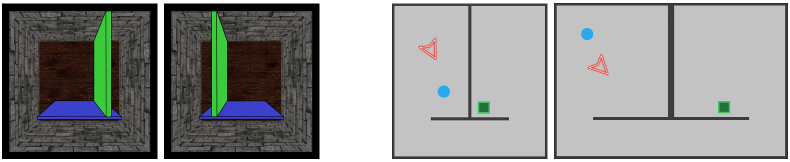
We calculated the covered distance and compared it to the distance estimated by our participants. The *VR group* estimated their covered distance ($74.08m$)

lower than the *DE group* (127.92m). This is in line with the literature suggesting that in VR, people tend to underestimate the perceived distance [354]. In fact, the *VR group* covered an average distance of 101.56m ($SD = 6.60$) while the *DE group* covered an average distance of 104.57m ($SD = 6.73$).

Regarding the recognition of the non-Euclidean environment, we found that a higher immersion through VR enabled the participants to perceive certain mismatches while traversing the environment. Participants of each group recognized changes in the environment but had difficulties articulating what exactly had changed. As the *VR group* could use natural locomotion to traverse the VE, they could use sensory-motor coupling to find a mismatch between the virtual world and the sensory stimuli from walking. In particular, the number of steps could be counted by the participants when they walk through the environment. This increased suspicion by the *VR group* compared to the *DE group* which was not naturally moving during the study. The lack of sensory perception is one factor that makes the non-Euclidean illusion harder to detect.

In the *VR group*, eight out of twelve participants did not notice that the size of the VE changed. From the *DE group* nine out of twelve did not notice that the room-sized changed. These results suggest that the illusion was effective but in contrast to the sensory perception through natural walking there is potential that it can be uncovered more quickly. We recommend combining this approach with curved layouts [516] to further hide the non-Euclidean space from VR users.

To bolster this illusion, designers of virtual experience could consider distractions in VR similar to redirected walking [270] to further hide the non-Euclidean character of the VE. In the following, we address this in the remainder of this chapter. In particular, we use a distraction in the form of a minimap that suggests that the VE is Euclidean while in fact, it is not.



(a) Virtually Overlapping Rooms.

(b) Minimap for a 0% overlapping environment and a 50% overlapping environment.

Figure 7.5: (a) Top view of the two virtual rooms: The green walls are adjusted to create rooms that are overlapping. A user that traverses from the left room through the corridor (blue wall) into the right room would, in reality, walk in a smaller area than the rooms depict in VR. (b) Two minimaps that are used in VR to navigate the environment: The red arrow indicates the position of the user, and the blue circle indicates the position of the ball which the user has to pick up. The green rectangle depicts the position of the container in which the user should place the ball to fulfill the task.

7.3 Using a Minimap as a Distractor from Non-Euclidean VR

In the following, we introduce how we used a minimap to imply a Euclidean virtual space, although we manipulate the environment by introducing a virtual overlap. Therefore, we developed a second VR application that consists of two rooms that overlap to a certain degree (see Figure 7.5(a)). In a follow-up study, 12 participants traversed these rooms by natural walking. In sum, five consecutive levels with increasingly overlapping rooms. We incentified our participants to use the minimap through a specific task. Through that, we explored how the minimap affects the recognition of the non-Euclidean VR and determined when our participants recognized the mismatch.

7.3.1 Study Design

To investigate the minimap as a distractor in VR, we invited 12 participants to a lab study. Our participants fulfilled a task that required them to walk through our VR environment with five levels containing increasingly overlapping rooms. Our participants started in a room with 40% overlap (see Table 7.2). In

Level	Overlap/Extent of Base Room	Room Width	# Participants noticed overlap
Room 1	40%	2.10m	0/12 (+0)
Room 2	70%	2.55m	1/12 (+1)
Room 3	100%	3.00m	6/12 (+5)
Room 4	130%	3.45m	8/12 (+2)
Room 5	160%	3.90m	8/12 (+0)
Base Room	0%	1.50m	-

Table 7.2: The five levels containing virtual rooms and the corresponding overlap percentage which we used for the evaluation of the minimap in non-Euclidean VR. The last column shows the overall number of participants that uncovered the non-Euclidean VR illusion at the respective level (+ indicates the number of participants that uncovered the illusion at the given level). The base room is shown as a reference of size. It was not included in the study.

previous work, participants recognized the overlap at this threshold when no distraction or reassurance was used [96]. Also, our initial overlap is 10% below the threshold reported by Suma et al. [486]. The last room was overlapping 160% of the area of our basis room (see Table 7.2). Here, an overlap over 100% means that the overlapping room is larger than the overlapped room. We decided on the limit of 160% as it is more than twice as large as thresholds from the literature [486]. We recorded the entire study and encouraged the participants to think aloud while walking. This helped us to uncover when participants recognized the overlapping architecture. We concluded the study with semi-structured interviews.

7.3.2 Task and Minimap

For our study, we developed a task that required our participants to use the minimap in each level. The objective was to pick up a ball in one room and place it inside a specific container in the other room. The other room contained three containers. Hence, our participants had to look up the correct container on the minimap (see Figure 7.5(b)). For each level, this was repeated three times.

(a) Minimap in VR. (b) Dropping off a ball at a target. (c) Comparing room and corridor.

Figure 7.6: (a) A participant holds a ball. This ball must be dropped off into a specific container. On the minimap, the correct container is shown (green). (b) The participant drops off the ball into the correct container. (c) A participant standing on the edge of the corridor comparing its depth to the depth of the room. The minimap indicates a larger corridor as observable by the user.

7.3.3 Procedure

First, we welcomed our participants to our lab. The participants filled out our consent form and permitted audio and video recording throughout the study. After that, they were provided with the *Oculus Quest 1* HMD and were situated in a free area of a large and empty room. They put on the HMD and followed the instructions inside the VR app. First, the app informed them of the five levels they should traverse. The VR app reminded them to think aloud during the study. Next, the app introduced the objective of the task – picking up blue balls in one room and bringing them to containers in the other room. The participants were told that the minimap indicates the correct container to drop off the ball. After the participants acknowledged the introduction, the app once more reminded them to think aloud. Then, the participants entered the VR on Level 1 (40% overlapping rooms). They were picking up the blue ball (see Figure 7.6(a)) and dropping them off into the indicated container (see Figure 7.6(b)). After a ball was dropped off correctly, the participants were told by the app to walk back to the initial position. After they positioned themselves correctly, they could enter the next level. Between each level, we asked the participants if they noticed anything about the environment to find out if they noticed the overlap without hinting too much towards the illusion. After five levels, the app showed an ending screen indicating that participants could close the app and take off the HMD. After that, we conducted semi-structured interviews. We did not tell the participants that they were facing a non-Euclidean VR environment in advance.

7.3.4 Apparatus

To explore the influence of our minimap, we developed a VR app in *Unity3D*. The app consisted of two rooms (see Figure 7.5(a)). A wall in every room (see Figure 7.5(a), highlighted in green) can be adjusted to manipulate the room size. From each room, the user could enter a corridor that is separated from the rooms by a wall (see Figure 7.5(a), highlighted in blue). In VR, the minimap was floating in front of the participants and followed their movement (see Figure 7.6a). The minimap showed a red arrow indicating the participant's position, a blue circle indicating the ball that needs to be picked up, and a green square, i.e., the target container (see Figure 7.5(b)). To illustrate what the participants were facing during the study, here are two examples. The two maps in Figure 7.5(b) show two different VEs. The left minimap shows an environment that does not overlap. As the environment is quadratic, the minimap is quadratic too. The minimap on the right of Figure 7.5(b) is stretched on the x-axis indicating a larger VE with no overlap, but in fact, the two rooms are overlapping by 50%. That means that the user would traverse back into the physical area of the first room while entering the second room in VR. To assure that the virtual rooms are non-overlapping on the minimap, we stretched the minimap. Thus, the corridor between both rooms was prolonged on the minimap. Since users walked at a specific pace, users could observe their movement slightly faster on the minimap. To have enough space to use our app safely, we prepared an empty room of approximately $5m \times 8m$ in our department. The minimap was always active and could not be disabled by the participants.

7.3.5 Participants

We recruited 12 participants (9 male, 3 female, 0 other) with a mean age of 30 years ($SD = 7.50$, $Med = 28$ $IQR = 5.50$). We asked the participants to rate their previous experience with 3D games and VR on a 5-Point-Likert scale. They reported having good experience with 3D games ($Med = 5$) and some experience with VR ($Med = 3$).

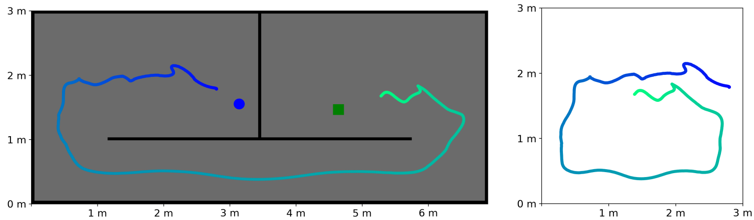
7.3.6 Results

In the following, we present the results of our investigation of the impact of the minimap as a distractor from non-Euclidean VR environments along with qualitative feedback. Therefore, we used thematic analysis to group the feedback of the participants. Two researchers coded statements independently. Afterward, we employed an affinity diagram [183] of the open codes and organized the codes into groups, which were then further refined into themes using an online whiteboard[34].

Illusion Threshold with a Minimap Eight out of our 12 participants stated that they uncovered the overlap within the environment. One while traversing the rooms with 70% overlap, five while traversing the rooms with 100% overlap, and the remaining two while traversing rooms with 130% overlap. Hence, the illusion was uncovered on average when rooms overlapped at around 100% ($M = 103.75\%$, $SD = 17.98$, $Med = 100$, $IQR = 7.5$). An overview is shown in Table 7.2. Figure 7.7 shows an example of the path on the minimap next to the real walking path taken by one participant traversing Level 4 that consists of two rooms with an overlap of 130%. We conducted a Cochran Q test to statistically compare the nominal data (overlap detected/not detected) of the different rooms. The test revealed significant differences ($Q = 22$, $df = 4$, $p < 0.001$). A post hoc pairwise McNemar test with Bonferroni correction revealed a significant difference between Room 1 and Room 4 ($\chi^2(2,12) = 6.125$, $df = 1$, $p = 0.013$, $r = 1.250$). Four participants did not mention that they noticed anything suspicious throughout the study. Taking these participants into account to calculate a lower bound, the results indicate that the threshold until the illusion can be uncovered is higher ($M = 122.50\%$, $SD = 30.31$, $Med = 115$, $IQR = 60$). Here, we assumed an overlap of 160% (max. overlap in this study) for the additional participants to calculate our results.

Illusion Break Through the Minimap We asked the participants how they had noticed the illusion. Two participants reported that they uncovered the illusion by observing their movement on the minimap. They noticed that the red arrow indicating the participants' position was moving faster on the minimap while the participants were walking through the corridor that connects the rooms. The increased speed of the cursor results from the fact that the minimap is stretched when two rooms overlap. This is necessary to show the participants a map with rooms arranged side-by-side while, in fact,

[34] Miro, `https://miro.com`, last retrieved on August 12, 2022



(a) The virtual walking path of one participant plotted on the minimap suggesting a Euclidean VE.

(b) The walking path the participant took in reality.

Figure 7.7: An exemplary walking path in VR and the physical counterpart. The two rooms overlapped by 130%. Color depicts walking time starting from blue to green.

the rooms overlap. Consequently, the participants' cursor moves faster in the corridor to match the movement of the participants in reality (see Figure 7.7(b)). One of these participants added: *"[...] the corridor here is shorter, or I'm moving faster, than when I'm in the room"*. Eight participants reported that they used the minimap to locate the ball they needed to pick up and where to drop it off. Two participants were frequently looking at the minimap while moving. Further, nine participants were not aware that the minimap grew wider with each room. Further, three participants did notice the illusion after overlaps at or above 100%. Only one participant found the minimap slightly bothersome while moving through the rooms because it was only needed when locking up the item or the drop-off container location and added: *"I thought, why should I look at it [the minimap], it's clear where I need to go [...], the level is not that complicated"*.

Illusion Break Through the Environment Six out of 12 participants reported recognizing that the number of steps needed to walk from one room to the other did not match their expectations with regard to the length of the corridor. As one participant stated that "The corridor here is shorter [...] than when I'm in the room", and another mentioned that "The room is bigger than it should have been after that corridor". Also, participants confirmed their suspicions by standing right on the edge of the corridor. From there, they could see that the room is as deep (or even deeper, depending on the current overlap) as the corridor is long (see Figure 7.6(c)).

7.3.7 Discussion

In the following, we discuss the results and derive recommendations for the development of overlapping VEs.

Illusion Threshold with a Minimap We found that, on average, the participants uncovered the overlap when it was more than twice as large as Suma et al.'s *"Impossible Spaces"* who used a similar setting [486]. In their evaluation, they deliberately let their participants know there is an overlap. This poses a limitation to our work. Future evaluations could further investigate this by comparing the perception of users who know about the non-Euclidean environment and users who do not. Nonetheless, we found that the uncovering can happen mainly in two different ways – through the minimap itself or the VE. We believe that the minimap provides a useful distraction but is dependent on the given scenario. Further distracting users could block their ability to detect the mismatch between map and environment. For example, Ciumedean et al. embedded a distracting task into the VR narrative. Through the distraction, an overlap of up to 60% remained undetected [96]. This promises that a combination of distractors, e.g., challenging tasks or visual navigation aids like our minimap, could enable larger overlaps, but future evaluations are needed.

Illusion Break Through the Minimap We found that the participants uncovered the illusion through the minimap. Suggesting a non-Euclidean environment with a 2D Euclidean surface results in a stretched map similar to a map of a globe where certain areas appear larger than they are. When traversing the stretched parts of the map, the cursor indicating the position of the user moves faster. This can be recognized by the participants and therefore has implications for the design of future non-Euclidean VR environments. For example, a designer of such worlds might consider this when using such navigation aids. For example, the map could be shown while the user is standing but is hidden while walking. Further, our minimap was stationary. Other types of minimaps that move with the user might better hide cues that hint at the non-Euclidean geometry of VEs. Such maps could be restricted to show only parts of the area around the user, not the entire environment. Here, cues on the side could help the user to navigate toward a destination outside the visible area, similar to off-screen visualization techniques [72, 197]. Further, the task we used to encourage participants to use the minimap could have influenced the results. As participants were forced to use the minimap to solve the task, they might tend to uncover the overlap through the map. If there is no need to use the map, the participants might recognize the overlap faster by observing the environment. This interplay between environment, minimap, and objective (i.e., the task) should be carefully considered when overlapping architectures are used.

Illusion Break Through the Environment Participants uncovered that they face non-Euclidean VR through the VE. The reduced number of steps hinted at a violation of the Euclidean geometry in VR. This was also observed by Suma et al. [486]. Furthermore, observing certain features in the VR environment helped the participants to uncover the illusion. For example, participants observed the length of the corridor and the depth of the rooms. When the overlap was too large, they could clearly observe the violation. This indicates that our participants had to distribute their attention between the minimap and the VE. They could see the next target on the minimap, but for navigation and collision avoidance, they had to focus on the environment. We conclude that our minimap does not distract its users too much while walking, and thus, they are still able to perceive the VE and possible violations. Future VR environments could be built to make such observations less likely. For example, using distractions like tasks for the user in VR from the field of redirected walking [270] to further hide illusion or employ distractions [96].

Recommendations and Future Work Our results point out that the minimap can help to distract from overlapping VR environments, but it is important to keep limitations in mind. VR designers and developers could incorporate a Euclidean map into their apps to extend the space for natural locomotion. This can be done entirely in software, and therefore, can work on any VR-HMD. Also, the minimap can be combined with existing methods like redirected walking [477], EMS [30], or task-driven distractors [96] to form a holistic solution that enhances natural locomotion experiences in VR. As each of these methods has its limitations and thresholds, combining or adapting them dynamically could bring real value to future locomotion experiences. Therefore, we suggest investigating these combinations in the future. We uncovered such a limitation of our minimap. The minimap led participants to uncover the overlapping rooms. Therefore, we suggest that the minimap is dependent on the scenario and could serve as additional means to hide overlapping VEs. Further research could investigate new designs of maps that manipulate the perception of VR users. Examples are a user-centered map that shows only parts of the area around the user or maps that distort the environment and thereby suggesting a non-overlapping architecture. Future work could get inspiration from the field of map projections and distortion, for example, Mercator projections that project a globe onto a plane to obtain a 2D map [345].

Limitations As we had no control condition to compare the effectiveness of our minimap, we had to rely on findings from the literature. Previous research suggests that an overlap of up to 50% remains uncovered by users [486]. When using task-driven distractions, the overlap can be increased by up to 60% [96], or up to 100% using procedural layout generation and change blindness [517]. Many different approaches can be used to hide an overlapping architecture. Therefore, we suggest that a minimap posed a new possible distraction but needs further investigation to determine its full distraction effectiveness and limitations. We can assume that fewer people would have noticed the overlap in a between-subject design. Our participants were continuously introduced to overlap changes during traversing the different levels, which could serve as a reference point for them.

7.4 General Discussion

We compared the effects of different levels of immersion on the perception of non-Euclidean VEs. Further, we investigated visual distraction via a minimap to disguise the non-Euclidean VE.

Influence of Immersion We compared the perception of two groups that traversed a non-Euclidean VE. The first group used a standard desktop PC, and the second group, immersed in VR, could use natural walking to traverse the environment. We found that an immersive VR experience leads to uncovering the non-Euclidean nature of the environment easier than the virtual experience through a desktop environment. An immersive VR environment addresses the sensory-motor system by natural walking and thereby allows its users to uncover a mismatch between the virtual and the real world by comparing visual and motor-sensory stimuli. For example, in our study, the participants who walked naturally in VR could count their steps to uncover a mismatch between the visual appearance of the VE and the physical space they traversed. The group that experienced the VE on a standard desktop PC, and thus, was less motor-sensory stimulated, could not rely on these modalities to uncover the non-Euclidean illusion. Developers of virtual experiences could aim for a higher level of distraction as suggested by the literature [96] when designing overlapping VEs to hide the non-Euclidean aspect. This could divert the attention of users away from the non-Euclidean VE.

Minimap as a Distractor With our minimap, we contributed a step towards confining the physical space needed for natural walking in VR by employing a distraction. In our approach, we used the minimap as a distraction from the non-Euclidean VE. Our minimap suggested that the virtual, self-overlapping environment is non-overlapping. This helped to hide overlaps up to 100%, and thus, further decreased the physical space needed for large VEs. In the future, VR systems or apps could incorporate such distractions to create more sophisticated and immersion-preserving natural locomotion experiences. A minimap can be implemented solely in software and can be used on any VR device. We pointed out several benefits and drawbacks when a minimap is used as a distractor from overlapping VEs. Therefore, we argue that future research is needed to fully consider the interplay between VR user, VR environment, and the underlying objective or task. Further, future research could combine our findings with other approaches, such as redirected walking or task-driven distractions to create infinite virtual worlds that can be explored using natural walking.

7.5 Conclusion

We conclude that our work is a step towards confining the physical space needed for natural walking in VR. We found that a higher immersion helps users to uncover the overlapping architecture of the VE more quickly due to the mismatch between the visual and the motor-sensory perception. For example, when the number of steps does not match the size of the VE, the non-Euclidean environment is recognized. Consequently, we employed a distraction in the form of a minimap that suggests that the VE is non-overlapping. With the help of the minimap, our participants uncovered the overlap at around 100%. This further decreases the physical space needed for large VEs. In future VR systems or applications, such visual distractions can be used to create more convincing VR experiences. Future research might combine our findings with other approaches, such as redirected walking [477, 267, 270] or task-driven distractions [96] to create infinite virtual worlds that are more likely accepted by VR users.

Summary and Key Findings

In this part, we introduced two approaches that enhance natural locomotion in VR. We first implemented an EMS-based redirection approach to enhance redirected walking. Next, we investigated the influence of immersion on the perception of non-Euclidean spaces in VR. To shift the users' attention away from such an overlapping environment, we employed a distractor in the form of a minimap. In the following, we present our key findings:

RQ 1: How can we reduce the physical space needed for natural locomotion in VR?

> ***Key Finding I*:** Manipulating the VR user: We showed that EMS can enhance redirected walking and thus reduce the physical space requirements for natural walking in VR. Therefore, we actuated the leg of a VR user to turn it outward with each step. Combined with a shifting of the user's view, we confined the physical space needed for natural locomotion to a circle with a radius of $5.48m$ – an improvement of about 25% compared to previous approaches, which required a radius of $22.0m$ [477].

RQ 2: How can we use the available physical space more efficiently for natural locomotion in VR?

> ***Key Finding II*:** Manipulating the VE: We found that a higher level of immersion leads to uncovering the overlap of the VE more quickly through the higher stimulation of the sensory-motor system. Hence, VR users perceive the mismatch between the VE and the real world more strongly. Designers and developers of VR experiences that are based on natural locomotion should keep this mismatch small or employ distractions to make their experience more convincing.

***Key Finding III*:** Manipulating the VE: We employed a reassurance or distraction in the form of a minimap which suggests that a VE is non-overlapping. With the minimap, the overlap was uncovered at around 100%. Designers and developers of VR experiences can incorporate such a minimap and thereby better hide their overlapping VEs from VR users. Consequently, we can utilize the physical space for natural walking in VR more efficiently.

We can answer **RQ 1** with our *Key Finding I*. Here, we can conclude that we can enhance redirected walking through the actuation of the user's leg via EMS. Our approach can help prevent encounters with limiting obstacles such as walls, and thus preserve immersion. Through EMS, we can steer VR users away from physical obstacles to preserve immersion and avoid possible encounters with physical objects that would conflict with the virtual experience.

We can answer **RQ 2** with our *Key Findings II + III*. For disguising non-Euclidean architectures, we conclude that a minimap that reassures the Euclidean integrity of the virtual architecture can help to bolster the created illusion as the attention of VR users is diverted. Through this distraction, we can use the physical space more efficiently through the deployment of larger self-overlapping architectures. Overall, we can conclude that taken together, our approaches for locomotion can be used to reduce the conflicts between the virtual and the real world, and thus, form a step towards increased autonomy of VR users that walk through possibly infinite virtual worlds.

IV

Integrating the Real World

Today's HMD offer a variety of sensing capabilities like physiological sensing or positional tracking. For example, the *Oculus Quest I+II* allows for inside-out positional tracking, making the device standalone, mobile, and independent from external sensors which need to be set up at static locations. This enables sensing the physical environment in great detail, and thus, allows for better integration of the real world into virtual experiences. Advancements in machine learning and in particular in the field of object recognition [412] and sense-making of 3D scenes like recognizing the semantics and meaning of contained objects automatically [591] could foster the seamless integration of real-world objects into future virtual experiences. These advancements can enable new integration possibilities by combining the real and the virtual world and thereby enable novel opportunities for CR systems. In this part, we approach such integration possibilities from two directions. One direction toward the environment and its objects and one towards VR users and their physiological responses.

First, we consider real-world objects, which we integrate to allow the VR user the sensations of haptic experiences. While synthetic content like rendered images, e.g., photorealistic faces [538] and auditory recordings or synthesis (e.g., realistic speech synthesis [372]) works well on current VR devices, providing haptics for virtual objects remains challenging [306]. One reason for this is the limitations of VR controllers to mimic myriads of differently-shaped virtual objects and their haptic properties (e.g., texture and weight). Controllers of current VR systems mainly rely on vibration to provide users with haptic feedback. Yet, controllers cannot replicate different surfaces or textures. When users grasp objects, they fail to provide physical boundaries. Hence, the user's hands pass through impenetrable objects impacting immersion or presence negatively [245]. Another interesting aspect of such an integration is the possibility to bypass certain laws of physics within the VE. For instance, we apply different levels of transparency to integrated objects to allow for a better view of the underlying task in VR. Thereafter, we create illusions by manipulating the apparent size of integrated objects and investigate to which degree VR users believe such illusions. Through that, we can reduce the number of haptic props needed to mimic matching haptics for a larger quantity of virtual objects. Here, we answer the following RQ: **How can we enhance the user's virtual experience by manipulating the appearance of real-world objects in VR? (RQ 3)**

Next, we tend towards the VR user. As modern HMDs allow for physiological sensing. Here, eye-tracking technology can be integrated using additional hardware or is even integrated into HMDs by default. With advancements in the field BCIs, we believe that brainwave-based interaction and the underlying sensory capabilities will be an integral part of future VR-HMDs. These devices could integrate electrodes to record EEG data, and thereby, enabled a wide array of novel interaction possibilities. To investigate these possibilities, we employed physiological sensing to control a virtual narrative. In particular, we investigated brainwave-based interaction with the VE using the SSVEP interaction paradigm [518]. SSVEPs have become attractive in the domain of HCI due to their robustness [131], reasonable signal-to-noise ratio [470], and high input resolution [476], allowing one to reliably distinguish between light sources flickering at different frequencies using cortical activity. By looking at the respective flickering items, users can reliably select elements and type text [10, 218], control hardware (e.g., wheelchairs [333]), or navigate VEs [259]. Also, the visual presentation of SSVEP stimuli went through an evolution to better integrate them with current UIs. This ranged from the use of light emitting diodes (LEDs) [536], abstract flickering elements on the computer screen [597], to the integration of flickering elements in MR environments [274]. SSVEPs have been successfully evaluated in AR [534] and are slowly becoming popular for immersive hands-free interaction in VR [19]. VR benefits from the integration of SSVEP stimuli into VEs. Thereby, they provide VR designers and developers an additional interaction channel and methods to estimate which elements attract the user's attention. Traditional SSVEP-based interaction often uses flickering objects [597] (e.g., black and white flickering squares), which often do not blend with the VE. Therefore, there is a huge potential that they are recognized as artificial by VR users. Therefore, we designed SSVEPs stimuli which blend with the VE. Our stimuli are designed to appear as natural objects that are part of the VR narrative. In contrast to such flickering stimuli, our stimuli in form of butterflies elicit brain responses through natural wing movement and therefore appear seamlessly integrated with the virtual world. With our research, we answer the following RQ: **How can we integrate BCI-based sensing to provide additional interaction modalities in VR? (RQ 4)**

This part includes the following two chapters:

- **Chapter 8:** In this chapter, we investigate how well-known, real-world objects that are handled by users every day can be included in virtual experiences to the advantage of VR users. In particular, we use a haptic prop in form of a pen to allow for 2D-sketching in VR. Through the manipulation of the transparency of the virtual representation of the pen and the VR user's hand, we assessed differences in the sketching accuracy. Next, we manipulate the virtual size of real-world objects that we integrated into the VR experience. Here, we investigate to which degree we can increase the size of the virtual objects until the VR user recognizes a mismatch.
- **Chapter 9:** In this chapter, we introduce our approach that allows for interaction in VR using sensing capabilities beyond the currently available sensing channels in today's VR-HMDs sensing. Here, we use brain waves to trigger events in VR via the SSVEP paradigm. In particular, we designed novel SSVEP stimuli that blend with the underlying VE. This allows us to integrate SSVEP stimuli in VR experiences without the need for disruptively perceived SSVEP stimuli elements. In particular, we assess the classification accuracy and subjective perception of our stimuli.

Chapter 8

Utilizing Real World Objects in Virtual Reality

This chapter is based on the following publications:

- **Jonas Auda**, Roman Heger, Uwe Gruenefeld, and Stefan Schneegass. "VRSketch: Investigating 2D Sketching in Virtual Reality with Different Levels of Hand and Pen Transparency". In: *INTERACT 2021*. Bari, Italy, 2021.
- **Jonas Auda**, Uwe Gruenefeld, and Stefan Schneegass. "Enabling Reusable Haptic Props for Virtual Reality by Hand Displacement". In: *Mensch und Computer*. Ingolstadt, Germany, 2021.

VR headsets have become increasingly popular for both consumers and professionals in recent years. In this context, the integration of haptic objects promises enhancements for serious VR applications. For example, tasks such as 3D modeling [113], note taking [401], or exploring spreadsheets [151], among others could integrate haptic objects

VRSketch: Investigating 2D Sketching in Virtual Reality with Different Levels of Hand and Pen Transparency

Teaser Video

Enabling Reusable Haptic Props for Virtual Reality by Hand Displacement

Presentation Video

(QR Codes are clickable in PDF)

like tools with which users are familiar with. Bringing existing applications to VR is not restricted to implementing their original functionalities. For sketching, VR allows one to implement new ideas and features that are not feasible in the real world e.g., 3D modeling [223] or sketching in mid-air [113, 119]. Moreover, VR enables users to be immersed in their favorite surroundings without any visual distractions as they would appear, for example, in an open office space. Further, VR allows the investigation of creative content in 3D space alone or together with others [150]. For example, an artist could get an impression of how a painting appears in a museum, gallery, or to viewers. Designers could quickly sketch a logo and add it to a product to get first impressions of their work [227] or feedback from customers. Engineers could sketch ideas and discuss the implications of different design decisions in the context of technical drawings.

Sketching is a haptic experience. Therefore, when we shift sketching in VR, we should consider ways to provide appropriate haptic feedback. Rendering haptic textures [2, 16] or creating the illusion of weight [417] can enhance the VR experience. Previous research proposed various approaches to provide haptics to all kinds of virtual objects. To provide users with believable haptic sensations, previous work proposed different approaches, like body-worn devices such as gloves [56, 93, 124] or suits [291, 258]. For example, Lee et al. introduced a haptic controller – *TORC* – that addresses haptics perceived at the thumb and two fingers [280]. The controller allows for grasping and squeezing virtual objects by applying matching forces to the fingertips. Their results showed that the controller could outperform *HTC VIVE* controllers in terms of precision when manipulating virtual objects. Gu et al. extend haptic feedback to all fingers through a hand-worn exoskeleton [163]. The exoskeleton could apply force feedback to the fingers of its user. Through an archery task in VR, they evaluated how the induced force-feedback influenced the performance of users. Here, the applied force feedback resulted in a significantly lower error rate.

Other approaches used haptic props [86, 89, 541, 47, 256, 202, 454, 42] that function as a physical proxy to objects presented in VR. The latter has the advantage that they can be shared by co-located users, are easy to create (e.g., with 3D printing), and can be used without the need for electronic components. However, providing matching haptic props that resemble arbitrary virtual objects is often not feasible. Even if objects have the same shape or size, it makes sense to reduce the number of haptic props [36, 89]. Thus, researchers suggested reusing a limited set of haptic props to represent a larger number of virtual objects [41, 594, 36, 89].

In this chapter, we focus on integrating real-world objects in VEs to provide haptic experiences for VR users. We introduce two evaluations. First, we introduce *VRSketch*. The *VRSketch* system integrates a hardware pen in VR. This allowed the user to use a familiar real-world object for 2D sketching. In VR, we can bypass certain laws of physics. This allows for novel sketching environments that can overcome some restrictions of the real world. For instance, transparent hands or pens which are not prone to occlusion. While hand or pen transparency for sketching in VR sounds promising, to our knowledge, its effect on user performance has not been investigated in research thus far. Insight into the application of transparency to sketching utilities or the user in VR and its influence on the performance of the user could help VR designers and developers to improve future applications and experiences and enhance user performance by applying transparency to certain virtual objects.

In the remainder of this chapter, we investigate to what degree we can manipulate the size of virtual objects which is represented by one physical prop. To create the illusion of differently sized objects in VR, we displaced the position of the user's virtual hands during the interaction with virtual objects. This allows for reusing one haptic prop for a multitude of differently sized virtual objects. In this chapter, we answer the following RQ: **How can we enhance the user's virtual experience by manipulating the appearance of real-world objects in VR? (RQ 3)**

8.1 Sketching in VR with Different Levels of Hand and Pen Transparency

Previous work has frequently explored hand transparency for integrating physical keyboards in VR, enabling occlusion-free typing [254, 530]. Their study results look promising, suggesting that novice users benefit most from transparent hands [254]. For sketching in VR, different commercial solutions exist (e.g., Google Tilt Brush[35] and Gravity Sketch[36]). Additionally, some researchers explored sketching experiences in VR [119, 113]. However, all existing solutions focus on 3D sketching only, using VR controller-input (e.g., Gravity Sketch) or pen-input with different types of haptic feedback [119, 113]. So far, little research explored 2D sketching in VR, which remains relevant,

[35] Google Tilt Brush, `https://www.tiltbrush.com`, last retrieved on August 12, 2022

[36] Gravity Sketch, `https://www.gravitysketch.com`, last retrieved on August 12, 2022

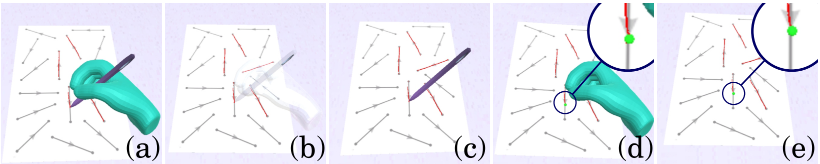


Figure 8.1: The five transparency variations of hand and pen for sketching in VR: (a) both opaque $H_{100}P_{100}$, (b) both semitransparent $H_{50}P_{50}$, (c) hand invisible and pen opaque H_0P_{100}, (d) hand opaque and pen is replaced by a cursor $H_{100}P_0$, and (e) only the cursor with invisible pen and hand H_0P_0.

for example, for early design stages or user interface design. More importantly, no existing studies provide a systematic evaluation of users' performance with controller/pen or hand transparency.

Therefore, we investigate the effect of different levels of hand and pen transparency on 2D sketching in VR. To enable accurate sketching in VR, we developed a sketching system called *VRSketch* that allows tracking of a physical pen, the user's hand, and a sheet of paper to sketch on. The tracked items are integrated into the VR experience in real-time, enabling fluid sketching. In a user study, we compare sketching performances for different hand and pen transparency levels for drawing on a 2D surface; a sheet of paper (see Figure 8.1). Our results show that higher pen transparency allows users to sketch faster, while not losing accuracy. Moreover, while drawing participants achieved a mean deviation of slightly above 0.1cm for each of the investigated techniques, indicating overall good performance for 2D sketching in VR.

In the following, we propose a system called *VRSketch* that allows sketching in VR. We use this system to conduct a comparative evaluation of five different levels of hand and pen transparency to understand the impact on users' 2D sketching performance.

8.1.1 Related Work

In the following, we review previous work exploring pen input for AR and VR, and hand/pen occlusion for different input modalities.

Pen Input for Augmented and Virtual Reality

As pens offer users a familiar form of input, they have been frequently investigated for AR and VR.

For AR, researchers explored how digital pen input can be used to annotate analog paper documents, augmented via either projection [540, 206, 462] or by using an HMD [286]. Interestingly, annotations written with the help of an AR pen are processable with Optical Character Recognition (OCR), and the resulting text can serve as input to interact with applications [286]. Beyond written text, pen input also allows direct ways of interacting with AR applications, for example, to navigate menus [526]. Moreover, previous works investigated pen input in AR for 3D modeling, empowering users to design based on three-dimensional real-world objects [527].

For VR, researchers examined different interaction types with a digital pen in different scenarios. For example, for pointing and selecting interactions [387] in scenarios such as interacting with spreadsheets [151]. Also in the focus of previous work is text input either by selecting letters on a virtual keyboard [62] or with the use of OCR [154]. Moreover, previous work studied sketching in VR using a pen as the input device. Here, an early approach is the Virtual Notepad by Poupyrev et al. [401]. The Virtual Notepad enables users to take notes and sketches in an VE, using a tracked tablet and pen. In later years, sketching with a pen in VR was primarily used for 3D sketching, often in the context of 3D modeling. In this context, either by expanding base sketches in the third dimension by lifting out single lines with pens [223] or by sketching lines mid-air [20, 113, 119]. The main focus of recent research on sketching mid-air is to create a believable haptic sensation for users. Results show that constraining the degrees of freedom by, for example, sketching on movable physical surfaces allows for higher accuracy [20, 119] and can enhance interactions [113]. Further, VEs can provide other helpful features like gridlines that allow the user to draw 3D sketches by hand [430].

In sum, for sketching in VR, researchers focused mostly on 3D sketching, aiming for believable haptic sensations when drawing mid-air. Thus, typical 2D sketching experiences received little attention, while they remain relevant for many use-cases and allow for more straightforward to implement haptic feedback.

Hand and Pen Occlusion for Input

One problem when using pens for input is the obscuring of content or interface elements. When using a pen on a tablet, up to 47% of a 12" display can be hidden by hand, pen, and arm [522]. Besides hiding parts of the interface, it can also result in a loss of precision and speed during input [276, 14]. To avoid occlusion, interfaces can detect occlusion and display content in visible areas [522, 590] or add offsets to controls [521]. However, while this improves precision for targeting tasks, it decreases the precision for tracing operations like sketching [279].

Another approach to compensate for occlusion while sketching is replacing the hardware pen tip with a semitransparent one rendered on the tablet [276]. A semitransparent pen tip leads to a 40% reduction in error rate and an improvement in drawing speed of up to 26% [276]. We adopt this established concept to VR and take it further by applying the transparency to the pen and the hand.

8.1.2 Sketching in Virtual Reality

The goal of our work is to understand the influence of hand and pen transparency on a user's 2D sketching performance in VR. Inspired by the idea of the *PhantomPen* [276], we extended the concept to include both the user's hand and the used pen. We hypothesize that transparency can improve performance, empowering users to sketch more precisely and quickly than they otherwise could. Furthermore, we are interested in optimizing the experience and precision of sketching in VR. To investigate VR sketching, we implemented the *VRSketch* system that allows real-time tracking of a physical pen, the user's hand, a sheet of paper, and a table.

To systematically explore the design space, we first identified pen and hand as two involved entities that may be improved by transparent rendering. Then, we continued by differentiating three levels of transparency (similar to the work of Knierim et al. [254]) that are invisible (0% opacity), semi-transparent (50% opacity), and opaque (100% opacity) for the hand and pen each. Semi-transparency in particular has the potential to help during spatial orientation by displaying information without occlusion of content [588]. The complete design space and the selected evaluation conditions are presented in Figure 8.2.

From the design space, we selected the following combinations of hand and pen transparency as conditions for our comparative study:

$H_{100}P_{100}$ is our baseline condition in which we render the user's hand and pen fully opaque, similar to a real-world environment (see Figure 8.1a).

$H_{50}P_{50}$ renders both hand and pen semi-transparent, providing spatial information and paper content (see Figure 8.1b).

$H_{0}P_{100}$ shows the pen as fully opaque with no transparency, but it does not render the user's hand (see Figure 8.1c).

$H_{100}P_{0}$ displays the user's hand as opaque with no transparency, while the pen is reduced to a small cursor point, representing the pen's tip (see Figure 8.1d).

$H_{0}P_{0}$ removes all occlusion caused by hand and pen, rendering only the small cursor representing the tip of the pen (see Figure 8.1e).

8.1.3 Evaluation

To investigate 2D sketching in VR and the benefits of semi- and full-transparency for pen and drawing hand, we conducted a comparative user study with the selected conditions from the design space (see Figure 8.2). We opted for these conditions as they seemed promising to uncover the effects of transparency on sketching while keeping the experiment time within a reasonable limit. Especially the semi-transparency applied to the pen and hand seemed promising from the literature [254]. Future research might investigate the remaining conditions of the design space.

Study Design

To investigate different pen and hand transparency levels for sketching in VR, we conducted a within-subjects controlled laboratory user study in VR with the *Oculus Rift* headset. Our independent variables were technique with five levels ($H_{100}P_{100}$ vs. $H_{50}P_{50}$ vs. $H_{0}P_{100}$ vs. $H_{100}P_{0}$ vs. $H_{0}P_{0}$, see Figure 8.1) and line type with two levels (*connected* vs. *unconnected*). Each

		Hand		
	Opacity	0%	50%	100%
Pen	0%	H_0P_0		$H_{100}P_0$
	50%		$H_{50}P_{50}$	
	100%	H_0P_{100}		$H_{100}P_{100}$

Figure 8.2: The design space for hand and pen transparency and the five investigated conditions for 2D sketching in VR.

technique was tested in a block consisting of four measured trials, with two trials evaluating *connected* lines and two trials evaluating *unconnected* lines. In each trial, participants had to draw a pattern consisting of 16 lines, drawing 64 lines for each block in total. To make the task more realistic, we varied the lines' orientation, introducing 16 different orientations (starting at 0° with 22.5° steps). Within each block, each line orientation was tested twice for each of both line types. We counterbalanced all blocks and the line types within each block using a Latin-square design to avoid learning effects. We used quantitative methods to evaluate sketching performance, taking pattern completion time, sketching accuracy, and the questionnaires as our dependent variables.

For this study, we assessed which levels of hand and pen transparency result in the best sketching performance in VR. Therefore, we posit the following hypotheses:

H_1 Semi-transparent rendering of the user's hand results in the shortest pattern completion times because it allows users to see the paper underneath while not losing spatial understanding.

H_2 We expect higher sketching accuracy for all conditions that render the pen semi-transparent or opaque compared to conditions in which it is fully transparent and replaced by a cursor because the cursor does not convey posture.

Apparatus

We implemented the *VRSketch* system to enable 2D sketching via pen in VR. We create an empty virtual room, centered around a sketching table, presented on the *Oculus Rift* headset. The scene was created using the *Unity3D* game engine 2018.2.20f1 and was running on a *Microsoft Windows* PC with an *Intel i7-7700K*, 32GB RAM, and an *Nvidia Geforce GTX 1080 Ti*. We spatially synchronized VR and reality by tracking the real-world scene with an OptiTrack system and its *Motive* 2.2.0 motion capture software. The tracking apparatus involved seven *OptiTrack Prime^x 13W* cameras near the sketching table to enable a high precision capturing of the sketching movements (see Figure 8.3). Furthermore, four additional OptiTrack Prime^x 13 cameras were placed at a greater distance for more general tracking. For the physical representations, we used a 3D-printed pen and a DIN A4 sheet of paper, both shown in Figure 8.3. The paper was glued to a thin sheet of acrylic glass for durability and flatness. Both had a unique configuration of retro-reflective markers to get tracked as rigid bodies by the OptiTrack system. Besides, the user's hand was tracked by wearing a thin glove with markers. Thus, we could render both the hand's general position and the grip motion when picking up the pen. We also tracked the table, the chair, and the VR-HMD to complete the spatial synchronization. After initial positioning, the head movement was tracked by the sensors of the HMD. The lines, sketched by the user, are determined and rendered by the Unity application by determining the pen tip's contact points with the paper. For measuring the sketching precision, the calculated line points were logged with timestamps. We controlled the degree of transparency for hand and pen via adjusting the alpha channel of the corresponding texture in the Unity game engine. The corresponding tracking data was streamed and logged using our *VinteR* middleware (see Chapter 3).

Participants

We recruited 20 volunteer participants (7 female, 13 male, 0 other), aged between 19 and 60 years ($M = 33.3$, $SD = 13.7$). None suffered from color vision impairments. Participants with corrected-to-normal vision were requested to wear their contacts or glasses during the study. We asked participants to rate their sketching skills on a 7-point Likert scale from 1 (cannot sketch at all) to 7 (can sketch on a professional level). Participants stated that they had limited sketching skills (Med=2.05, IQR=2.0). Furthermore, we asked participants for their experience with VR. Five participants had never tried VR before, three used it once, and twelve participants said they use a VR headset regularly (at least once a month).

Figure 8.3: Hardware setup of the *VRSketch* system where hand, pen, paper, table, and chair are tracked via configurations of retro-reflective markers. Seven of the eleven OptiTrack cameras are close to the table for more precise tracking.

Procedure

At the beginning of the study, we informed participants about the procedure and asked them to sign a consent form. Afterward, we collected the participant's demographic data, sketching skills, and experience with VR. We then introduced the participant to the Oculus Rift and adjusted the headset for optimal fit and correct interpupillary distance. Then, we started the study. The study was conducted in five blocks for each participant, with one technique tested in each block. We counterbalanced all blocks using a Latin-square design. In each block, participants first took a seat at the sketching table, put on the tracked glove, and the HMD and picked up the tracked pen. Each block started with a warm-up pattern, which participants could try until they indicated that they were familiar with that block's respective technique. After the warm-up, participants continued with the measured trails. Participants had to trace lines in four test patterns for each block, two unconnected, and

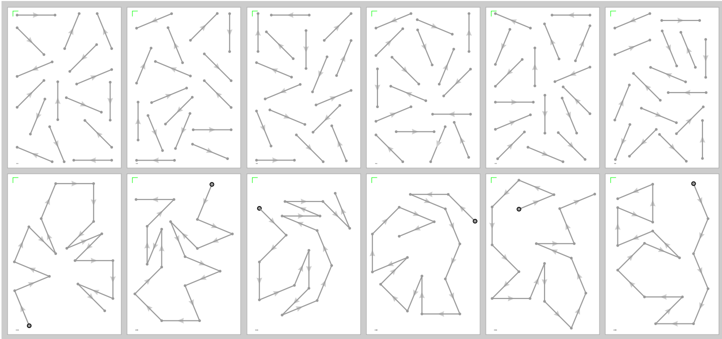


Figure 8.4: Overview of the unconnected test patterns in the upper row and the connected ones in the lower row. The lines had to be drawn in the direction of the arrows.

two connected ones (see Figure 8.4). After one pattern was complete, the experimenter started the next pattern. After all four patterns were complete, the participants could take off the headset, pen, and glove, and fill out the questionnaires: UEQ-S [443], NASA Raw-TLX [185] and IPQ [444]. After completing all blocks, we conducted a final interview with the participants asking them about their impressions of sketching in VR and the individual techniques. Each participant took approximately 70 minutes to finish the experiment.

Data Preparation

In addition to the observations of users' impressions, sketching precision is used for the quantitative evaluation of the different techniques. We use the mean deviations of the drawn lines from the corresponding target lines of the patterns to measure precision. Four out of 400 (1%) recorded patterns were corrupted due to technical difficulties and replaced with the same participant's matching pattern of the same technique. We first corrected the lines' position and rotation according to the paper's position to calculate the mean deviations (see Figure 8.5).

The line points were each assigned to a specific target line, as shown in Figure 8.5b and c. A point was always assigned if its minimum distance to the target line was less than $1cm$, whereby in the case of connected lines, the bisector between two lines served as the limit for the assignment. The

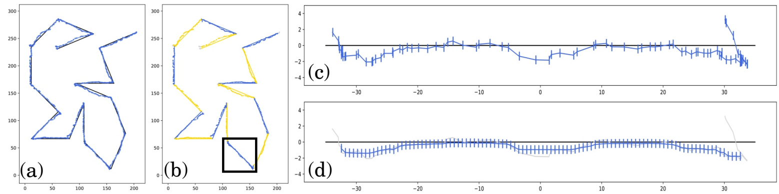


Figure 8.5: To calculate the mean deviation, the points of the sketched lines (a) are assigned to the lines of the target pattern (b). The assigned points are rotated around the center of the target line and the center is moved to the origin (c). The points are restricted to the area between the start and end of the target line, and the sketched line is resampled with 100 equidistant points (d).

Comparison			W	Z	p	r
$H_{100}P_{100}$	vs.	$H_{50}P_{50}$	2291	3.22	0.011	0.25
$H_{100}P_{100}$	vs.	$H_{100}P_0$	2654	4.96	<0.001	0.39
$H_{50}P_{50}$	vs.	$H_{100}P_0$	2318	3.35	0.007	0.26
$H_{100}P_0$	vs.	H_0P_0	742	-4.21	<0.001	0.33

Table 8.1: Significant comparisons of pattern completion times for the different techniques (with r: > 0.1 small, > 0.3 medium, and > 0.5 large effect).

lines were resampled at 100 equidistant points in line with previous work [20, 527] (see Figure 8.5e). The mean deviation of a drawn line from its target line is then calculated as the arithmetic means of the Y-values' amounts at the measurement points.

Results

In the following, we present the results from our study analysis. We use mean (M) and standard deviation (SD) to describe our data. We do not assume normal-distribution of our data, and thus, apply non-parametric tests. We ran Friedman tests and post-hoc Wilcoxon Signed-rank tests with Bonferroni correction to show significant differences.

Pattern Completion Time To understand how quickly participants were able to sketch with each technique, we looked at their pattern completion times. The times in ascending order are: $H_{100}P_0$=41.88s (SD=16.25s), H_0P_{100}=44.08s (SD=15.37s), $H_{50}P_{50}$=45.86s (SD=19.01s), H_0P_0=48.32s (SD=23.13s), and

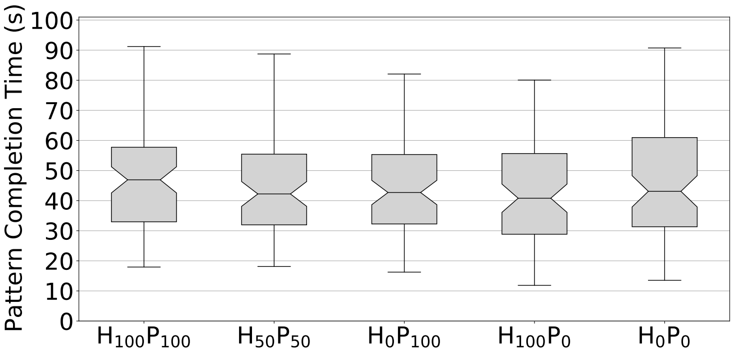


Figure 8.6: Boxplots of pattern completion times for the different techniques.

$H_{100}P_{100}$=50.17s (SD=21.66s). Figure 8.6 compares the pattern completion times. A Friedman test revealed a significant effect of the technique on pattern completion time (χ^2(4)=35.91, p<0.001, N=20). Post-hoc tests showed significant differences between some of the evaluated conditions (see Table 8.1). For the completion time, we conclude: $H_{100}P_0 < H_{50}P_{50} < H_{100}P_{100}$ and $H_{100}P_0 < H_0P_0$. For H_0P_{100} we cannot make a statement.

Sketching Accuracy Throughout the study, participants drew exactly 6400 lines. To evaluate the sketching accuracy of each technique, we applied our data preparation step described in Section 8.1.3. The mean deviations of each line within each technique in ascending order are: $H_{100}P_{100}$=1.02mm (SD=0.55mm), $H_{50}P_{50}$=1.04mm (SD=0.55mm), H_0P_{100}=1.06mm (SD=0.55mm), $H_{100}P_0$=1.06 mm (SD=0.6mm), and H_0P_0=1.08mm (SD=0.58mm). The mean deviations are compared in Figure 8.7. We applied a Friedman test, which revealed no significant differences between the techniques (χ^2(4)=8.23, p=0.083, N=20).

Sketching Accuracy for Different Sketching Directions The area in the direction of sketching can be occluded, for example, by the virtual pen or the hand of the VR user. Hence, the sketching direction could influence sketching performance. To gain further insights into the effect of the transparency, we reviewed the influence of the sketching direction on the sketching accuracy by clustering the different line orientation into quadrants. The quadrants are $Q1$: upper right, $Q2$: upper left, $Q3$: lower left, and $Q4$ lower right. For example, if a line is drawn towards the upper left relative to its starting point, it

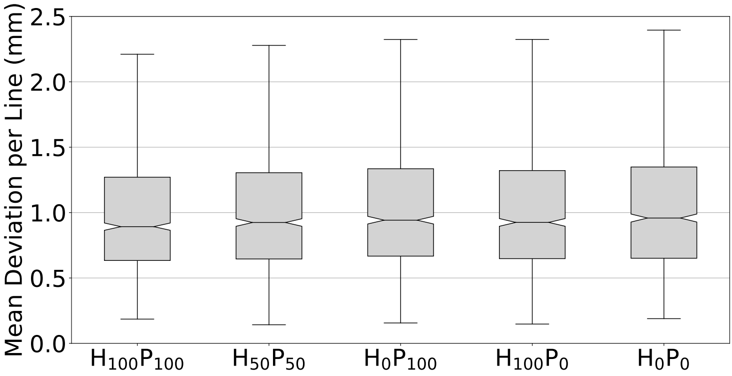


Figure 8.7: Boxplot of the mean sketching deviations for the different techniques.

Technique	$Q1$	$Q2$	$Q3$	$Q4$
$H_{100}P_{100}$	0.97 (SD 0.51)	0.96 (SD 0.46)	0.92 (SD 0.49)	1.06 (SD 0.54)
H_0P_{100}	1.04 (SD 0.53)	1.03 (SD 0.55)	0.94 (SD 0.49)	1.09 (SD 0.57)
$H_{100}P_0$	1.05 (SD 0.61)	1.08 (SD 0.51)	1.02 (SD 0.58)	1.09 (SD 0.65)
H_0P_0	1.05 (SD 0.61)	1.13 (SD 0.58)	1.06 (SD 0.6)	1.11 (SD 0.56)
$H_{50}P_{50}$	1.08 (SD 0.59)	1.15 (SD 0.61)	1.08 (SD 0.57)	1.14 (SD 0.61)

Table 8.2: The mean sketching deviation (in mm) per technique and quadrant.

belongs to $Q2$. The edge cases are clustered as follows: drawing upwards $Q1$, drawing to the left $Q2$, drawing downwards $Q3$, and drawing to the right $Q4$. The mean deviations for each technique and quadrant are shown in Table 8.2. To analyze the data of the different quadrants, we compared both the different techniques in each quadrant and the different quadrants of each technique.

Comparison of Techniques within Quadrants We performed Friedman tests for each quadrant. For $Q1$ ($\chi^2(4)$=4.15, p=0.386, N=20) and $Q4$ ($\chi^2(4)$=3.88, p=0.422, N=20), we observed no significant differences between the techniques. However, the Friedman tests for $Q2$ ($\chi^2(4)$=24.09, p=0, N=20) and $Q3$ ($\chi^2(4)$= 20.64, p=0, N=20) revealed a significant effect of the technique on the mean deviation. Post-hoc tests showed significant differences between some of the conditions (see Table 8.3). We conclude that $H_{100}P_{100}$ leads to significantly higher accuracy than $H_{50}P_{50}$, H_0P_{100}, and H_0P_0 in $Q2$

Quadrant	Comparison			W	Z	p	r
$Q2$	$H_{100}P_{100}$	vs.	$H_{50}P_{50}$	20404	-3.19	0.014	0.13
$Q2$	$H_{100}P_{100}$	vs.	H_0P_{100}	18443	-4.37	<0.001	0.17
$Q2$	$H_{100}P_{100}$	vs.	H_0P_0	19110	-3.97	0.001	0.16
$Q3$	$H_{50}P_{50}$	vs.	$H_{100}P_0$	20066	-3.39	0.007	0.13
$Q3$	$H_{50}P_{50}$	vs.	H_0P_0	19947	-3.46	0.005	0.14
$Q3$	H_0P_{100}	vs.	$H_{100}P_0$	20438	-3.16	0.015	0.13
$Q3$	H_0P_{100}	vs.	H_0P_0	20780	-2.96	0.03	0.12

Table 8.3: Pairwise comparisons of mean deviations with significant results for the different techniques in the quadrants $Q2$ and $Q3$.

Technique	Comparison			W	Z	p	r
$H_{100}P_{100}$	$Q1$	vs.	$Q4$	19307	-3.85	0.001	0.15
$H_{100}P_{100}$	$Q2$	vs.	$Q4$	18994	-4.04	<0.001	0.16
$H_{100}P_{100}$	$Q3$	vs.	$Q4$	21033	-2.81	0.03	0.11
$H_{50}P_{50}$	$Q1$	vs.	$Q3$	31759	3.67	0.001	0.15
$H_{50}P_{50}$	$Q2$	vs.	$Q3$	32367	4.04	<0.001	0.16
$H_{50}P_{50}$	$Q3$	vs.	$Q4$	19011	-4.03	<0.001	0.16
H_0P_{100}	$Q2$	vs.	$Q3$	33294	4.6	<0.001	0.18
H_0P_{100}	$Q3$	vs.	$Q4$	19255	-3.88	0.001	0.15

Table 8.4: Pairwise comparisons of mean deviations with significant results for the techniques $H_{100}P_{100}$, $H_{50}P_{50}$, and H_0P_{100}.

and that $H_{50}P_{50}$ and H_0P_{100} lead to significantly higher accuracy than $H_{100}P_0$ and H_0P_0 in $Q3$.

Comparison of Quadrants of each Technique For the comparison of mean deviations in the different quadrants for each technique the Friedman tests for the techniques $H_{100}P_0$ ($\chi^2(3)$=3.61, p=0.307, N=20) and H_0P_0 ($\chi^2(3)$=6.3, p=0.098, N=20) revealed no significant differences. For the techniques $H_{100}P_{100}$ ($\chi^2(3)$=12.1, p=0.007, N=20), $H_{50}P_{50}$ ($\chi^2(3)$=19.19, p=0, N=20), and H_0P_{100} ($\chi^2(3)$=14.79, p=0.002, N=20) the Friedman tests revealed a significant effect of the quadrants on the mean deviation. Post-hoc tests showed significant differences between some of comparisons (see Table 8.4).

Here we conclude that for technique $H_{100}P_{100}$ $Q4$ is significantly worse than for all other quadrants, that for $H_{50}P_{50}$ $Q3$ is significantly better than all other quadrants, and that for H_0P_{100} $Q3$ is significantly better than $Q2$ and $Q4$.

Questionnaires Furthermore, we asked participants to fill out three different questionnaires (NASA Raw-TLX, User Experience Questionnaire, and

Technique	Pragmatic Quality Median	Pragmatic Quality IQR	Hedonic Quality Median	Hedonic Quality IQR	Overall Quality Median	Overall Quality IQR
$H_{100}P_{100}$	1.0	2.31	1.62	1.0	1.19	1.56
$H_{50}P_{50}$	1.75	1.62	1.88	1.31	1.75	1.22
H_0P_{100}	1.62	2.12	2.0	1.31	1.62	1.28
$H_{100}P_0$	0.75	1.62	1.62	0.81	1.38	0.81
H_0P_0	1.5	1.81	1.5	0.81	1.62	1.22

Table 8.5: Results of the UEQ-S for the different techniques.

iGroup Presence Questionnaire) after each technique. In the following, we report on the gathered results using median and interquartile range (IQR).

NASA Raw-TLX To evaluate the workload of the different techniques, we analyzed the results of the NASA-TLX. The median scores in ascending order are: $H_{100}P_0$=18.75 (IQR=19.58), H_0P_0=19.17 (IQR=21.25), H_0P_{100}=20.42 (IQR=12.08), $H_{100}P_{100}$=20.83 (IQR=20.62), $H_{50}P_{50}$=22.92 (IQR=14.17). To compare the scores, we conducted a Friedman test that revealed no significant effect of the technique on the NASA Raw-TLX score ($\chi^2(4)=5.83$, p=0.212, N=20).

User Experience Questionnaire For insights on the user experience, we conducted the short version of the UEQ (see Table 8.5).

To compare the overall quality of the individual techniques, we conducted a Friedman test which revealed a significant effect. However, a post-hoc test did not reveal any significant differences.

iGroup Presence Questionnaire The results of the iGroup Presence Questionnaire (IPQ) are shown in Table 8.6. A Friedman test revealed a significant effect of the technique on the overall score. Post-hoc tests showed a significant difference between $H_{100}P_{100}$ and H_0P_{100} (W=16, Z=-2.77, p=0.04, r=0.44), meaning that rendering hand and pen opaque results in lower presence, than rendering only the pen opaque and not the hand.

8.1.4 Discussion

In the following, we discuss the most important findings of our user study.

Technique	General Presence Med	General Presence IQR	Spatial Presence Med	Spatial Presence IQR	Exp. Realism Med	Exp. Realism IQR	Involvement Med	Involvement IQR	Overall Score Med	Overall Score IQR
$H_{100}P_{100}$	4.0	1.0	4.2	1.05	2.75	0.81	2.75	1.19	3.32	0.96
$H_{50}P_{50}$	4.0	1.0	4.3	1.25	2.75	1.31	2.75	0.88	3.54	1.07
H_0P_{100}	4.5	1.0	4.1	1.5	3.0	1.06	3.0	1.25	3.46	0.91
$H_{100}P_0$	4.0	1.0	4.0	1.1	2.75	1.25	2.75	0.75	3.39	0.68
H_0P_0	4.0	1.0	3.9	1.45	2.88	0.94	2.88	1.06	3.11	0.89

Table 8.6: Results of the IPQ for the different techniques.

Pattern Completion Time In our results, we found that the more the opacity of the pen is reduced, the faster participants were able to sketch. This result is in line with similar findings in previous work. For example, Lee et al. found that rendering the pen tip transparent also increases the sketching speed [276]. In contrast, reducing the opacity of the hand resulted in longer pattern completion times. However, in H_1, we expected a semi-transparent rendering of the user's hand would result in the shortest completion time. We could not verify this in our study, and hence, cannot accept our hypothesis H_1. However, mixing transparency and opacity, one on the hand and one on the pen, resulted in shorter completion times compared to both elements being fully transparent or fully opaque. This might indicate that providing both, an overview by transparent elements and spatial information by visible elements, together could indeed be beneficial. In the future, further research could investigate more fine-grained levels of transparency to uncover its definite influence on completion time.

Sketching Accuracy We found no significant influence of transparency on user's accuracy, neither for transparency of the hand nor for the pen. Therefore, we cannot accept our hypothesis H_2. While this result is in line with previous work (e.g., transparent hands for typing on physical keyboards [254]), we expected a higher sketching accuracy for semi-transparent rendering as it empowers users to see otherwise occluded sketch areas. Nonetheless, we think that we did not observe an effect because humans may have adapted to this constraint due to excessive practice (writing with a pen is one of the first skills we learn at school). Overall, the measurements with a maximum mean of 1.08mm for mean deviation show the high precision of VR sketching with *VRSketch*. In comparison, Arora et al. [20] found a mean deviation of 2.54mm (SD=1.87mm) for the data subset with the closest conditions of drawing straight, short lines on a horizontal writing surface using a VR-HMD. We downloaded the corresponding GitHub repository[37] and applied our algorithm shown in Figure 8.5. The high precision of sketching with the *VRSketch* system confirms the positive effect of concrete writing surfaces and visual guidance aids, as shown by Arora et al. and Wacker et al. [20, 527].

Accuracy and Sketching Direction For example, for $H_{100}P_{100}$, sketching in Q4 (downright / below hand and arm) was significantly worse than in all other directions, which shows the influence of occlusion as described by Vogel et al. [522]. In general, from our results, we learned that fully seeing the hand makes it easier to sketch away from arm and hand, while eradicating the pen makes it more challenging to sketch towards the down left quarter. Based on our findings, we suggest that it may be beneficial to adapt the transparency, dependent on the sketching direction dynamically, to reach an optimal accuracy.

Perceived Workload For the NASA Raw-TLX [185] questionnaires, we observed that not rendering the pen resulted in a lower workload. In contrast to previous work [254], we found that not rendering the hands did not lead to a significantly higher workload. Quite the opposite, transparent and opaque hand and pen resulted in a higher workload. However, these results were not statistically significant.

User Experience and Presence In the conducted UEQ-S questionnaires, we did not find any significant differences between the techniques. Nevertheless, our findings point in the direction that seeing the hand fully visible results in less pragmatic quality, while overall, the results indicate a good user experience. Seeing only the pen significantly increases presence compared to seeing the pen and virtual hand. This finding is very interesting and in line with some VR games[38] that as soon as one grabs an object, do not render the users' hands anymore but instead only show the object that the user is holding.

Limitations Our work is limited by the rather complex setup that we used to implement our *VRSketch* system. It relies on several expensive OptiTrack sensors and enough space to set up the tracking system. Nonetheless, we argue that as VR advances tracking accuracy improves, and in a few years, it may be possible to track physical objects in our surroundings to integrate them into the

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[37] VR Sketching Study Data and Analysis Code, `https://github.com/rarora7777/VRSketchingStudyCHI17`, last retrieved on August 12, 2022

[38] Job Simulator, `https://store.steampowered.com/app/448280/Job_Simulator`, last retrieved on August 12, 2022

experience (as is demonstrated with integrated hand-tracking on the Oculus Quest).

8.1.5 Conclusion

We investigated five different pen and hand transparency levels for sketching in VR. We proposed the *VRSketch* system that integrates users' hands and a pen into a virtual sketching environment. Our results show that drawing lines with our *VRSketch* system, on average, results in a mean deviation of slightly above $0.1cm$. Moreover, we could show that not seeing the pen allows users to draw more quickly while not losing accuracy. In the future, we want to experiment with dynamic transparency that adjusts pen and hand rendering based on the user's current sketching or writing direction.

8.2 Enabling Reusable Haptic Props by Hand Displacement

We showed in the previous evaluation that manipulating the virtual appearance of integrated real-world objects can enhance task performance. Nonetheless, it remains unclear to what degree visual illusions conceal size differences between haptic props and their virtual counterparts.

Therefore, we investigate how strong we can manipulate the virtual size of one physical prop of fixed size. To create the underlying illusion of differently-sized virtual objects, we displaced the position of the user's hands in VR during the interaction with virtual objects. When users reach out to an object in VR, their virtual hand positions are displaced by adding an offset to the virtual hand, ensuring that users touch the virtual object at the same moment they make contact with the physical prop. Hence, proprioception and visual perception differ when the displacement is applied. To investigate this mismatch, we conducted a user study with twelve participants and two tasks. In the first task, we used a linear displacement function and incrementally increased the size of the virtual object to understand at which point participants perceived the mismatch. In the second task, we compared three displacement functions (linearly, exponentially, or logarithmic) and increased and decreased the size of the virtual object to see which function works best.

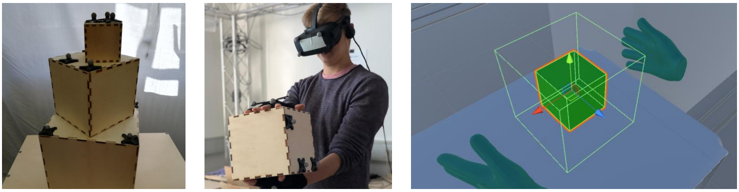


Figure 8.8: Left: We track haptic props to enhance the virtual experience. Middle: A VR user investigating a virtual box while holding a prop. Right: The virtual view. The haptic prop is rendered transparent (outer green box). To the user, only the solid green box was visible in virtual reality.

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

8.2.1 Related Work

Previous research has investigated a wide array of approaches to address haptics in VR. Body-worn haptic devices such as gloves [56, 93, 124], suits [291, 258], or handheld devices [198] were developed to address the sensation of touch at different parts of the human body. Also, directly manipulating the body via EMS could provide haptics to VR elements, e.g., heavy virtual boxes or static objects like virtual walls [294, 296]. In the following, we introduce research related to haptic props which we use in our approach.

Haptic Retargeting To mimic haptics for multiple virtual objects, Azmandian et al. investigated how one haptic prop can be re-purposed through haptic retargeting [36]. The idea is to re-use one physical object to resemble the haptics of various virtual objects. When users reach out to different virtual objects, their physical movement is manipulated by visual illusions, e.g., displacing the virtual arm. Through this manipulation, the users reach out in the direction of physically present objects without noticing. Other approaches show that such props could also change their shape before being picked up to match the expectations of a VR user [315]. Cheng et al. redirect the user's hand while reaching out to a virtual object to a specific physical proxy that

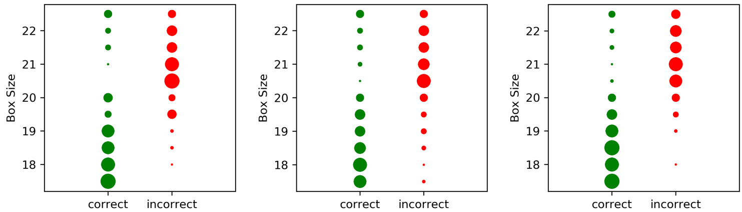


Figure 8.9: Aggregated estimation of the box size when using the linear displacement function (f_1, left), the logarithmic displacement function (f_2, middle), and the exponential displacement function (f_3, right).

matches the expected haptics of the virtual object [89]. They found that participants accepted a redirection up to 40°. Zenner and Krüger showed that users were unable to detect a hand displacement of approx. 4.5° in horizontal and vertical direction [585]. Further, they showed that users were not able to detect that the virtual hand was displaced up to 13.75% farther or up to 6.18% less far away from them. Zhao et al. extend haptic retargeting to complex shapes by applying a continuous mapping between physical and virtual objects [594]. Physical objects with similar topology were used to resemble the haptics of virtual objects. Yang et al. apply haptic retargeting to a controller creating a haptic illusion while grabbing a virtual object with chopsticks [570]. In this case, the haptic retargeting was not applied to the user but to the controller, i.e., the chopsticks opening angle. Bergström et al. showed how different virtual objects could be represented by one physical object by resizing the user's grasp [48]. The results show that virtual objects could be up to 50% larger than their physical haptic counterpart. Further, researchers published toolkits that provide techniques for retargeting to ease their deployment in VR [583].

In our work, we re-target the hands of the users to the surfaces of differently sized virtual objects when the users touch a physical prop with a fixed size. Similar to previous research that investigated the re-purposing of physical props [48]. We could show that virtual objects could be up to 50% larger than their physical counterpart.

8.2.2 Hand Displacement

To re-target the hands of VR users, we displace their virtual hands while they were interacting with virtual objects and in reality with a physical prop. We

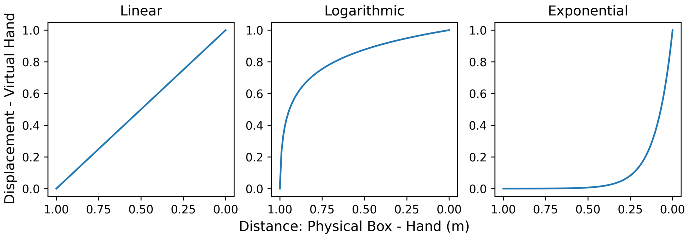


Figure 8.10: The three functions we used to displace the virtual hand position - f_1 (left), f_2 (middle), f_3 (right). The x-axis describes how far away the physical hand is from the closest point of the physical box. The y-axis describes the amount the offset that is added to the virtual hand dependent on the distance. Here, 0 means no offset is added to the hand, and 1 means that the full offset is added to the hand, i.e., the full distance between the physical touching point and the virtual touching point.

developed three functions that displace the position of the virtual hand of the VR user. These functions add an offset to the position of the virtual hand dependent on the distance between the user's real hands and the surface of the physical prop. The functions are designed to align the virtual hand with the surface of the virtual object when the user touches the physical prop. This also works for virtual objects that are smaller than the physical prop. On the right-hand side of Figure 8.8, we show an exemplary scenario. Here, the surface of the physical prop is rendered transparently. The user could only see the green boxes in VR. We developed three functions that determine the offset in a linear, logarithmic, and exponential fashion (f_1, f_2, f_3, see Figure 8.10).

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

We added an offset to the virtual hand when the distance from the real hand to the center of the physical prop is less than one meter. Adding this offset instantly when the user comes near the physical object would lead to a sudden leap of the virtual hand. This could be recognized by the user. Therefore, we designed the three displacement functions that determine the amount of offset added to the virtual hand position dependent on the distance of the real hand to the physical prop (see Figure 8.10). The linear function was designed to add the displacement offset continuously while the hand of the user approaches the surface of the physical prop. The logarithmic function was designed to add the largest amount of the displacement offset while the hand is still far away from the surface of the physical object, while the exponential function adds the majority of the offset when the hand is close to the surface of the physical prop. We designed these three different functions to investigate if the participants perceive the virtual hand displacement differently when it is applied either linearly, logarithmically, or exponentially.

8.2.3 Evaluation

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

Setup We built three differently sized wooden boxes (see Figure 8.8, left) which served as physical props. One small box ($10cm$), one medium-sized box ($20cm$), and a large box ($30cm$). We attached markers to every box to track their position and orientation using an *OptiTrack 13W* system. Further, we built a VE (see Figure 8.8, right). The environment consisted of a large room with a table in the middle. We aligned the VE with the study environment which also contained a table in the middle. Both, the virtual and the physical table were equal in size. In the VE, the participants could see virtual representations of their hands. These hands were fixed in size. The tracking data was streamed using our *VinteR* middleware (see Chapter 3). The virtual hand length was $18cm$ which is around the average human hand length (average female and male hand length: $16.9cm \pm 0.9$ and $18.3cm \pm 0.9$ respectively [164]). The physical boxes were placed in the back of the study room. As we positioned a wall in the physical and the virtual scene, the participants could neither see the physical nor the virtual boxes at the beginning of the study. Only when the participant arrived in the lab the three differently sized physical boxes were visible to them. We deliberately let the participants know that there is more than one box and that they are of different sizes.

First Task In the first task, the experimenter took a physical box and handed it across the virtual table over to the participants. The movement of the physical box was mapped to a virtual box which the participants could see in VR. The experimenter always handed the same medium-sized physical box ($20cm$) to

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

Table 8.7: Number of boxes shown to the participants until they recognized a mismatch in size between the virtual and the physical box. Also, the corresponding virtual box sizes are shown. A star (*) indicates that the participant did not notice the manipulation after investigating 20 boxes (i.e., twice the size of the physical box). After 20 boxes, the trial was stopped.

the participants. Only the size of the virtual box was different in VR. We used the linear function (f_1) in this task to displace the virtual hands. The participants then had to determine if the box they saw in VR matched the size of the box they were physically holding and then hand it back to the experimenter. During investigating the box two-handed, the participants could rotate, squeeze and re-grasp it as desired. This process was repeated up to 20 times, increasing the virtual box size by five percent ($1cm$) of its original size ($20cm$) each time. By the time the participants realized that they were handed the same box all the time, we stopped and continued with the second task. When the participants did not notice the manipulation, we also stopped handing further boxes after they had investigated 20 boxes. After 20 boxes, the virtual box was twice as large as the haptic prop. We confirmed that these participants had not noticed the manipulation through a semi-structured interview at the end of the study. The results for each participant are shown in Table 8.7. On average, the manipulation was uncovered after 11.5 boxes. This results in a cube with a side length of $31.5cm$ on average. That is around 50% larger than the physical prop. However, we observed a large standard deviation ($SD = 7.61$).

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

In Figure 8.9, we aggregated the answers of all participants estimating if the physical box was smaller, larger, or equal in size compared to the virtual box while the position of their hands was manipulated with the different displacement functions. On the y-axis, the size of the virtual boxes is shown. The x-axis shows if the estimation was correct or incorrect. The size of the green or red dots indicates how many participants guessed either correct or incorrect. When using the linear displacement function, participants estimated the size of the given boxes on average 5.83 ($SD = 1.6$) times correctly. Also, 5.83 ($SD = 1.46$) boxes were estimated correctly while using the logarithmic function. Using the exponential function, the box size was estimated on average 6.08 ($SD = 1.61$) times correctly. Our results indicate that the participant's estimation is not strongly affected by the displacement functions. We observed similar patterns for each of the displacement functions.

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

Limitations Our sample size of 12 participants was rather small. Also, we had an imbalanced gender distribution (11 male, 1 female, and 0 other). Future studies could aim for a larger, more balanced sample size. Also, we had a fixed hand size in VR i.e., the average human hand size of females and males. This might lead to differences in estimation [43]. Future work could adjust the hand individually to the participants to make their estimation more precise.

8.2.4 Discussion

The evaluation of the displacement functions showed that the participants could hardly estimate if the size of a virtual box matches the physical one they were holding if the manipulation of the hand position does not exceed a certain threshold. In the study, on average, the participants noticed the manipulation after the virtual box was 50% larger than the physical prop (20cm side length). Due to a rather high standard deviation ($SD = 7.61$), this threshold might need further investigation. The qualitative results point out that more than half of the participants were not sure if they received the same physical prop. These participants thought we were handing them differently sized props. This underpins the 50% threshold and is in line with previous approaches that used smaller haptic props [48].

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

8.2.5 Future Work

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

Conflicts in Multi-User VR Environments Manipulating the virtual hand position results in a mismatch between the virtual and physical environment. This can introduce conflicts in co-located multi-user VR scenarios. For example, if two users want to shake hands but their virtual hand position differs from the real hand position, they can not touch each other. Future research might investigate how severe these conflicts affect VR experiences and how they can be resolved if hand displacement is applied. We propose to investigate if the different displacement functions (i.e., linear, logarithmic, exponential) are suited to resolve conflicts in multi-user VR environments by dynamically applying an offset to reuse haptic props while preserving physical interaction between users. Similar to approaches that redirect VR users to meet again after their walking path was altered [330].

Other Body Locations Future VR systems might be able to track the whole body of a user, making it possible to interact with knees, feet, or elbows. To the best of our knowledge, there is no research neither on how these body parts can be manipulated in a way to reuse haptic props with different virtual representations. Interacting with feet, for example, could be useful for exergaming [575] or training simulations that make use of different haptic props. Future research could investigate the effects of manipulating the offset of other virtual body parts to broaden the interaction space.

Safety Critical Scenarios Manipulating the virtual position of physical props might induce safety issues. For example, a climbing simulation in VR might benefit from reusing haptic props to enhance realism [445]. Manipulating the hand or feet position improperly might lead to severe issues or injuries. A climber might fall off a climbing wall when the VE suggests physical props at the wrong position, or a climber reaches out too quickly for a haptic prop and reaches into empty space because of the mismatch between the virtual and the physical world.

8.2.6 Conclusion

We developed three displacement functions that manipulate the virtual hand position of a user in physical-prop-enriched VR. This manipulation can make users believe that virtual objects are differently sized than their physical counterparts. Our study showed that with a physical box of $20cm$ side length, the manipulation was uncovered after the virtual box was 50% bigger than the physical one when we used a linear displacement function. This is in line with previous approaches that used smaller haptic props [48]. Further, we explored if the three displacement functions (i.e., linear, logarithmic, and exponential functions) affect the size estimation of our participants. Preliminary results for all three displacement functions pointed towards being perceived similarity by the participants, but further investigation is needed. We suggest investigating stronger manipulations. This could uncover thresholds that might help designers of haptic VR environments to create more convincing touch interactions with physical props. In the future, VR environments could be experienced in arbitrary real-world settings [90]. The physical and virtual worlds could be combined to create a more immersive experience [202, 454]. Here, displacement functions could be investigated if they are suitable to enhance the degree of freedom for the VR narrative, i.e., manipulating the shape and size of virtual objects while employing haptic features of real-world objects that serve as haptic props.

Chapter 9

Beyond Default Sensing Capabilities of VR-HMDs

This chapter is based on the following publications:

- **Jonas Auda**, Uwe Gruenefeld, Thomas Kosch, and Stefan Schneegass. "The Butterfly Effect: Novel Opportunities for Steady-State Visually-Evoked Potential Stimuli in Virtual Reality". In: *Augmented Humans*. Kashiwa, Chiba, Japan, 2022.
- **Jonas Auda**, Uwe Gruenefeld, Thomas Kosch, and Stefan Schneegass. "The Butterfly Effect: A Showcase Study". In: *To be submitted*.

Teaser Video   Presentation Video
(QR Codes are clickable in PDF)

In the previous chapter, we approached the VE by integrating real-world objects in VR. This allowed us to give them a physical manifestation in order to provide a more natural interaction experience. In this chapter, we focus on the VR user.

Currently, VR users can interact with VEs using mainly three popular modalities; controllers [135, 541, 280], hand-tracking [323], or eye-tracking [475, 482]. While these technologies work well and improve constantly, newly emerging technologies like BCIs find their way into the VR sector [259]. Sensing the VR user's EEG can be used for a variety of scenarios like gaming or for assessing physiological effect [200, 290]. For VR, in particular, SSVEPs showed great potential to provide an additional interaction modality besides the most common interaction modalities. Despite this potential, there are still some open challenges regarding the integration of SSVEP stimuli in VR experiences.

9.1 Blending SSVEP Stimuli with Virtual Reality

In general, VR aims for immersive experiences letting users dive into a digital world that feels like their own reality. However, current representations of SSVEP stimuli are rendered in an abstract form of mostly flickering squares or circles, making it difficult to integrate SSVEP seamlessly into the VE. Although past research reported that integrating SSVEP in VR can be successfully achieved [259], virtual experiences are disrupted by presenting abstract SSVEP stimuli that do not fit the VE. We argue that SSVEP stimuli should blend into the VR experience. This can enable novel interaction scenarios with fewer adverse effects on immersion and presence. Past research investigated alternative SSVEP representations such as rotating items [413] or flickering menu navigation elements [19]. Hence, there exists a research gap regarding the comparison of the classification accuracy of abstract stimuli like menu items and blending stimuli that match the appearance of the VR environment. Therefore, we investigate how the appearance of SSVEP stimuli can affect the classification accuracy and user acceptance in VR. In this chapter, we answer the following RQ: **How can we integrate BCI-based sensing to provide additional interaction modalities in VR? (RQ 4)**

SSVEPs are cortical responses that occur when one is stimulated visually at a consistent frequency [518]. For example, viewing a light source at a constant frequency causes a measurable resonance at electrodes placed on the occipital lobe [131], a posterior part of the brain responsible for visual perception. Early work in neuroscience realized the potential of SSVEP, requiring only a low amount of data and short training times to achieve satisfactory results [515,

Figure 9.1: A VR user looking at butterflies. The butterflies elicit SSVEP responses through either flickering or flapping wings.

597]. Since cortical activity is passively generated, the use of SSVEP for people with physical impairments moved into the focus of research [140].

As promising as this sounds, the seamless integration of SSVEP stimuli into VR remains challenging. Therefore, we investigate stimuli that blend with the underlying VE to make them less disruptive to preserve an immersive VR experience and, at the same time, provide a robust and accurate interaction modality. Therefore, we evaluate how different SSVEP parameters impact classification accuracy in VR. We started by surveying past HCI literature regarding commonly used SSVEP frequencies. We then performed a first study to compare these frequencies regarding their classification accuracy. We selected a triple of frequencies that yielded the highest classification accuracy for a second study. For this study, we designed SSVEP stimuli in form of butterflies with three levels of *shape realism* (*low*; *moderate*; *high*, see Figure 9.2). These stimuli elicit SSVEP responses through different animations –*flickering* wings or *flapping* wings. In terms of classification accuracy, we found that *flickering* wings outperformed *flapping* wings. Our results show that the butterfly with quadratic and *flickering* wings yielded the highest accuracy (78.7%) for the classification of the three frequencies. For a *flapping* butterfly with real wing contours, we obtained a smaller classification accuracy (67.5%). Subjectively, participants perceived the butterfly with realistically shaped wings as most natural in terms of appearance and movement.

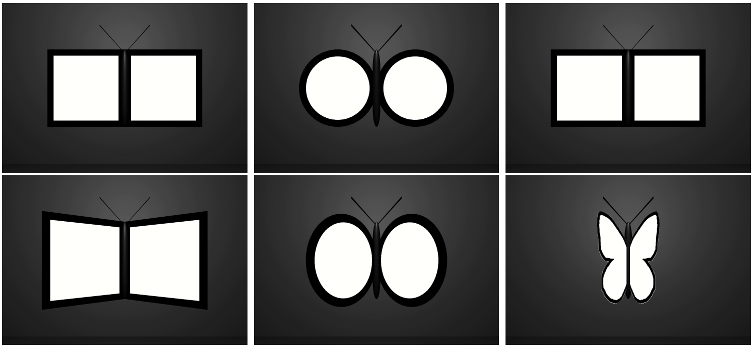


Figure 9.2: Three butterflies with different levels of shape realism. **Left:** Low shape realism. **Middle:** Moderate shape realism. **Right:** High shape realism. The butterflies in the upper row elicit SSVEP responses through *flickering* wings, while the butterflies in the lower row elicit SSVEP responses through *flapping* wings.

To demonstrate the applicability of our stimuli, we present a showcase study in which six participants played a VR game solely interacting with our butterfly stimuli that were rated most realistic. Our participants interacted successfully with butterflies in VR. Our showcase shows that SSVEP stimuli can blend with a given VR scene while maintaining the ability to stimulate the human brain. We showed that this can be accomplished by either *flickering* or *flapping* wings. Especially, butterflies with *flapping* wings represent a compelling example for blending SSVEP stimuli in VR that are not recognized as artificial or disrupting.

Our findings provide VR developers insights that help them better understand the trade-off between classification accuracy and a realistic appearance of SSVEP stimuli that blend with VR environments. We chose butterflies for our approach because the large wings size allowed us to use their anatomic properties to excite the VR users' retinas. Further, natural scenes are common in VR. Therefore, we opted for a commonly occurring animal that has wings and can float in the air to make its appearance in front of the user plausible. Nonetheless, butterflies do not occur in every VR scenario. Therefore we used them as an example for SSVEP-based interaction in VR. To put our results into perspective, we outline more SSVEP stimuli integration opportunities for future research endeavors. Our work serves as an initial example for integrated

SSVEP stimuli in VR to kick-off research that explores the underlying design space.

The contribution of this chapter is threefold: We summarize commonly used SSVEP frequencies, which we evaluated in a first study (N=12) by utilizing machine learning to compare classification accuracies. We performed a second study (N=12) evaluating how different realism levels of our SSVEP stimuli affect the classification accuracy and the associated subjective appearance ratings. Finally, we assess the feasibility of our stimuli through a showcase study (N=6), showing that participants can successfully interact in VR using our presented stimuli.

9.2 Related Work

Previous research showed that SSVEPs have a high robustness, satisfactory information transfer rate, and good signal-to-noise-ratio [284], making them suitable for BCI-based interaction. Exemplary scenarios range from steering wheelchairs [333, 285], controlling prosthetic hands [347], providing text input through spellers [556, 284, 524], or interaction in VR [474, 19, 50, 259]. Available low-cost BCIs, such as the OpenBCI *Ganglion*[39] can be efficiently deployed as they do not require a rigorous setup of hardware [28]. As a result, a wide array of research emerged in HCI using the SSVEP interaction paradigm.

9.2.1 SSVEP Stimuli Characteristics

SSVEP stimuli can be displayed with different characteristics. Previous research investigated the robustness of SSVEP stimuli properties including different frequencies, sizes, shapes, colors, and patterns. SSVEP frequencies can be divided into three frequency ranges. Low frequencies are centered around $15Hz$, medium frequencies around $31Hz$, and high frequencies around $41Hz$ [535]. In this context, Kuś et al. identified a continuous range of suitable frequencies for strong SSVEP responses, ranging from $12Hz$ to $18Hz$ [264].

[39] OpenBCI – Ganglion Board, `https://shop.openbci.com/collections/frontpage/products/ganglion-board`, last retrieved on August 12, 2022.

The selection of suitable frequencies is important since the frequency selection has an essential influence on the interaction performance [524].

SSVEP responses can be elicited through stimuli using blinking LEDs or flickering graphical elements on displays [597]. Previous approaches used differently colored LEDs, rendered black and white flickering shapes on displays, or pattern reversal stimuli which are alternating graphical patterns (e.g., checkerboards) [597] or motion-reversal stimuli [563]. Moreover, stimuli in motion like spinning [413] or repeatedly size-changing shapes [94] elicit SSVEP responses. Lately, SSVEP was adopted for interaction in AR [525, 534] and VR [19, 299].

9.2.2 Interacting with SSVEP

SSVEP stimuli induce mental load and visual fatigue during interaction [351, 352]. Xie et al. compared periodic flickering to motion-reversal stimuli [562]. In terms of mental workload, motion reversal stimuli outperformed periodic stimuli. Long-term BCI interaction can also employ motion-reversal stimuli to reduce visual fatigue. To enhance the visual comfort of SSVEP stimuli, Rekrut et al. compared SSVEP responses of spinning icons to traditional flickering stimuli [413]. They showed that spinning icons could perform equally well than traditional SSVEP stimuli in terms of classification accuracy while they were perceived as less tiring. Many SSVEP-based approaches are restricted to abstract tasks. Therefore, everyday use cases were investigated by Bi et al. [51]. They evaluated SSVEP-based interaction with a Head-Up Display (HUD) integrated into a vehicle's windshield. They classified SSVEP responses to control a simulated car. They showed that a SSVEP-based HUD can indeed be used to control a car.

However, previous approaches rely mainly on 2D displays or LEDs [556] to elicit SSVEP responses. Other approaches used SSVEP in AR [534]. For example, controlling a smart home via a SSVEP-based AR-UI [525]. In contrast to these approaches, VR relies heavily on interaction with a synthetic, 3D world. Previous approaches investigated a variety of SSVEP stimuli in immersive VR environments. Simply adopting 2D stimuli useful on flat displays in VR might not fit the three-dimensional character of VEs. For example, a black and white flickering square floating in mid-air in a VR fantasy game. Prior work showed that SSVEP in VR improves user engagement (e.g., higher information transfer rate) compared to 2D displays [259]. Hence, SSVEP in VR promises a wide array of interaction possibilities in the future.

We are confident that the full potential of SSVEP-based interaction in VR does not rely on the classification accuracy only. Instead, we argue that the appearance of the presented stimuli should blend into the VR world rather than disrupting the virtual experience. To investigate this, we designed SSVEP stimuli that have the potential to blend with the VR environment while eliciting SSVEP responses that can be measured robustly. Before we introduce our approach, we introduce prior work to ground our research.

9.2.3 SSVEP-based Interaction in Virtual Reality

Choi et al. investigated classification accuracy and visual comfort of SSVEP stimuli in VR [94]. To control an avatar in a VE, they employed two stimuli types – a Grow Shrink Stimulus (GSS) and a Pattern-Reversal Checkerboard Stimulus (PRCS).

Stimuli that were subjectively more comfortable to participants showed higher classification accuracy. Nonetheless, the authors state that more investigations are needed to generalize the results. With this in mind, we designed our own set of SSVEP stimuli for VR with varying visual appearances.

Stawicki et al. employed an SSVEP-based virtual control of a vacuum cleaner robot in VR [474]. They compared traditional SSVEP stimuli on a 2D display to an immersive VR scenario. They achieved a better information transfer rate in VR as well as a lower task completion time than on a traditional PC setup. To navigate a VE, Stawicki et al. compared SSVEP-based interaction with traditional PC environments to immersive VR using HMDs [473]. Through flickering rectangles, participants could move through the VE by focusing on rectangles each associated with a specific movement. They found that in VR participants needed fewer commands to navigate the VE. Further, participants traversed the environment 50% faster when using a VR-HMD. On top of that, participants were more aware of the VE when using HMDs compared to a traditional PC setup. Ma et al. combined SSVEP-based BCI with eye tracking for text entry in VR [299]. Through the combination of these two modalities, they achieved a higher information transfer rate compared when using a single modality. They were able to achieve an input speed of 10 words per minute. In terms of accuracy, their VR approach outperformed similar approaches that relied on displays to elicit SSVEP responses [475]. A playful approach by Koo et al. used SSVEPs to move a ball through a maze in VR [259]. The ball was viewed from a bird-eye view. Around the ball, there were flickering squares. Focusing on one of the squares lets the ball move in the direction of the square. The goal was to steer the ball to the end of a maze. Through a study, they found that interacting in VR resulted in shorter playtime, and consequently, in a higher information transfer rate than playing the game using a traditional 2D display.

In essence, previous research shows the great potential of SSVEP-based interaction in VR. In contrast, our work provides insights into the trade-off between satisfactory interaction stability and visual comfort for SSVEP stimuli in VR. We envision that a robust SSVEP-based contactless interaction for persons with physical impairments [333] can make future VR apps more accessible.

A closely related previous example for this is *Sublime*. Here, Armengol-Urpi et al. proposed a concept that incorporates stimuli into a VR environment [19]. In a VE, users could focus on flickering movie covers in a virtual menu to select a movie to watch. While focusing on the movie covers, loading bars indicate when the selection is triggered. Then the movie started. During playback, an additional object could be focused to get back to the previous menu. In this approach Armengol-Urpi et al. used higher frequencies (above $41Hz$ [535]). Similar to this approach, we integrated SSVEP stimuli into VR objects rather than displaying them as an artificial GUI element. We believe this enhances the virtual experience and thus, makes SSVEP-based interaction more applicable. Concretely, these stimuli should blend in a given VE, and thus, are not recognized by the users as stimuli. Therefore, we developed stimuli in form of virtual butterflies with different levels of *shape realism* that elicit SSVEP responses through *flickering* or *flapping* wings. *Flapping* wings can work similarly to GSS [94] or spinning icons [413] as they change their angular size while being focused by the user. As prior work hints toward a connection between visual comfort and classification accuracy [94], we believe that, especially in VR, it is important to find a suitable trade-off between classification accuracy and visual appearance.

9.3 General Approach

In this section, we introduce our approach to well-suited and realistically-shaped stimuli for SSVEP-based interaction in VR. We first extracted nine commonly used frequencies from the literature. Out of these nine frequencies, we determined three frequencies with the highest detection accuracy in our first study with twelve participants. We used these three frequencies in our second study to train a classifier (i.e., Support-Vector Machine (SVM)) to

Stimulus Type	Frequency Range	Stimulus Device	Reference
Flickering Rectangles	5, 6, 7.5, 8.33, 8.57, 10, 12, 12.5, 15, 6-20 Hz	Display	[463, 233, 213, 214]
Flickering Squares	6.0, 6.25, 6.67, 7.50, 7.57, 8, 8.6, 9, 10 Hz	Display	[414, 359, 293, 434]
Flickering Circles	6, 6.67, 7.5, 8.57, 10, 12, 15 Hz	Display	[176, 178, 177, 122]
Flickering Checkerboard	8, 9, 11, 12, 15, 20, 25 Hz	Display	[559, 337]
Flickering Square	6.25, 8, 9, 10 Hz	Smartphone	[369]
LED	5.783, 6.75, 8.65, 11-19, 30-48 Hz*	LEDs	[208, 505, 497]
Flickering Squares	8-15.8 Hz**	VR-HMD	[299]
Flickering VR Objects	42, 43, 44, 45 Hz	VR-HMD	[19]
Flickering Rectangles	4, 6, 8, 9, 10, 11, 12, 13, 15 Hz	AR-HMD	[525, 534]

Table 9.1: Overview on frequencies used in the retrieved literature using the query *"Brain-Computer Interface" AND "SSVEP"* on the *ACM Digital Library*. A * indicates increments of 2 Hz and ** indicates increments of 0.2 Hz in a range of frequencies.

detect SSVEP responses elicited through our stimuli in form of butterflies with different levels of shape realism and different wing animations – with *flickering* or *flapping* wings. Further, we obtained subjective feedback on perceived realism, movement, visual pleasantness, and ability to focus on the stimuli. During our studies, we followed the local ethical process.

Identification of Suitable Frequencies To design our butterfly-shaped stimuli, we first obtained a frequency range that is frequently used for SSVEP responses. Therefore, we conducted a brief literature review. We queried the *ACM Digital Library* on May 25, 2021, with the following search terms *"Brain-Computer Interface" AND "SSVEP"*.We retrieved 92 items from the library. From the results, we selected publications that investigated SSVEP-based interaction and extracted the frequencies used in the experiments. We ignored literature that used BCIs with other interaction paradigms than SSVEP (e.g., P300 [411]). Further, we solely considered *research-articles*s, *short-papers*s, *abstract*s, and *survey*s. We excluded literature that did not report on the frequencies used in their experiments. In Table 9.1, we present an overview of the gathered frequency ranges together with further details like stimulus type and devices used for stimulus emission.

Study I: Selection of Suitable Frequencies We selected a set of 72 unique frequencies which were used in previous SSVEP studies (see Table 9.1). Then, we counted the occurrences of all used frequencies and removed all frequencies which occurred fewer than three times. Furthermore, we removed decimal frequencies to avoid interpolation between two frequencies. This resulted in the following nine frequencies: $6Hz$, $8Hz$, $9Hz$, $10Hz$, $11Hz$, $12Hz$, $13Hz$, $14Hz$, $15Hz$. In Study I, our participants viewed squares flickering at each of these frequencies while we measured cortical activity at the occipital lobe. Twelve participants took part in this study. After the study, we compared the classification results of each possible frequency triplet. After extracting the triplet with the highest classification accuracy, we continued with our second study in which we manipulated the appearance and animation of our butterfly-shaped stimuli using this frequency triplet.

Study II: Evaluation of Accuracy an Appearance We developed three SSVEP stimuli in the form of butterflies with increasing realism regarding their shape and stimulus type (see Figure 9.2). We intended to increase the realism of the shapes by alternating their wings from square wings (i.e., *low shape realism*), similar to the square used in Study I or previous work [259, 475, 473], over round wings (i.e., *moderate shape realism*) to real wing contours (i.e., *high shape realism*) of a real butterfly. The use of a butterfly was inspired by previous research that successfully evaluated navigation using SSVEP butterflies in a non-VR environment [282]. Butterflies have relatively large wings compared to their body. These large wings allowed us to create a large stimulus area to excite the retina of an observer. To elicit SSVEP responses through the natural movement of the butterfly, we animated the wings to move up and down at specific frequencies, and thereby, changing their angular size. This elicits SSVEP response similar to spinning icons [413] or a GSS [94]. Our butterflies flapped their wings from 90° upwards to 90° downwards and back at a specific frequency.

9.3.1 Study Apparatus

For both studies, we developed a VR app in *Unity3D*. The VR app placed the user in a dark room with gray walls. Thereby, we could reduce the influence of external factors and focus on the evaluation of the tested stimuli. The VR app was configured in *Unity3D* to display either a square stimulus or the butterflies with different levels of shape realism and wing animation. In Study I, the app displayed a black and white flickering square measuring $0.4m \times 0.4m$ at a $1m$ distance (see Figure 9.3, right). The square was colored white with a black frame. The white area covered $1.162m^2$. For reference, $1m$ in VR corresponds to $1m$ in reality. In Study II, the app displayed our butterflies once at a time (see Figure 9.2). One wing of our *low, moderate, and high shape realism* butterflies encompassed a white area of $1.16m^2$, $0.88m^2$, and $0.60m^2$ respectively. From the center of our butterflies to the farthest point on the wings, we measured a distance of $48cm$, $40cm$, and $33.6cm$ for our *low, moderate, and high shape realism* butterflies. To run the VR app, we connected an *Oculus Quest 2* to a PC via an *Oculus Link* cable. This allowed us to operate the VR app from outside the VR-HMD while monitoring the EEG signal (see Figure 9.3, left) and simultaneously the 1st person-view of the participants. In our setup, we had a constant refresh rate of $72Hz$. The stimulation signal was modeled using a square wave in a custom shader for best performance. We measured around $7.33lx$ illuminance per eye emitted by the HMD using a photometer[40] when showing a *low shape realism* butterfly when it was rendered fully white and wings were spread to the maximum (see Figure 9.2). When showing a *moderate shape realism* and *high shape realism* butterfly, we measured $6.33lx$ and $5.67lx$ respectively. As the maximum frequency was $15Hz$ in Study I, we were certain that our stimuli were presented properly as the refresh rate of

[40] Photometer: VOLTCRAFT LX-10, range: 0 - 199900 lx

Figure 9.3: For our study apparatus, we use an Oculus Quest 2 VR-HMD and OpenBCI Ganglion EEG board. **Left:** A participant wearing a VR-HMD focusing on a stimulus. **Right:** The same participant in VR, focusing on a black and white flickering square.

our VR-HMD was about five times higher ($72Hz$) than $15Hz$. Additionally, we recorded the stimuli with an external highspeed camera[41] from within the VR-HMD. By checking the recording frame by frame, we were certain that our stimuli were presented properly.

We recorded the EEG signal using an *OpenBCI Ganglion EEG board* since its electrodes can be easily integrated into VR headsets while maintaining a signal recording quality comparable to medical-grade devices [130]. The *Ganglion* operates with a $200Hz$ sampling frequency and has 4 input channels. We used 2 of the 4 available channels to sample EEG signals. We placed the electrodes on the occipital lobe of the participant at *POz* and *Oz* according to the 10-20 system [207]. We placed the ground electrode on the right earlobe and the reference electrode on the left earlobe in Study I. However, we changed the position of the reference electrode to *Cz* since it improved the signal quality in Study II. We streamed the EEG signal from the *OpenBCI GUI* to our VR app using the Open Sound Control (OSC)[42]. The VR app annotated the EEG signal with the current stimulus frequency and stored it in comma-separated files for later analysis and classifier training.

9.3.2 Data Processing and Machine Learning

In the following, we introduce our data pre-processing and machine learning approach to classify the SSVEP responses elicited through our stimuli.

[41] Camera Model: ELP-USBFHD08S, max. frame rate: 720p@260 fps

[42] Open Sound Control (OSC), `www.opensoundcontrol.org`, last retrieved on August 12, 2022

Preprocessing and Classifier Training: Study I

We divided the raw EEG signal into epochs relating to the displayed frequencies. We average the raw EEG signal of the electrodes *POz* and *Oz* to obtain a single signal. This is a known method to denoise biomedical signals [373]. One second of data was removed from the beginning and end of each trial to remove signals that are unrelated to cortical activity. Each epoch was high pass filtered at $0.1Hz$ and low pass filtered at $40Hz$. We have intentionally selected a cutoff at $40Hz$ to include harmonic frequencies. Including additional harmonic frequencies is known to increase the classification accuracy due to the occurrence of more robust features [348]. We performed a *Short-time Fourier transform* on two-second slices with an overlap of one second. The obtained frequency bins per second were labeled with the displayed SSVEP stimulus [78], representing the feature vectors used to train a SVM [100]. We performed a grid search to find the optimal hyperparameters for the test set [212]. We evaluate the classifier performance through cross-validation with $k = 10$, where $k-1$ folds were iteratively used for training, and the remaining fold was used for evaluation.

Preprocessing and Classifier Training: Study II

In Study II, we recorded the EEG data while displaying our butterfly stimuli. We obtained raw EEG recordings along with annotations with the respective frequency of the stimuli. Then, we applied the following pre-processing steps. First, we averaged the signal similar to Study I (*POz* and *Oz*, Ref *Cz*, GND *right earlobe*) and created buckets with 200 samples each by using a sliding window approach with a step size of one. As we repeated the stimuli exposure three times per frequency, we separated the second block from the first and third block to use it for testing. Next, we normalized each bucket using *zero-mean normalization* and applied a band-pass filter from 0.1 to $40Hz$. We then computed the Fast-Fourier-Transform (FFT) of each bucket. As a result, we obtained a training set and test set of transformed buckets for each frequency. We then trained our SVMs with the training set and tested it on the test set.

9.4 Study I: Selection of Suitable Frequencies

The goal of the first study was to determine a combination of best-performing frequencies identified by previous research. In this study, participants were viewing abstract SSVEP stimuli using the frequencies from the literature while we recorded cortical activity.

9.4.1 Study Design

We conducted a within-subjects laboratory user study in VR using our previously described apparatus to compare the most reported frequencies (see Section 9.3.1). In this study, we showed a square stimulus in the center of the participant's FoV, flickering between black and white with different frequencies. Our only independent variable was *frequency* with the nine levels (*6Hz*, *8Hz*, *9Hz*, *10Hz*, *11Hz*, *12Hz*, *13Hz*, *14Hz*, and *15Hz*). Each frequency was displayed three times to the participants, each for ten seconds. Between the ten seconds of exposure, we had a five-second break in which no stimulus was visible. Participants received a short break after each block. The frequencies displayed in each block were counterbalanced using a Latin square design. During each trial, we measured the participants' cortical activity as described in Section 9.3.1. This results in an overall data collection of 30 seconds per participant and frequency. In our analysis, we focused on the selection of a triplet yielding the highest detection accuracy. We have selected an overall number of three frequencies since previous research found this number suitable for interaction [282]. In the following, we assess which triplet combination of the nine frequencies provides the best detection accuracy for SSVEP in VR.

9.4.2 Procedure

Participants were introduced to the purpose and procedure of the experiment at the beginning of the study. We asked participants if they are affected by neurological disorders (e.g., epilepsy) to ensure participation without risk. Then, we asked participants to fill out a demographics questionnaire. Next, we started to set up the devices used in our experiment. First, we helped participants to mount the passive gold cup electrodes on their heads (see

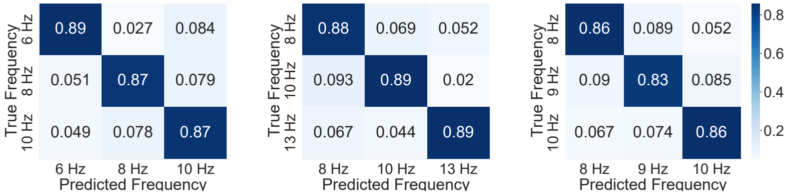


Figure 9.4: Confusion matrices of the three frequencies yielding the highest accuracies. **Left:** Classification using 6, 8, and $10Hz$. **Middle:** Classification using 8, 10, and $13Hz$. **Right:** Classification using 8, 9, and $10Hz$.

Section 9.3.1). We conducted several measures to verify the correctness of our data collection. We ensured that the impedance of each electrode is lower than $25kOhm$ throughout the experiment. We asked participants to close their eyes to verify measuring the visual cortex by observing spikes in the alpha band. Then, we stimulated the participants with three test frequencies (i.e., $7Hz$, $8Hz$, and $12Hz$) through a $240Hz$ LED display[43]. We chose these frequencies for initial testing as they worked well during the development process. Through the *OpenBCI GUI*, we observed the signal in the frequency domain to assure the correct SSVEP responses. We continued with helping the participants mount the VR-HMD when responses to all three frequencies were visible. We checked the impedance again after mounting the HMD. If the impedance remained the same, we stimulated the participants in VR with our three test frequencies and checked again the responses to the stimuli in the frequency domain. We continued with the data recording described in Section 9.4.1 when the verification steps were accomplished. Each participant took around 30 minutes to finish the study.

9.4.3 Participants

We recruited 12 volunteers (8 male, 4 female, 0 other), aged between 23 and 33 years ($M = 28.3$, $SD = 3.3$). Three participants had a corrected-to-normal vision, and one participant reported colorblindness. None of the participants stated any neurological disorders, and every participant assured us not to be affected by epilepsy. Participants were asked to rate their experience with VR

[43] Acer LED Display, `https://www.acer.com/ac/en/US/content/predator-series/predatorxb2`, last retrieved on August 12, 2022.

Frequency Triplet (in Hertz)	Accuracy	Precision	Recall	F_1 Score
(6, 8, 10)	83%	.80	.80	.80
(8, 10, 13)	83%	.80	.80	.80
(8, 9, 10)	82%	.79	.78	.78
(8, 10, 12)	82%	.78	.78	.78
(6, 8, 14)	82%	.81	.81	.81

Table 9.2: The five frequency triplets that achieved the highest accuracy.

on a 7-point Likert scale (1: no experience; 7: expert-level experience). Most participants stated that they were familiar with VR ($Med = 4.5$, $IQR = 2.5$).

9.4.4 Classification Results

We assessed the classification accuracy for every possible combination of three frequencies from the literature. This resulted in 84 distinct frequency combinations. We applied the classification procedure described in Section 9.3.2 separately to each participant by training and evaluating a SVM. We averaged the resulting performance metrics of each classifier and for each frequency combination to obtain the best performing frequencies. On average, we received 106 feature vectors per frequency combination and participant for training the SVMs. Each feature vector included 40 features (i.e., one for each frequency power bin). A grid search [212] suggested a radial basis function kernel and a regularization parameter of $C = 2$ for evaluation.

We calculate the precision, recall, and F_1 scores as performance metrics for each participant. In addition, we calculate the accuracy as the number of correct predictions divided by the number of total predictions. We multiplied the accuracies by 100 to obtain percentages. We then calculated the accuracy, precision, recall, and F_1 scores for each participant and for each frequency triplet. We then averaged the accuracy, precision, recall, and F_1 scores of all participants to obtain four single performance metrics. The accuracy ranged between 67% (i.e., the lowest accuracy was achieved by [6, 9, 12]) and 83% (i.e., the highest accuracy was achieved by [6, 8, 10]). Table 9.2 summarizes the five best-performing frequency triplets along with their accuracies. Figure 9.4 shows the confusion matrices of the three best-performing frequency triplets.

We observed the highest classification accuracy for [6, 8, 10] with an accuracy of 83% (F_1 = .80), followed by [8, 10, 13] with an accuracy of 82% (F_1 = .80), and [8, 9, 10] with an accuracy of 82% (F_1 = .78). Overall, high accuracies were achieved for all frequency triplets. An exemplary spectrogram of one participant (P7) shows the distinct pattern of the elicited SSVEP responses in Study I (see Figure 9.5).

Discussion

We conducted Study I to obtain a set of SSVEP frequencies for reliable classification using machine learning. Therefore, participants focused on black and white flickering squares in VR. We used nine common frequencies selected from related work while we recorded cortical data. Afterward, we examined the classification accuracy by evaluating all possible frequency triplets.

Our results show that all frequency triplets provide sufficient accuracy over the expected chance level, where our reported accuracies are similar to values reported by past research [78]. However, a particular difference in accuracy exists between triplets with low accuracy (e.g., [6, 9, 12] reaching 66%) and triplets with high accuracy (e.g., [6, 8, 10] reaching 83%). We noticed that high-scoring frequency triplets have a large number of harmonics in the feature space (i.e., $0.1Hz - 40Hz$). Previous work stated that classification accuracy improves when non-conflicting harmonics are present in the data set [348]. However, this comes at the cost of reducing the number of usable frequencies. For example, $6Hz$ and $12Hz$ share harmonics multiple times. This explains why triplets such as [6, 9, 12] showed a poor performance. Although the best triplets conflict with harmonics as well with higher frequencies, they still provide enough distinct features resulting in a more robust classification. Reaching high classification accuracies is a major objective of BCI research to maintain a solid interaction experience for the user. Hence, we decided to continue with the [6, 8, 10] frequency triplet.

9.5 Study II: Evaluation of Appearance and Accuracy

In our second study, we continued with the three frequencies which we could classify most accurately in Study I. The goal of the second study was to investigate the influence of factors that introduce more realism to the used stimuli. Inspired by previous work [282], we selected a butterfly to elicit

SSVEP responses. We evaluated butterflies with different shapes. Here, we had three levels of *shape realism* and different *stimulus types* which are *flickering* or *flapping* wings.

9.5.1 Study Design

To investigate the influence of different levels of shape realism on SSVEP stimuli, we conducted a within-subjects laboratory user study in VR using our described apparatus (see Section 9.3.1). We used a repeated-measures design to examine the influence of two independent variables on the accuracy of the visually evoked potential. Our independent variables were *shape realism* with three levels (*low* vs. *moderate* vs. *high*) and *stimulus type* with two levels (*flicker* vs. *flap*), resulting in overall six conditions. In each condition, we tested three different frequencies ($6Hz$ vs. $8Hz$ vs. $10Hz$). The conditions were counterbalanced using a Latin-square design. Within each condition, we recorded three trials of each *frequency*. During each trial, we measured participants' EEG response as described in Section 9.3.1.

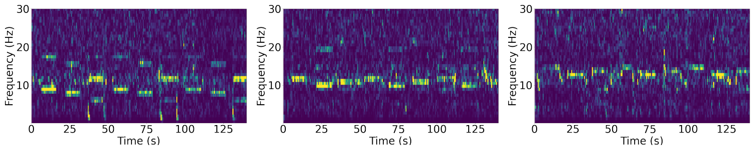


Figure 9.5: Spectrogram of P7 during the pre-study. **Left:** Low frequencies $(8, 9, 10Hz)$. **Middle:** medium frequencies from $(10, 11, 12Hz)$. **Right:** High frequencies $(13, 14, 15Hz)$. When the participant was exposed to a $10s$ stimulus, one can see the higher amplitude of the stimulus frequencies and their harmonics. In between, when now stimulus was applied in the $5s$ break, gaps are visible.

For Study II, we posed the following hypotheses:

H_1 : We expect that the *stimulus type flicker* leads to better classification accuracy than *flap* because the state change for *flicker* is binary while *flap* is a continuous motion that contains mostly intermediate states while the extremes are visible for only a short time.

H_2 : We hypothesize that a higher *shape realism* results in participants perceiving the stimulus as more realistic.

9.5.2 Procedure and Participants

In the beginning, we introduced participants to the purpose and procedure of our second study. Thereafter, we asked participants for their consent to the study conditions. We started the study by setting up the devices involved (see Section 9.3.1). Then, we ensured that the impedance of each electrode was lower than $25kOhm$ and assured that we obtain a clear EEG signal similar to the procedure in Section 9.4.2. If everything looked as expected, we continued with the main part of the study.

For each participant, we tested the six conditions with different levels of *shape realism* and *stimulus type* in our VR app to obtain training data and evaluate the classification performance (see Figure 9.2). We configured our VR app to display the butterfly stimuli of each condition in blocks of 10 seconds for each of the three selected frequencies from our first study. Before each block, there was a break with a duration of 5 seconds. This was repeated three times to obtain a 30 seconds recording of EEG data for each frequency per stimulus. We stored the raw EEG signal in CSV files, including annotations of the displayed frequency. After each trial, we asked participants to rate 7-point Likert statements to assess their subjective perception of the stimulus and gathered informal feedback from the participants in semi-structured brief interviews. Overall, the study took 45 minutes on average. We recruited the same 12 participants that also participated in Study I (see Section 9.4.3).

9.5.3 Results

For descriptive statistics, we report mean (*M*), median (*Med*), and interquartile range (*IQR*). Effect sizes of performed statistic tests are reported with r (r=0.1 small effect, r=0.3 medium effect, and r=0.5 large effect).

Effects on Classification Accuracy

For classification accuracy (in percentage), we report the F1 scores of the classifiers as the harmonic means of recall and precision. We observed that recall and precision performed similarly across conditions, and thus, decided that the F1 score is a good measure to reflect on both. In the following, we compare the F1 scores for the trained classifiers to understand how they are affected by our independent variables. For each participant, we trained one classifier for each condition (*shape realism* x *stimulus type*) and took their F1 scores for our analysis. We adjusted the p-values with a Bonferroni correction considering all comparisons. For adequate statistical power, we investigated our independent variables separately (i.e., fewer overall comparisons result in less *p*-adjustment).

Shape Realism We consider the effect of *shape realism* on the F1 score for each level of *stimulus type* individually (see Figure 9.6). For *flicker*, the median (interquartile-range) F1 scores for the levels of *shape realism* are (in desc. order): *flicker+low*=78.7% (IQR=17.6%), *flicker+moderate*=71.6% (IQR=31.4%), and *flicker+high*=67.5% (IQR=29.3%). A Friedman test revealed a significant effect ($\chi^2(2)$=7.39, p=0.025, N=12). A post-hoc test using Wilcoxon Signed-rank with Bonferroni correction showed a significant difference between *flicker+low* and *flicker+moderate* (W=539, Z=3.24, p=0.005, r=0.38), meaning *low* works significantly better than *moderate* for *flicker*. For *flap*, the median (interquartile-range) recall rates for the levels of *shape*

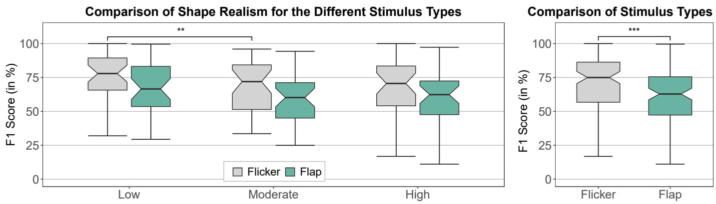


Figure 9.6: Comparison of recall rates. **Left:** comparison of the different levels of shape realism for each of the two stimulus types. **Right:** comparison between the investigated stimulus types: *flicker* and *flap*. The significance levels are: *(<0.05), **(<0.01), and ***(<0.001).

realism are (in desc. order): *flap+low*=70.0% (IQR=29.4%), *flap+high*=60.1% (IQR=21.0%), and *flap+moderate*=57.7% (IQR=17.8%). A Friedman test did not reveal a significant effect (χ^2(2)=1.06, p=0.590, N=12).

Stimulus Type We consider the effect of *stimulus type* on the F1 score. The median (interquartile-range) recall rates for the different levels of *stimulus types* are (in descending order): *flicker*=72.1% (IQR=27.4%) and *flap*=62.0% (IQR=22.8%) (see Figure 9.6). As we do not assume normality and compare two matched groups within subjects, we directly performed a Wilcoxon Signed-rank test. Here we found a significant effect of *stimulus type* on recall rate (W=4229, Z=3.94, p<0.001, r=0.27). This indicates that *flicker* has significantly better performance than *flap*.

Subjective Ratings

After each condition (*shape realism* x *stimulus*), we asked participants to rate two statements with 7-point Likert items (1=strongly disagree, 7=strongly agree). All ratings are shown in Figure 9.7.

Shape Realism For the first statement, “the stimulus shape looked realistic,” the ratings for the conditions are reported in Figure 9.7. A Friedman test revealed a significant effect of condition on rating (χ^2(5)=35.49, p<0.001, N=12). A post-hoc test using Wilcoxon Signed-rank with Bonferroni correction showed significant differences (see Table 9.3).

Natural Movement For the second statement, “the stimulus movement looked natural,” the ratings for the conditions are reported in Figure 9.7. Grouped by the *stimulus type*, the median (interquartile-range) ratings are (in descending order): *flicker*=2 (IQR=3) and *flap*=3 (IQR=3). A post-hoc test

Comparison			W	Z	p	r
flicker+low	vs.	*flicker+moderate*	6	-2.43	0.047	0.50
flicker+low	vs.	*flicker+high*	1.5	-2.96	0.004	0.60
flicker+moderate	vs.	*flicker+high*	2.5	-2.76	0.015	0.56
flap+low	vs.	*flap+moderate*	5	-2.26	0.076	0.46
flap+low	vs.	*flap+high*	0	-3.09	0.001	0.63
flap+moderate	vs.	*flap+high*	0	-2.98	0.006	0.61

Table 9.3: Pairwise comparisons of conditions concerning subjective responses concerning *shape realism*.

using Wilcoxon Signed-rank with Bonferroni correction showed a significant difference between *flicker* and *flap* (W=129.5, Z=-2.07, p=0.037, r=0.24), meaning the movement of *flap* looked significantly more realistic than *flicker*.

Participants' Feedback

Besides the statement ratings on realism and movement, we gathered informal feedback from our participants after each trial. We used thematic analysis to group the feedback of the participants. Two researchers coded statements independently, resulting in 82 open codes. Next, we employed an affinity diagram [183] of the open codes and organized the codes into groups, which were then further refined into themes using an online whiteboard[44].

General Feedback Participants described the butterfly with *low* or *moderate* shape realism as glaring, overwhelming, or exhausting: *"This was exhausting [...] it just blinked and did not move. I stared into whiteness."* (P9 on moderate shape realism, flickering butterfly). Regarding the shape of the butterfly, participants stated that the two wings made were distracting and made it difficult to focus on the stimulus: *"It looked like a TV. And two different sides to focus on are difficult because you don't know where to focus. When I focused on one side, the other side was distracting me"* (P5, on low shape realism, flickering butterfly). Also, the participants missed textures or colors on the wings of the butterflies, *"Colorful wings would be cool! Then I wouldn't even recognize this as a stimulus."* (P8 on high shape realism, flapping butterfly) and P6 commented on a high shape realism, flapping butterfly: *"This was the best stimulus so far. I had no problems focusing on the stimulus, and the movement felt like the natural movement of a butterfly."*

[44] Miro, `https://miro.com`, last retrieved on August 12, 2022

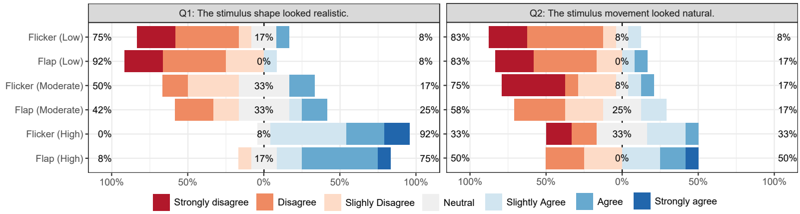


Figure 9.7: Subjective ratings with 7-point Likert-items for each condition tested. **Left:** subjective ratings for the shape realism of the butterfly shape. **Right:** subjective ratings for the naturalness of the butterfly movement.

Flickering On the one hand, our participants stated that flickering was easier and less chaotic to focus on: *"This time I looked more at the wings, it was easier to focus on [the flickering wings] than the moving wings[...]."* (P1, on high shape realism, flickering butterfly). On the other hand, they stated that flickering wings are not realistic: *"Flickering is easier to focus but not that realistic"* (P8 on a moderate shape realism, flickering butterfly).

Flapping On the one hand, the participants stated that the wings flapped too fast: *"It looked more like a flicker book to me."* (P3 on a low shape realism, flapping butterfly). Participants used the butterflies' bodies as a reference point to focus on when the butterflies were flapping their wings: *"[...] When the wings were in motion, the body was easier to focus."* (P1, on high shape realism, flickering butterfly). Some participants perceived the flapping wings as less realistic and stated that the wing motion negatively influenced the focus on the butterfly. On the other hand, the participants liked the flapping wings and stated that the stimulus was less intense than flickering wings: *"The flickering, especially at high frequencies, was unpleasant. This was not the case when the wings were flapping."* (P3 on a low shape realism, flickering butterfly) and *"The realistic, flapping [butterfly] was the most pleasant. Through the flap, it is more pleasant in general and not as intense [as flickering]."* (P2, on high shape realism, flapping butterfly). One participant stated that through a more realistic shape, the flapping motion appeared more realistic: *"[...] the shape of the wings appeared more realistic when they were in motion [...]."* (P1 on moderate shape realism, flapping butterfly).

Focus Several participants stated that the butterfly's body helped them keep their focus on the stimuli while the wings were flapping. They stated that the fixed body was easier to focus on than the moving parts: *"It was easier to focus! I could concentrate on the [butterfly's] body, and the stimulus was around* *it."* (P2, on moderate shape realism, flapping butterfly). Also, the form of the wings helped the participants to maintain focus when the butterfly's wings were flickering: *"The round form makes it easier to focus a circle [...]."* (P1 on moderate shape realism, flickering butterfly). The realistic contours were perceived similarly: *"Through its contours, the stimulus was better to focus."* (P1, on high shape realism, flickering butterfly). In contrast, participants stated to have problems focusing on the butterflies because they were more realistic: *"The stimulus resembles the butterfly flying, and I focused on the shape and details of the butterfly. I did not really know where to focus the stimulus."* (P8, on moderate shape realism, flapping butterfly). Several participants stated that the butterflies with realistic contours were distracting them because they investigated the wings: *"Through the complex form, I tended to investigate it [...]. It was difficult to keep the focus centered on the butterfly because I felt urged to scan the butterfly with my eyes."* (P1, high shape realism, flickering butterfly).

Levels of Shape Realism The shape realism was perceived differently by our participants. The butterfly with a low shape realism was perceived as *"machine-like"* (P9 on a low shape realism, flapping butterfly), or it resembled an *"[...] old TV with an antenna."* (P1 on a low shape realism, flickering butterfly) or it would fit in video games like *"Minecraft"* (P8 on a low shape realism, flickering butterfly). Unlike most participants, one appreciated the butterfly with round wings the most: *"I think that the round wings looked more realistic than the wings with real contours. I find them more pleasant"* (P9). Our participants stated several times that they liked a high level of shape realism: *"The shape of the wings looks realistic here. But I missed flapping wings. This would appear more realistic to me."* (P8, on high shape realism, flickering butterfly). After perceiving the high shape realism butterfly with flapping wings, P8 added *"I think this looks like a butterfly! The shape matches, and it's flapping."*

9.5.4 Discussion

We assessed the different levels of *shape realism* and *stimulus type* of different butterfly configurations in terms of classification accuracy and subjective appearance in Study II. In the following, we discuss the results.

Classification Accuracy We found that *flickering* wings resulted in a significantly higher F1 score. This shows that *flickering* outperforms *flapping* wings in terms of classification accuracy. Therefore, we can accept our hypothesis H_1. We argue that while wings are flapping, the participants could see the white area of the wings growing and shrinking, similar to GSSs [94] or spinning stimuli [413]. This results in a less effective stimulus than black and white flickering wings and is in line with previous observations [94].

When we analyzed the influence of the shape on the classification accuracy, we observed a higher median for a *flapping* butterfly with *high* shape realism than for a butterfly with *moderate* shape realism even though it comprises a smaller white wing area. There is a tendency toward the claims from the literature that suggest that stimuli preferred by users perform better in terms of classification accuracy [94]. But we could not show an effect here. Still, a *flapping low shape realism* butterfly performed best. Here, we must acknowledge that it had the largest wing area. For *flickering* wings, we observed different results. Here, a *flickering* stimulus with *low* shape realism performed significantly better than a *moderate* butterfly. This could be attributed to the smaller white area of the round wings. Further, our participants reported that they scanned interestingly shaped wings and therefore had some difficulty maintaining focus. Participants reported that focusing on the body of the butterfly with round wings was easier due to the gap between its body and its wings. Therefore, the stimulating wings might not be in full focus of the participants. This could result in less classification accuracy. Focusing on details of *flapping* wings might be difficult for users as they move quickly. This could be a benefit of flapping stimuli as users do not tend to focus on details. Instead, they look at the entire stimulus. For *flapping wings*, we did not find any significant differences. We conclude that when designing stimuli, it is important to consider how users perceive the difficulty of keeping their focus on the stimuli. Especially during long-term interaction, this could have a negative impact.

Shape Realism In terms of appearance, our participants rated the *flickering* butterflies with realistic contours to appear significantly more realistic than the butterflies with *low* or *moderate* shape realism. We observed the same for butterflies with *flapping* wings. Therefore, we accept H_2.

Flickering vs. Flapping Subjectively, our participants perceived the flapping butterflies as significantly more natural than butterflies with flickering wings. However, flickering stimuli resulted in higher classification accuracy. Here, we face a trade-off in terms of classification reliability and stimulus appearance. In VR, realism is an important factor for users to immerse in virtual worlds. Therefore, we argue that in some cases, it is acceptable to employ stimuli that appear more realistic, in our case *flapping* wings, and at the same time sacrifice a certain percentage of classification accuracy. For example, in a game, an animal that elicits SSVEP responses could look at the player, but if the detection fails, the player would not notice a big difference. Overall the game would be more interactive. Also, long-term interaction might benefit from visual pleasant stimuli to mitigate adverse side effects on the user like mental load [562] or visual fatigue [351, 352].

When we compared the classification accuracy of our stimuli that were preferred by our participants in terms of *shape realism* and *stimulus type*, we did not observe mixed classification accuracy of stimuli that were rated more visually pleasing than others. We could not show that a visually more pleasant stimulus positively influences the classification accuracy of SSVEP stimuli as suggested by the literature [94] across all levels of shape realism. Still, a *high* shape realism butterfly achieved a slightly higher classification accuracy than a *moderate* one, even with a smaller stimulus area that excites the users' retinas. Here, we suggest further investigating factors of our butterfly stimuli such as the shape, colors as well as textures, or wing speed. Overall, our stimuli that appeared more pleasant to our participants still achieved satisfactory classification accuracies applicable to a wide array of applications in VR.

9.6 Showcase Study: Shoo Away Butterflies

To showcase our butterfly stimuli in a realistic VR application, we developed a VR mini-game. In this game, participants had to focus on three butterflies that were resting within the VE (see Figure 9.1). When focusing on a butterfly was detected, the butterfly would fly up in the air for 4 seconds, and then it would land on the object it flew away from at a slightly different position. The objective during the game was to make the butterflies fly as much as possible within one minute by focusing on them until they fly off.

9.6.1 Apparatus

Different from the first two studies, we developed a VR application that orchestrated a variety of different 3D models to showcase the feasibility of our approach in less controlled conditions. In essence, our VR application resembled a forest scene with three equally spaced out tree stumps (see Figure 9.8). On each of them, a butterfly was resting, and participants were asked to shoo away the butterflies by looking at them. Due to the limited FoV of the VR-HMD, one butterfly was out of view when facing either the left or right butterfly. Nevertheless, since we wanted to investigate the feasibility of our SSVEP approach, we did not distinguish between in-view and out-of-view butterflies but rather completely relied on the EEG signal for triggering them.

To detect the focused butterfly, we streamed the EEG signal via OSC to a *Python* application that runs our pre-trained SVMs. The signal of two channels was first buffered in two First In First Out (FIFO) queues with a maximum length of 200 samples. This matches one second as the *OpenBCI Ganglion* operates at $200Hz$. When the two queues contained 200 samples, we ran our classification every 20ms, which resulted in 50 predictions per second. To classify the signal, we averaged the two channels and normalized the result using *zero-mean normalization*. Next, we applied a band-pass filter from $0.1Hz$ to $40Hz$. We calculated a FFT of the filtered signal and classified the transformed signal using our SVM similar to previous approaches [51, 78]. Here, we used our pre-trained SVMs to detect the focused butterfly. We stored the prediction in a prediction queue with a maximum length of 100 predictions. We then selected the command on basis of a majority vote number of occurrences of a prediction related to one of the three used frequencies. As a threshold for each frequency, we used the *f1-score* from training the classifier. For example, if a class had a *f1-score* of 0.85, we would issue a start command when 85 predictions if this class are present in the prediction queue. When these thresholds were exceeded, we sent commands to the VR game to start the corresponding butterflies. Through this, we minimized the chance of false predictions due to small movements by the participants and through external interference or artifacts.

In the background, we logged the head movement of the participants and the movement of the butterflies as well as in-game events similar to other analytical approaches for MR user sessions [364, 7, 73]. This allowed us to replay the sessions, calculate the participants viewing angles, and determine when the butterflies flew off. Out of the recorded data, we were able to calculate if the butterflies that flew of were in sight of the participants at the given time.

Figure 9.8: The VR mini-game we developed as a showcase for our investigated *stimulus types*. **Left:** stimulus with black and white flickering butterflies wings. **Right:** stimulus with butterflies flapping their wings. **Both:** from left to right, the butterflies were *flickering* or *flapping* with 6, 8, or 10 Hz.

9.6.2 Design and Procedure

Our showcase study was conducted as a within-subjects laboratory user study. We had one independent variable *stimulus type* with two levels (*flicker* vs. *flap*), resulting in two conditions overall. Both conditions used the butterfly with high *shape realism* (see Figure 9.2, right). The first condition employed the butterfly with *flickering* wings (see Figure 9.8, left) and the second conditions a butterfly with *flapping* wings (see Figure 9.8, right). We choose these stimuli based on the rating regarding *shape realism* in Study II: Levels of Realism. Each participant played the game two times, one time for each condition. The conditions were counterbalanced. Each game (condition) lasted exactly one minute. For each of the two conditions, we used one SVM trained with the data from Study II (see Section 9.3.2). After each game, the participants rated four statements on a 7-Point Likert scale. The showcase study took, on average, 15 minutes per participant.

9.6.3 Participants

We recruited six volunteers (2 female, 4 male, 0 other), aged between 23 and 33 years ($M = 29.0$, $SD = 4.69$,$Med = 31.5$, $IQR = 7.0$). Two participants had a corrected-to-normal vision. None of the participants reported colorblindness. None of them stated that they had any neurological disorders, and every participant assured us not to suffer from epilepsy. Participants were asked to rate their experience with VR on a 7-point Likert scale (1 = no experience, 7 = experts). They stated that they were familiar with VR ($M = 2.5$, $SD = 1.52$, $Med = 2.5$, $IQR = 1.75$). Of these six, three already attended the main study, and three did not participate in the prior studies. We deliberately chose three participants that were known to our classifier and three unknown to show that the classification can be generalized to unknown users.

9.6.4 Results

In the following, we report on the results that we gathered for our showcase study.

Stimulus Type

We report the median (interquartile-range) number of butterflies each participant triggered for the different stimulus types: *flicker*=11 ($IQR = 3$) and *flap*=16 ($IQR = 3$). Nevertheless, since the used VR-HMD does not provide eye-tracking, we cannot verify that the number of butterflies triggered contains only correctly triggered ones. Hence, we calculated the angle between the participants' forward vector and the vector pointing towards the butterfly that was triggered, which we refer to as the deviation angle. For each stimulus type, we measured the following median (interquartile-range) deviation angles: *flicker*=26.8° ($IQR = 16.0°$) and *flap*=22.7° ($IQR = 5.1°$). A Wilcoxon Signed-rank test did not reveal any differences between the *stimulus types*. However, upon further investigation, we observed larger differences between participants, particularly between known and unknown participants.

Known vs. Unknown Participants

For the showcase study, we included three participants that were known and three participants that were unknown to our classifier. To understand the influence on the achieved performance, we report the median (IQR) deviation angles (between the forward vector and the vector pointing to the butterfly) for the two types of participants: *known*=12.9° ($IQR = 9.3°$) and *unknown*=15.8° ($IQR = 52.4°$). While the median angles do not differ much, the IQR for unknown participants hints at incorrectly triggered butterflies for *unknown* participants. To investigate this effect, we performed a Wilcoxon Signed-rank test. Here, we did not find a significant effect between known and unknown participants (W=1218, Z=−1.93, p=0.054). All deviation angles for each *stimulus type* grouped by unknown and known participants are shown in Figure 9.9.

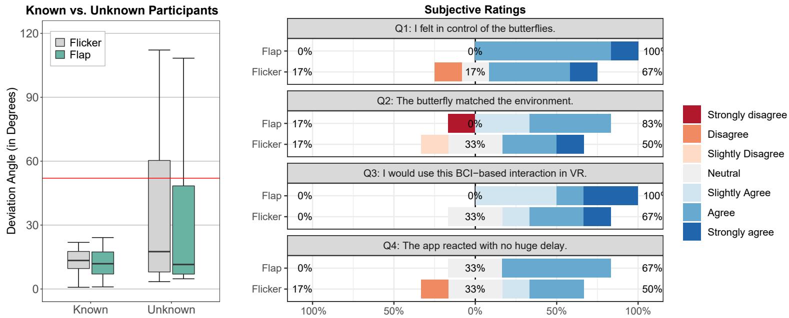


Figure 9.9: Results from showcase study. **Left:** comparison of known and unknown participants concerning their deviation angle (head rotation to the butterfly that was triggered). The red line marks the border of the FoV of the used VR headset (overall 104° but from center to border 52°). **Right:** subjective ratings from participants on four different statements for *flap* and *flicker*.

Subjective Ratings

After each condition (*flicker*, *flap*), we asked participants to rate four statements with 7-point Likert items (1=strongly disagree, 7=strongly agree). All ratings are shown in Figure 9.9. Participants stated that they felt in control of the butterfly for *flicker* ($Med = 6$, $IQR = 1.5$) and *flap* ($Med = 6$, $IQR = 0$). Moreover, they said that the butterfly matched the VE for *flap* ($Med = 5.5$, $IQR = 1$) and slightly for *flicker* ($Med = 5$, $IQR = 2$). Participants agreed that they would use the BCI-based interaction in VR with *flicker* and *flap* ($Med = 5.5$, $IQR = 1.75$). Finally, they slightly agreed that the app reacted with no huge delay for *flicker* ($Med = 4.5$, $IQR = 1.75$), while they agreed for *flap* ($Med = 6$, $IQR = 1.5$).

Participants' Feedback

After the participants played the mini-game in each condition, we gathered informal feedback.

General After the participants played our game in each condition, we gathered informal feedback. Our participants mentioned a delay until the butterflies flew off when they were focusing on them: *"I felt a delay, otherwise, it was very good!"* (P6). P1 stated that *"[...] sometimes the butterflies flew off quickly and sometimes they just do not want to."*. Further, they stated that the interaction *"in a way felt like eye-tracking. When I focus on something it changes like gaze-based applications"* (P5). Moreover, the participants missed colorful butterflies: *"In the current environment they fit, but the colors were a bit off [...]"* (P5).

Flickering Some participants preferred the flickering butterfly over the flapping one: *"Through the flapping wing, it was a bit restless. [...] I liked the flickering more"* (P6). In contrast, participants stated that the flickering butterflies looked two-dimensional: *"They were looking different than the others [flapping butterflies]! They were just 2D and blinking"* (P1).

Flapping Some participants preferred the flapping over the flickering wings: *"[...] It fits the environment, and the butterfly was more pleasant to look at. [...]"* (P3). They stated that flapping butterflies appeared more realistic: *"The movement was more realistic!"* (P4). Another liked the flapping wings but added that some butterflies reacted more quickly than others: *"I like the wings more, and I strongly believe the right butterfly responded quicker"* (P5).

9.7 General Discussion

In the following, we discuss the results from our studies along with limitations and future research suggestions.

Trade-off Between Detection Accuracy vs. Stimuli Appearance Our findings suggest that there is a trade-off between the performance and the appearance of our stimuli. This trade-off should be considered when integrating such stimuli in VR. If the interaction must be robust in terms of classification accuracy, a *flickering* stimulus might be well-suited. When appearance or proper Computer-generated imagery (CGI) is more important than performance, stimuli with matching animation, in our case *flapping* wings, could be integrated into VR as they blend into the surrounding environment through a plausible animation. This would help to preserve the narrative of the virtual experience. We obtained promising feedback from our participants, who stated that more realism might further disguise the fact that our butterflies are SSVEP-eliciting stimuli. We conclude that our findings are transferable findings to other real or fictional animals with wings, including but not limited to birds, flies, bees, or dragons. Beyond these, it is not clear how generalizable our findings are to other objects. However, a wide array of research demonstrates the potential of SSVEP for non-flickering stimuli [413, 19], including ours, suggesting great potential for blending SSVEP stimuli in VR in general.

Level of Detail and Perception Not all VR apps rely on complex graphic pipelines, photo-realistic details, or a high level of detail. Therefore, we argue that stimuli with a less detailed shape, such as the butterfly with round wings, could serve as SSVEP stimuli in VR, which are built of low poly meshes with a minimal number of details. Overall, our participants rated the butterfly with real wing contours as the most realistic but also stated that butterflies with round wings could have use cases. Here, one interesting statement regarding the butterfly with square wings caught our attention. For games such as *Minecraft*, a butterfly would blend into the environment well. So, we argue that the expectation of VR users can influence the perception of the SSVEP stimuli if a plausibility illusion is created [456]. This could be further investigated by embedding different stimuli designs into VR with varying graphical properties (e.g., colors and textures). Hence, our findings are valuable in terms of the evaluated levels of shape realism. We believe that it is important to not entirely focus research on the most realistic SSVEP stimuli only but rather on a variety of different levels of each dimension that the SSVEP design space has to offer. Many parameters can be adjusted when using such SSVEP stimuli in VR. As we did not investigate the whole design space in our evaluation, we believe that our work is an initial starting point that can serve as a basis for future research. Here, the whole spectrum of shapes, different animals or other non-living objects, textures, and colors, as well as more types of animations, span a humongous design space that needs further investigation.

Showcase: Shoo away Butterflies We found that our participants were able to play the VR game with our SSVEP stimuli in the form of butterflies, even though some of them were unknown to the used classifier. We found evidence that inherent properties like the motion of VR objects can be used to elicit SSVEPs and still be part of the VR narrative. Through subjective feedback, we found that the participants felt in control and that our stimuli fit into the VR environment. Nevertheless, participants unknown to the classifier showed a tendency for higher false-positive rates; however, with the low sample of six participants, we did not find any significant differences. The likelihood of false-positive classification of SSVEP responses increases when people are unknown to the classifier. Therefore, we suggest using non-calibrated classification for non-critical applications, where spontaneous interaction is likely, and the number of frequencies is small.

9.7.1 Limitations

We acknowledge various limitations that could have affected our evaluation. First, our stimuli shaped as butterflies are not applicable in every available VR scenario. For example, users would not expect butterflies in an urban setting. This is a limitation of our specific design. To overcome this, creative ideas of VR developers and designers are needed. We outline some inspirational ideas in the future work section. Further, the detection accuracies and the subjective perception of the stimuli could be influenced by the surrounding VR environment. We placed the users in a dark room. This reduced the influence of external factors, and we could focus on the evaluation of the presented stimuli. We argue that the detection accuracies could differ when our stimuli are deployed in more complex VR settings. For example, user movement and different light conditions can influence the interaction with our stimuli. Further, the subjective perception of the stimuli could change. Future research could investigate influencing factors when deploying such stimuli in an end-user VR app. Next, we did not rely on VR-HMDs with integrated eye-tracking. Therefore, we cannot quantify which parts of the butterflies were mostly focused on by the participants and which were not. Eye-tracking could reveal which areas of our stimuli were focused on the most by our participants. This would help to better understand which features of the stimuli attract the attention of VR users.

9.7.2 Future Work

We showed that *flapping* wings could effectively be used as an SSVEP stimulus in VR. This motivates us to outline promising research objectives regarding SSVEP in VR.

The size of our butterflies was larger than butterflies in reality. This was necessary to ensure that SSVEP responses are large enough to be measured by our EEG device. Future work could investigate to what degree the stimuli can be reduced in size while SSVEP responses can still be measured. The decline of the detection accuracy could be attributed to the decreasing wing size of our butterflies when increasing shape realism or the perception of the participants as suggested by the literature [94]. Future evaluations could take this and other variables into account like stimuli distance or moving stimuli as butterflies tend to fly in jagged trajectories. Shrinking the butterflies to a size users are familiar with can further enhance virtual experiences. Also, swarms of butterflies could be investigated.

SSVEP stimuli that allow triggering events or determine the user's focus in future VR games could be generated through the environment itself. One could consider a car driving through a forest. When the sun is low, the light goes through the forest and is blocked by the trees. Depending on the car's velocity, the light is visible only for a specific moment, resulting in a flickering stimulus. This can trigger events when users focus on a specific area of the environment. An equivalent for room-scale approaches could be a lamp behind a fan. The angular velocity of the fan, together with the fan's wings that block the light from the lamp, creates a flickering SSVEP stimulus. VR developers could use such mechanisms to ensure that the user focuses on objects of interest.

With our stimuli, we plan to conduct a study that investigates them in a variety of realistic VR environments. We plan to integrate further environments into our showcase VR game that uses our stimuli to let the player engage in a playful activity. This would allow us to evaluate our stimuli in different real-world scenarios. As our participants wished for colorful butterflies, we would introduce colored butterflies and repeat our studies. In the future, different wing patterns will be investigated, similar to PRCS [597]. Our participants stated that the wing motion was sometimes too fast. Here, we could slow down the wing motion and use a combination of *flickering* and *flapping* wings to elicit SSVEP responses while maintaining realistic wing movement. As we face a large design space here, we will start future investigations with a systematic analysis of influencing factors and parameters to lay out the dimensions which can impact the performance of our SSVEP classifiers. These could be, for example, different lighting conditions, form factors, color, textures, further animations, as well as static vs. moving implementations of the butterflies or other stimuli which elicit SSVEP responses in a similar way. For example, other animals or the aforementioned future work approaches (e.g., lamps or blocked sunlight).

9.8 Conclusion

In this chapter, we investigated SSVEP stimuli in VR in the form of butterflies with three levels of realism. To elicit SSVEP responses, we developed two stimuli types: *flickering* and *flapping* wings. To assess their suitability for interaction in VR, we first extracted three suitable frequencies through a brief literature survey and subsequent prestudy. We conducted our main study with the three best performing frequencies to obtain training data to train classifiers and to assess the subjective realism of our stimuli. We tested two stimuli that were best-rated in terms of appearance by our participants – a butterfly with realistic contours – in a showcase study using either *flickering* or *flapping* wings to elicit SSVEP responses. We showed that our stimuli design in the form of a realistic butterfly with *flapping* wings can be used for SSVEP-based interaction in VR, but is still outperformed by a *flickering* stimulus. Hence, we argue that the stimuli should be selected based on the VR scenario. If performance is required, stimuli with lower levels of realism should be employed. If stimuli should fit the VR environment and robustness can be neglected, then higher levels of realism can be used to enhance the VR experience.

Summary and Key Findings

In this part, we introduced our approaches to integrating the real world into virtual experiences. First, we integrated physical objects from the users' environment to enhance the virtual experiences. Afterward, we tend to the VR users and integrated their neurological responses into the VE to broaden their interaction possibilities. In the following, we present our key findings:

RQ 3: How can we enhance the user's virtual experience by manipulating the appearance of real-world objects in VR?

***Key Finding I*:** We showed that different levels of pen and hand transparency can enhance 2D sketching in VR. On the one hand, we found that a reduced opacity of the pen results in faster sketching. On the other hand, we found that sketching in the direction of the user's hand and arm with an opaque pen resulted in decreased sketching accuracy. Therefore, we suggest adapting the transparency, dependent on the sketching direction dynamically, to reach an optimal accuracy.

***Key Finding II*:** We showed that the virtual representation of a physical prop in form of a box could be scaled up by 50% before VR users recognize a mismatch. Below this threshold, we can trick the proprioceptive sense of the human body and thereby allow for reusing haptic props to mimic the haptics for virtual objects of different sizes.

RQ 4: How can we integrate BCI-based sensing to provide additional interaction modalities in VR?

> ***Key Finding III*:** We presented a way to integrate SSVEP stimuli directly into objects present in VEs. We showed that our stimuli design in the form of a realistic butterfly with *flapping* wings can be used for SSVEP-based interaction in VR. We envision that stimuli are selected based on the VR scenario, thereby allowing for seamless integration and thus, preserving immersion. Here, an important aspect is performance. A *flickering* stimulus might outperform a *flapping* one. If performance is required, stimuli with lower levels of realism can provide robust interaction possibilities. If the stimuli should fit the given VE environment and robustness can be sacrificed, then higher levels of realism can be used to enhance the VR experience. To use such stimuli, designers and developers of VR experiences can use the movement of virtual objects, similar to our approach using a butterfly.

We can answer **RQ 3** with *Key Finding I+II*. First, we showed that we can provide benefit to users when we apply transparency to the virtual representation of integrated physical objects. Here, VR offers the possibility to bypass physical constraints like occlusion, which is an inevitable restriction in reality. We conclude that future VR experiences can benefit not only from mimicking the real world as close as possible but rather from considering if certain constraints from the real world can be circumvented to provide benefits to VR users.

We can answer **RQ 4** with *Key Finding III*. We found a trade-off between the performance and the appearance of our stimuli. We recommend that VR designer and developers consider this trade-off when integrating such stimuli into their applications. If the interaction must be robust in terms of classification accuracy, a *flickering* stimulus might be well-suited. When appearance is important, more pleasant-looking stimuli with matching animation could enhance the VR experiences. To broaden the applicability of our approach, we proposed a bulk of future work. In particular, we face a large design space that needs exploration in future research endeavors.

V

Enriching the Virtual World

In the previous part, we utilized and integrated elements of the real world like physical objects or user data into VR to enhance virtual experiences and broaden interaction possibilities. When we refer to the integration of objects, there is a distinction between objects that have a purpose in the virtual and also in the real world (e.g., a pen or the hands of a user) and objects that are specifically designed to support VR users (e.g., VR controllers). In this part, we focus on the latter. Similar to VR controllers, which are designed with the sole purpose of being the interaction medium to virtual content, we introduce our approaches that can broaden the interaction space in VR. In this part, we focus on two research areas. First, we enhance remote collaboration through passive haptics. Second, we provide haptics to virtual UIs through flying haptic proxies using drones.

One advantage of collaborative work is that it allows one to combine knowledge and collectively shape solutions, thus incorporating different users' perspectives. This can benefit various application areas ranging from problem-solving and content layouting to architecture and manufacturing tasks [205, 273, 511]. In this context, VR is a promising technology that can enable collaboration across a distance. To make the corresponding interaction with virtual content more graspable, we envision that future VR systems could integrate all kinds of physical objects from their environment and employ them as haptic props. This could enable remote users to create a collective solution by using physical objects in their location. Here, the fundamental challenge is the interaction with remote physical objects. One can manipulate the own local object as well as the virtual representation of a remote object but not manipulate the actual remote physical object. Yet, collaborators may be of distinct expertise, where an ability to manipulate remote objects directly can become helpful. Related work, for instance, suggests augmenting objects with motors [99, 416] or using teleoperated robot arms for remote control [127]. Others envisioned indicating the collaborators' manipulation by physically recreating it in their location [191, 174]. However, these approaches either require extensive hardware augmentation or user effort. Thus, we seek alternative ways to tackle this challenge. In this context, we pose the following RQ: **How can we enhance remote collaboration in VR through passive haptic props? (RQ 5)**

Thereafter, we switch from approaches for haptics in remote VR scenarios to haptic feedback through drone-mounted end effectors. In the literature, drones gained a lot of attention [134]. For example, previous research focused on the usage of drones that are employed as physical proxies for virtual objects experienced by users in VR [3, 210, 250, 251]. Here, drones are equipped with haptic props and textures to mimic the haptics of virtual objects experienced or manipulated by VR users. Other approaches used drones to realize UIs in the real world. Gomes et al. presented *BitDrones* a 3D tangible display [153]. Here, drones are brought in the air to build up a flying UI. Different types of drones provide different interaction possibilities. Furthermore, Braley et al. introduced *GridDrones* [63]. Here, numerous drones are controlled simultaneously to create a touchable UI by flying in a specific formation. Each drone resembles one voxel of a shape created by the drone formation. Through different interaction techniques, users could manipulate the flying UI, for example, dragging one drone to move the entire formation. Thus, we argue providing haptics through a generic set of UI elements in VR using drones is a viable solution. In the following, we introduce our approach for such flying input devices. Our approach is based on our *Flyables Toolkit* which we introduced in Chapter 4. Through the evaluation of the *Flyables Toolkit*, we answer the following RQ: **How can we deploy flying UIs to provide haptic feedback in VR? (RQ 6)**

This part includes the following two chapters:

- **Chapter 10:** In this chapter, we introduce a new approach that engages users more actively and closely preserves the notion of physical manipulation across local and remote spaces. Our idea is to use passive haptic props in each physical location for the interaction with virtual objects. These haptic props have a variable representation in the VE and can be used to control the available virtual objects. We explore this in two ways of ownership of the assigned virtual objects: *SingleOwnership* and *SharedOwnership*. *SingleOwnership* restricts collaborators to manipulate only the virtual objects that are associated with their local haptic props, whereas *SharedOwnership* allows transferring virtual objects between remote locations by taking over ownership with haptic props.

- **Chapter 11:** In this chapter, we utilize drones to provide a haptic UI in VR. Therefore, we developed and evaluated the *Flyables* toolkit. The toolkit controls a set of drones equipped with customized 3D-printed UI elements. These elements serve as physical proxies for virtual UI elements with which VR users can interact. This works as follows: As soon as a virtual UI element is visible in VR, a quadcopter equipped with a matching physical UI element – which we call a *Flyable* – is steered to the location where a VR user expects to touch or grab it. During our design process, we developed five 3D-printed UI elements derived from classical input devices: a *button*, a *knob*, a *joystick*, a *slider*, and a *3D* *mouse*. This enables users to experience haptic feedback that matches the shape of the virtual UI element. Additionally, the *Flyable* acts as an input device, fostering a similar experience as using a UI element in the real world (e.g., a real button, joystick, or slider). Moreover, *Flyables* have the advantage over VR controllers that the user does not need to carry them all the time, which leaves their hands free. In the future, this could enable a more natural gestural interaction [313, 331, 520]. Finally, we present a related evaluation of drones landing on the human body to pave the way towards mobile VR. In particular, we envision drones starting from the user's body, serving as a flying UI and then landing when an interaction is not needed anymore.

Chapter 10

Haptic Props for Remote Collaboration in VR

This chapter is based on the following publication:

- **Jonas Auda**, Leon Busse, Ken Pfeuffer, Uwe Gruenefeld, Radiah Rivu, Florian Alt, and Stefan Schneegass. "I'm in Control! Transferring Object Ownership Between Remote Users with Haptic Props in Virtual Reality". In: *Symposium on Spatial User Interaction*. Virtual Event, USA, 2021.

Teaser Video | Presentation Video

(QR Codes are clickable in PDF)

Lots of future collaborative work could shift to VR, and thus, collaborators can be located apart from each other. With technical advancements, we envision that future VR systems could integrate physical objects and provide them as haptic props. As such, we think that haptic props can give remote users the possibility to create a collective solution by using physical objects present in their location. Here, the fundamental challenge is the interaction with remote physical objects. In the following, we investigate how users can interact with remote objects using local haptic props. Therefore,

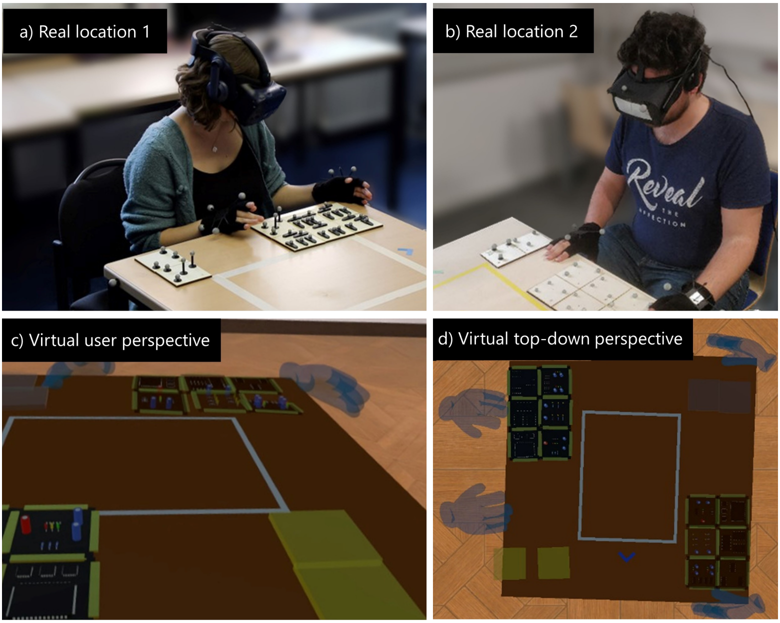


Figure 10.1: Remote VR collaboration can be extended with physical elements such as tables and props (a-b). Physical local and virtual remote objects are mixed in the UI (c-d) to seamlessly interact with all the objects.

we developed a distributed VR collaboration system using our *VinteR* infrastructure (see Chapter 3). We used our distributed environment to answer the following RQ: **How can we enhance remote collaboration in VR through passive haptic props? (RQ 5)**

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

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

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

10.1 Related Work

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

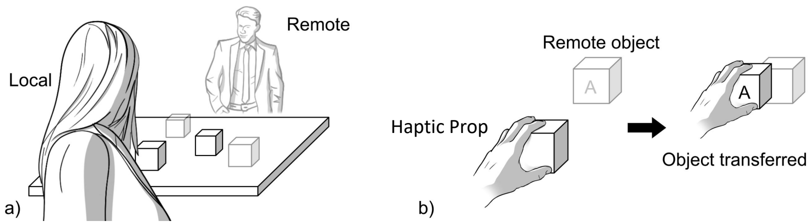


Figure 10.2: (a) A local and a remote user collaborating using virtual objects which are assigned to haptic props. (b). A remote object is transferred to the local object. This transfer can be triggered when a local object intersects a remote object.

10.1.1 Video-based Remote Guidance

As one of the first efforts, Kuzuoka investigated experts collaborating remotely over a screen with a HMD user [265]. The user's HMD included a small display that showed the collaborator's finger pointer image to indicate position. The evaluation showed that gestures improved task performance, with fewer words needed. Other methods for providing input to the collaborator are annotations through gestural sketching [376], visual hand embodiment, and cursor pointers [137]. The latter describes two fundamental ways to support the collaborator: pointing gestures for reference and representational gestures to convey the form and nature of actions. Kirk and Fraser compare unmediated hands, hands together with sketching, and digital sketching only, either presented on a monitor or projected into the work space [247]. No difference was found for output location (monitor or projected), but hand gestures had the highest performance. Others extended screen-based input to communicate rotation and translation of objects [5].

10.1.2 VR-based Collaboration

Traditional voice or video-based remote guidance confines the collaboration, e.g., from ambiguous language [493] or confusion [196]. Hence, VR-based collaboration approaches that go beyond voice and video-based guidance are promising for co-located [375] and remote collaboration [52]. It is beneficial for the experience when collaboration happens synchronously [173]. However, collaboration can be asymmetric, meaning users can collaborate using different technologies [471, 219]. Moreover, previous work shows that 3D-based collaboration is not limited to two users [433, 179] and allows group-to-group telepresence [45]. Yet, it requires efficient interaction concepts to enable fluid collaboration [560].

An essential part of remote 3D-based collaboration is reconstructing collaborators' bodies [203, 263] and their physical environment [142], allowing scenarios such as *Holoportation* [374]. Awareness cues, such as gaze and head movement, can be added for a more realistic collaboration [391, 482, 418]. Previous work found task performance to benefit from a combination of these awareness cues [175]. Others have explored how hand gestures and sketches can be integrated into collaboration scenarios [144, 461]. Studies found that hands are very intuitive [495] and increase task performance accuracy [461]. Hence, we utilize them for our scenario, empowering collaborators to communicate via pointing and gestures.

10.1.3 Physical Object Integration

Tangibles

Tangibles allow computer interfaces to be closer to the physical world by providing users with haptic feedback [174]. They can enhance task performance (e.g., allow for more precise input [99]), achieve a higher learning gain, and perceive problem-solving as playful [440]. Tangible interfaces for collaboration were introduced in 1998 [66]. They often require active components to reflect the movement of the tangibles at other physical locations [415]. Prior work explores scenarios, such as playing air hockey over distance [340] or transmission of shapes [283]. Nonetheless, the active components remain technically challenging, making them less generalizable (cf. air-hockey scenario [340]).

Haptic Props

Combining tangibles with VR is promising as aspects of the physical object (e.g., visual appearance) can be added in real-time, enabling a more universal usage [191]. These generic physical objects are often referred to as haptic props, designed to give users the sensation of touch (e.g., as passive [316] or active haptic props [191]) without a strict 1:1 mapping between object and function. How to enable more expressive physical sensations in VR has been explored before. For example, people can physically move objects in the background of the virtual session [92, 88], the prop itself can dynamically change weight [581], and can be actuated through robots [320, 595] or quadcopters [3]. It is also possible to use dynamic repurposing of interaction elements, such as the passive haptic [36] or the user's manual input [89, 594] to be able to interact with a more diverse set of props. Complementarily, our research investigates the increasing expressiveness of haptic props for remote collaboration where local and remote props are mixed.

Collaborative Haptic Props

For co-located collaboration, these haptic props can be shared by users [191], whereas if remote, each collaborator needs their own set of haptic props [112]. Previous work frequently studied asymmetric collaboration that uses a combination of AR for a novice user on-site and VR for a helping remote expert [371, 85, 120]. Nevertheless, in many scenarios it makes sense to utilize symmetric collaboration between VR users (e.g., problem-solving [273], content creation [98], or training [179]). Different types of active haptic props have been proposed in the literature that can reflect manipulations by remote collaborators [112, 191]. Additionally, the teleoperation of a robotic arm can allow users to manipulate remote objects [127]. However, these systems are more challenging to construct and require additional components such as motors or displays. We extend the prior work by a study of how remote and local users can interact with passive haptic props and utilize them in a synchronous collaboration task.

10.2 Haptic Props for Collaboration

We introduce our approach to collaboration using passive haptic props in an immersive VR environment (see Figure 10.2). Our approach is split up into two integral parts – *SingleOwnership* and *SharedOwnership*. First, we introduce how we use passive haptic props to interact with virtual objects, and we present how collaborators can help others to solve tasks by creating virtual instructions using these props (*SingleOwnership*). Second, we describe techniques for sharing ownership of virtual objects across remote locations using haptic props. These techniques are inspired by established concepts like *copy* and *cut* known form standard desktop PCs (*SharedOwnership*). Since concepts are well-known and ubiquitously available, we were interested in how they apply to the utilization of haptic props.

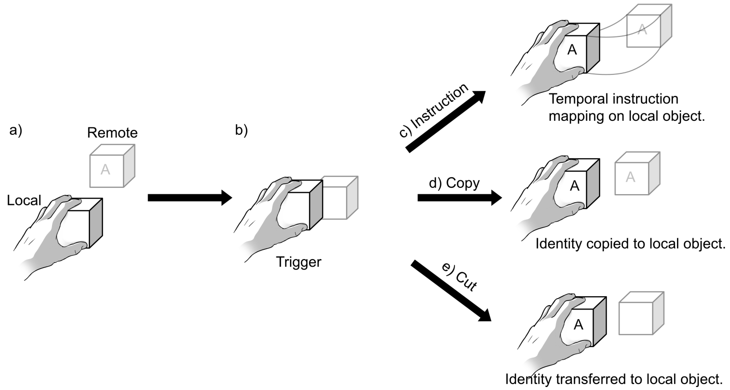


Figure 10.3: Three ways of handling ownership of the local user to a remote user's object. First, intersecting a local object with a remote object starts the interaction (a-b). Then, an instruction indicates where to place the remote object (c). Techniques (d) and (e) transfer the ownership from a remote to a local user. Either a copy of the virtual object is created (d), or the identity of the virtual object is assigned to the local haptic prop (e). The remote object then turns into a blank.

10.2.1 Interacting with Haptic Props

In a remote collaboration scenario, each collaborator possesses a set of haptic props which are mapped to virtual objects (see Figure 10.2a). The goal is to place the virtual objects in a specific arrangement using haptic props. As it is not possible for a local collaborator to move remotely located haptic props, we need a mechanism to manipulate virtual objects mapped to remote haptic props using local haptic props. For example, in Figure 10.2b, a remote object is reassigned to the local haptic prop by transferring its virtual representation. This is one example of how haptic props can be used to interact with remote objects. To enable seamless collaboration, haptic props need clear semantics. In the following, we introduce how we accomplished that by giving our haptic props two states.

Assigned Haptic Props and Blank Haptic Props

Our collaboration techniques are based on two different states of haptic props. The haptic props can either be assigned to virtual objects that are part of the collaboration task or can be blank. If the haptic prop is assigned to a virtual object, the collaborator that physically possesses the haptic prop is the owner of the virtual object and can move it around in VR. If the haptic prop is blank, it can be used to interact with virtual objects assigned to remotely located haptic props (see Figure 10.2b). These two states form the basis of our collaboration techniques. In the following, we introduce our techniques in greater detail.

10.2.2 Techniques for Single Ownership

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

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

Haptic Props for Remote Instructions This technique allows collaborators to create instructions for each other using blank haptic props similar *Virtual Replicas* introduced by Oda et al. [371]. *Virtual Replicas* are representations of physical objects that are manipulated by a remote collaborator. The virtual replica can be augmented virtually by an expert with annotations to instruct the remote collaborator. This helps in scenarios in which experts give instructions to trainees or people with different levels of expertise collaborate. We combine remote instructions with haptic props to allow for the natural creation of instructions for remote collaboration. Our technique allows collaborators to intersect a blank haptic prop with a virtual object that is assigned to a remotely located haptic prop (see Figure 10.3 a-b). This triggers the creation of an instruction that associates the virtual objects with the blank haptic prop (see Figure 10.3 c). The remote collaborator can now follow the instruction to place the virtual object correctly.

10.2.3 Techniques for Shared Ownership

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

Taking Over Ownership via Copy One way to retrieve ownership of a virtual object is to copy it (i.e., assigning it from a remote to a local haptic prop). To do so, a collaborator uses a blank haptic prop. To create a copy, a collaborator intersects a blank prop with a virtual object assigned to a remote haptic prop. (see Figure 10.3 a-b). The virtual object is copied to the blank haptic prop (see Figure 10.3 d). Now the copied object can be moved to the correct position without the collaborator's help. The remote collaborator keeps the piece assigned to their haptic prop.

Taking Over Ownership via Cut Taking over ownership of a virtual object can be accomplished by re-assigning it from a remote haptic prop to a local blank haptic prop. Similar to taking over ownership by copying a virtual object, cut allows a collaborator to use a blank haptic prop to retrieve ownership of a virtual object. To cut a virtual object, a collaborator intersects a blank haptic prop with a virtual object of the remote collaborator (see Figure 10.3 a-b). Then it is assigned to the blank haptic prop, and the remote haptic prop turns blank (see Figure 10.3 d).

10.3 Implementation

To evaluate the different collaboration techniques, we developed a distributed synchronized collaborative VR environment in which two collaborators can interact to accomplish their tasks. It is based on using a VR headset and motion-tracking technology at each location. This allows collaborators to be immersed in a VE integrating tracked physical components into the virtual scene. The code of the project is available under MIT license on GitHub[45].

10.3.1 Architecture

The environment consists of multiple instances of an application running in parallel in two separate locations. Each location uses an *OptiTrack* motion

[45] I'm in control on GitHub, `https://github.com/jonasauda/im_in_control`, last retrieved on August 12, 2022

capture system (120Hz, latency $\approx$ 8 ms, 0.02 mm precise) to track the collaborator and passive haptic props. In both locations, we calibrated the *OptiTrack* system. Our systems reported a mean 3D error of $<$ 0.5 mm in both our labs. In both locations, we calibrated the HMD systems and aligned them with the *OptiTrack* coordinate system. The arrangement of the cameras did not meet any special requirements except for providing sufficient tracking quality in the collaboration area. In our setup, the first location used an *HTC Vive Pro*, and the second location an *Oculus Rift*. The application was created with *Unity3D* and enables users to join a shared VE and interact with the given virtual objects that were assigned to haptic props. To allow for interaction between the two locations, local spatial data is synchronized in real-time with data from the remote client application via our *VinteR* middleware in distributed location mode resulting in a seamless, location-spanning VR environment (see Chapter 3).

10.3.2 Mixing the Virtual Environment with the Real-World

We created a VE consisting of a room with a table in the middle (see Figure 10.1 c-d). For each location, real-world objects can be integrated into the environment to enable VR-mediated collaboration (see Figure 10.1 a-b). Static objects such as tables, which have physical representations in both locations, are implemented as shared elements within the VE. Optically tracked haptic props are present on the table at the location of each collaborator. Virtual objects are linked to these haptic props. The motion of each tracked object is then applied to its virtual representations. Virtual objects present at the remote location are rendered transparent to easily indicate which objects are assigned to local haptic props and which to remotely located ones (see Figure 10.1 c). To give the collaborators a representation of themselves, the system tracks their hands via tracking gloves. We only show the hands of the collaborator, not a full avatar. We did not implement full finger tracking in the current stage of the system. As we had plenty of optically tracked objects, we went for a more simplistic approach. Hence, only a hand with static fingers was shown. Nevertheless, this still enables user-to-user pointing to collaborate. Collaborators were able to interact with the provided haptic props with their hands.

10.4 Evaluation

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

10.4.1 Virtual Environment

Our application allowed collaborators of each location to meet at a virtual table in the middle of a virtual room (see Figure 10.1). The tabletop measured 80cm $\times$ 80cm. Our VE consisted of a simple room with white walls and a wooden floor, clear of any distractions. At the table, the collaborators worked on the collaborative puzzle task. At each physical location, a collaborator sat at a real table in the middle of a tracking space. The virtual and physical tables match exactly in size to prevent any mismatch. The collaborators sat across from each other during the collaborative task.

10.4.2 Collaborative Puzzle Task

For the collaboration, we chose a circuit design scenario. The circuit aspect was not important to the evaluation but should give the impression of a meaningful task. The task resembled a puzzle task with circuit elements, which we call *puzzle task* from now on. The objective for a pair of collaborators was to assemble a simplified and scaled-up printed circuit board consisting of *Microprocessor* parts and corresponding *Circuit* parts (see Figure 10.4-a). The required arrangement consisted of 12 square components, represented by 10cm $\times$ 10cm wooden pieces that we call haptic props. The task was designed to elicit collaboration: each collaborator had knowledge about half of the complete solution. Hence, to complete the task, the collaborators had to support each other by sharing knowledge. The collaborator in one location was provided with a plan showing the target positions of *Circuit* parts, the

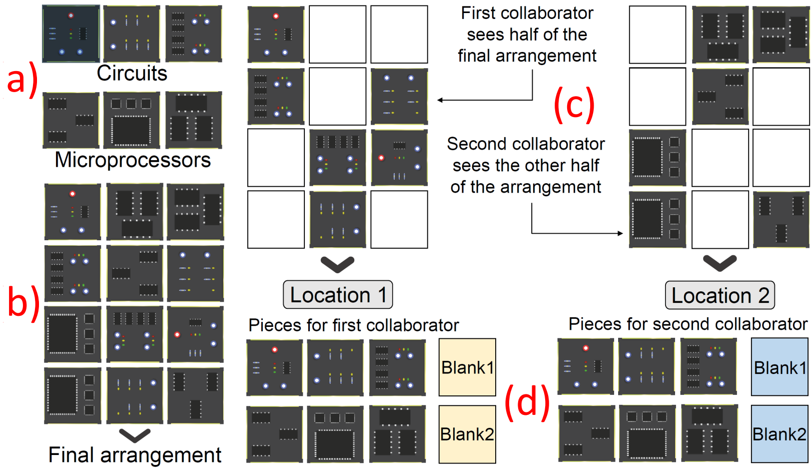


Figure 10.4: Puzzle Task: (a) The *Circuits* and *Microprocessors* pieces. (b) Plan showing the required arrangement of the pieces. (c) The first and second collaborator's part of the solution (exclusive knowledge). (d) components available at each location at the start.

other one with the target positions of *Microprocessor* parts (see Figure 10.4-c). At the beginning, each collaborator had six local parts: three of the type *Microprocessors* and three of type *Circuits* (see Figure 10.4-d). Hence, the collaborators could only place three of the six initial parts on their own and then had to collaborate to complete the arrangement.

10.4.3 Study Conditions

We explored *SingleOwnership* using two conditions: using haptic props to collaborate without interacting with remote virtual objects (*Baseline*) and using haptic props to instruct a collaborator (*Instruct*). Also, we explored *SharedOwnership* using two conditions: using haptic props to copy remote virtual objects (*Copy*) and using haptic props to transfer remote virtual objects to local haptic props (*Cut*). The different conditions can be seen in Figure 10.5 and are described in more detail in Section 10.2.2 and 10.2.3. During *Copy*, participants could revert puzzle pieces to blank haptic props by moving them into a dedicated red area in VR.

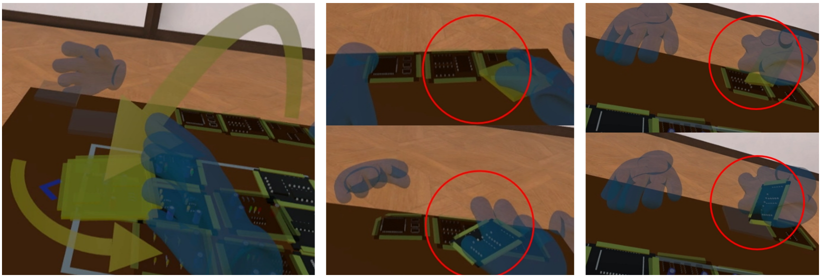


Figure 10.5: Left: An example of *Instruct*, where arrows indicate the position and orientation of the instructional object. Middle: *Copy* to copy a puzzle piece with a haptic prop by moving it inside the piece (top), hold for a second, then move out (bottom). Right: Similar procedure, but for *Cut* where a haptic prop retrieves ownership of a puzzle piece (and the original is removed).

10.4.4 Procedure

In the beginning, we welcomed our participants to the study. We introduced the overall procedure and answered open questions. After our participants gave their informed consent, we recorded demographic data. Then we situated them at the table and provided the VR-HMD and tracking gloves. We established a communication channel between the two locations using Skype[46]. The two collaborators could briefly introduce themselves. Each group of collaborators consisted of one participant and one confederate. The confederate was instructed to act as a newly instructed participant and did not know the research objectives. The confederate adjusted to the working pace of the participants. Further, the confederates were not instructed to make mistakes intentionally. In total, two different persons acted as a collaborator – one self-identified as male and one as female. We did not tell our participants that they were collaborating with a confederate. After both collaborators were situated at the desk and were provided with a VR-HMD, we introduced them to the collaboration task. Each participant completed the task in four conditions, with each condition involving two trials. To account for learning effects, we only took the second trial into account in the analysis. In the first trial, we made sure that the participants understood how to collaborate using the provided collaboration technique. For each condition, we measured task completion

[46] Skype, `https://www.skype.com`, last retrieved on August 12, 2022

time, the number of actions needed to fulfill the task, and the user experience (UEQ) [442]. For the study, the order of the conditions was counterbalanced. After each condition, the participants also filled out a questionnaire about helpfulness, verbal communication, and quality of collaboration. The study concluded with a brief interview session. Each participant took, on average, one hour for the study. We used a screen capturing tool to record the virtual setting during the study for later analysis.

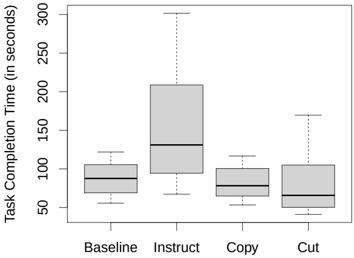
10.4.5 Participants

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

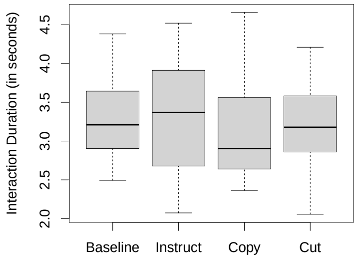
10.4.6 Results

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

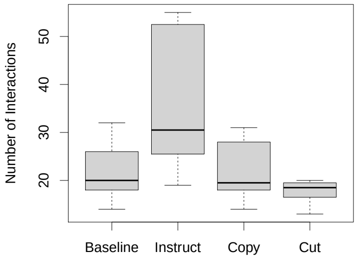
Task Completion Time We analyzed the TCT for each condition (see Figure 10.6(a)): for *Baseline* we observed an mean TCT of 88.89s ($SD = 21.72s, Med = 87.60s, IQR = 33.88s$), for *Instruct* 152.58s ($SD = 73.96s, Med = 131.06s, IQR = 111.88s$), for *Copy* 82.15s ($SD = 21.70s, Med = 78.20s, IQR = 32.32s$) and for *Cut* 80.89s ($SD = 38.42s, Med = 65.71s, IQR = 52.60s$). The Friedman test showed significant differences between the conditions (χ^2(2)=16.90, p=0.001, N=12). A post-hoc test using Wilcoxon Signed-rank with Bonferroni-Holm correction revealed significant differences between *Baseline* and *Instruct* (W=4, Z=-2.746, p=0.021, ϕ=0.56), *Instruct* and *Copy* (W=73, Z=2.67, p=0.029, ϕ=0.54), and *Instruct* and *Cut* (W=78, Z=3.06, p=0.001, r=0.63). Participants were slower in the *Instruct* condition than in *Baseline*, *Copy*, or *Cut*.



(a) Task completion times.



(b) Interaction duration.



(c) Number of interactions.

Figure 10.6: Results on interactions with haptic props.

Interaction Duration We compared the interaction duration with the haptic props of each condition. The mean interaction duration was 3.30s ($SD = 0.56s, Med = 3.21s, IQR = 0.72s$) for *Baseline*, 3.29s ($SD = 0.77s, Med = 3.37s, IQR = 1.14s$) for *Instruct*, 3.13s ($SD = 0.68s, Med = 2.90s, IQR = 0.76s$) for *Copy* and 3.52s ($SD = 1.41s, Med = 3.18s, IQR = 0.71s$) for *Cut* (see Figure 10.6(b)). A Friedman test showed no significant differences between the conditions (χ^2(2)=0.90, p=0.825). We compared the number of interactions with the haptic props (see Figure 10.6(c)). For *Baseline*, we observed a mean number of interactions of M=21.75 ($SD = 5.28, Med = 20.00, IQR = 7.50$), for *Instruct* we observed M=35.67 ($SD = 13.43, Med = 30.50, IQR = 26.50$), for *Copy* M=22.17 ($SD = 5.56, Med = 19.50, IQR = 10.00$) and for *Cut* M=20.75 ($SD = 9.56, Med = 18.50, IQR = 2.50$). A Friedman test showed significant differences (χ^2(2)=17.07, p<0.001, N=12). A post-hoc test using Wilcoxon Signed-rank with Bonferroni-Holm correction revealed significant differences between *Instruct* to *Baseline* (W=72.5, Z=2.633, p=0.032, *r*=0.54), *Instruct* to *Copy* (W=63, Z=2.71, p=0.023, *r*=0.55), and *Instruct* to *Cut* (W=78, Z=3.07, p=0.003, *r*=0.63). While using *Instruct*, the collaborators had to place two haptic props. First, one collaborator had to place one puzzle piece to create an instruction. Then the other collaborator had to place the corresponding puzzle piece according to the created instruction. Hence, we observe a higher number of interactions. Therefore, this result is dependent on the design of the technique rather than the collaboration performance.

User Experience Questionnaire Participants were asked to rate basic attributes of their experience after each condition using the *User Experience Questionnaire* (UEQ). We computed the hedonic, pragmatic, and overall quality of each interaction technique (see Figure 10.7). The overall scores are:*Baseline* M=2.00 ($SD = 1.52, Med = 2.00, IQR = 2.16$), *Instruct* M=1.85 ($SD = 0.84, Med = 1.81, IQR = 1.34$), *Copy* M=1.63 ($SD = 1.09, Med = 1.75, IQR = 1.94$) and *Cut* M=1.89 ($SD = 0.88, Med = 1.94, IQR = 1.56$). A Friedman test showed no significant differences between the conditions (χ^2(2)=1.89, p=0.60, N=12).

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

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

The *Instruct* condition was perceived very positively due to its low mental demand (*"It was intuitive and easy to follow the other person"* [P3], *"You could easily see what to do"* [P12]) and efficiency (*"We could multitask and already show each other where a tile would need to go"* [P1]). P8 stated that this condition brings about *"better collaboration compared to cut or copy where*

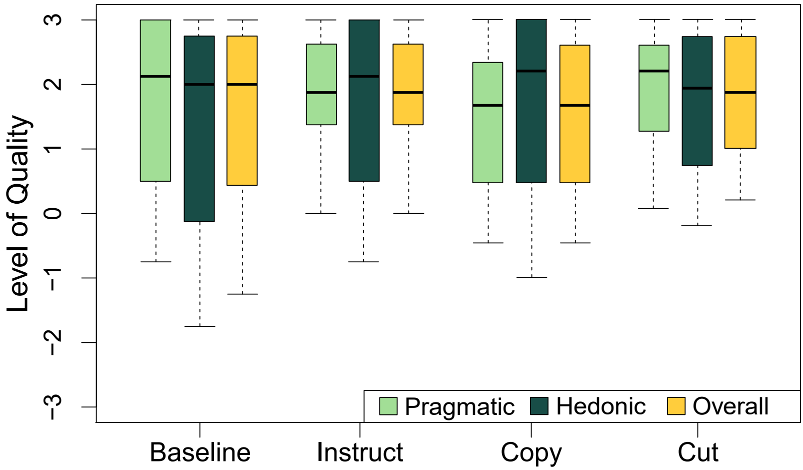


Figure 10.7: The scores of the User Experience Questionnaire.

no communication was necessary - here we had to work together to solve the task". On the other hand, P8 also noted that it was difficult to show the exact rotation of a component using instruction objects.

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

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

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

Collaboration Strategies We asked participants about any strategies they had developed throughout the study. Several participants reported that they always placed those components they had information about first. Then they turned their attention to their partner and the remaining components [P3, P7, P8, P12]. P7 considered the difficulty of describing a particular component's target position before deciding where to place components. By placing components on positions that *"would be more complicated to describe"*, P7 avoided a difficult description. As each component exists twice and target positions are interchangeable, there is an alternative target position for each component.

10.5 Discussion

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

Instructions Take More Time The addition of instructive props will, as expected, take more time than the baseline, albeit being useful to precisely guide the partner. We noted that the instructions affect the communication behavior; users stated to communicate less. This is in line with prior work on remote and immersive collaboration, such as Kuzuoka's Spatial Workspace Collaboration [265]. Less communication can be disadvantageous when engagement with peers is required but can be beneficial as well, e.g., using communication resources for other purposes. Furthermore, instructions can be created by one collaborator, who can then move on to the next object for an asymmetric way of interaction.

Baseline without instructions was perceived positively by the participants. They appreciated that they could use pointing to indicate the correct position of puzzle pieces. Another interesting aspect is how instructions might influence *learning* compared to a spoken description. Prior work showed that visual instructions generally lead to higher recall and rule transfer gains [319]. As a result, instructions might be particularly useful in application areas that include a learning process.

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

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

User Experience Overall, for all conditions, participants rated their user experience as high. The *Baseline* was rated highest, and *Cut* was rated lowest, with a small difference of 0.11. Here, a trend towards the higher end of the scale could be observed (see Figure 10.7), and we think a ceiling effect was present here. Thus, we did not observe any significant differences between the conditions.

Limitations We investigate haptic props with a particular form factor and made of a particular material (wood). This was appropriate for our use case since all haptic and virtual objects were similar in shape and size. A takeover in ownership via *Cut* and *Copy* may be perceived differently when the size of haptic props and virtual objects differ. Moreover, we used optical tracking to link haptic props to their counterparts that are shown to the collaborators. While collaborating, the collaborators had to make sure the optical markers of the props were not accidentally covered by their hands. It was possible to interact with the haptic props without covering the markers. Yet, this might have influenced collaboration. To have more control and reduce recruiting efforts, we used confederates. We created different levels of 'expertise' through training. However, this was not known to the participants. We instructed the confederates not to take over the collaboration and act as if newly introduced to the task. The confederate adjusted to the working pace of the participant but did not intentionally make mistakes. To our knowledge, no participant recognized that they were interacting with our confederates. Furthermore, participants completed each condition twice. We only evaluated the second attempt. Thus, we could instruct confederates to help the participants in the first attempt to ensure familiarity with the corresponding collaboration process. Nevertheless, using confederates with a certain knowledge of the task might bias the results by affecting the collaboration behavior. Pairs of novice collaborators might collaborate at different speeds or might communicate more frequently to exchange knowledge on how to use the different collaboration methods. Collaborators might have different levels of expertise [371, 85, 120] which also can influence collaboration performance. For example, a novice collaborator can adapt to the behavior of a collaborator who has a certain expertise. Finally, our smaller sample size increases the likelihood of Type II errors. To confirm our results, further investigations with larger sample sizes are required.

Future Work We envision haptic props as a scenario-specific tool that, for instance, could be ordered with the desired shapes for a domain-specific task, such as virtual meetings, media production, or interior design, where the number of shapes is foreseeable. For leisure activities such as gaming, a generic set of haptic props may be sufficient. Such a set does not necessarily match all the potential shapes of virtual objects within a VR game. However, this might still be acceptable if efficiency and accuracy are not the primary objectives. Future investigations could focus on enabling more generic forms that make use of dynamically fabricated or even shape-changing objects [338].

10.6 Conclusion

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

Chapter 11

Using Drones to Enhance Virtual Reality

This chapter is based on the following publications:

- **Jonas Auda**, Nils Verheynen, Sven Mayer, and Stefan Schneegass. "Flyables: Haptic Input Devices for Virtual Reality using Quadcopters". In: *Proceedings of the 27th ACM Symposium on Virtual Reality Software and Technology*. Osaka, Japan, 2021.
- **Jonas Auda**, Martin Weigel, Jessica R. Cauchard, and Stefan Schneegass. "Understanding Drone Landing on the Human Body". In: *Proceedings of the 23rd International Conference on Mobile Human-Computer Interaction*. Toulouse & Virtual, France, 2021.

Current VR systems provide immersive virtual experiences with high-quality visual and auditory stimuli. Designers can use such environments to present endless virtual worlds with myriads of interactive objects. However, the interaction capabilities are limited, as the most popular devices for manipulating virtual objects are controllers the user

Flyables: Haptic Input Devices for Virtual Reality using Quadcopter

Teaser Video Presentation Video

Understanding Drone Landing on the Human Body

Teaser Video Presentation Video

(QR Codes are clickable in PDF)

carries. While controllers provide great input capabilities for VR, the output capabilities are still limited. The haptic feedback controllers offer cannot simulate the variety of textures and form factors of virtual objects. Thus, researchers are investigating possible ways to overcome this limitation [589, 198, 3, 508, 431]. Drones have shown great potential to act as flying UIs [134] or can assist the users autonomously [8]. In VR, plenty of research has focused on employing drones as physical proxies for virtual objects [3, 210, 250, 251]. Here, drones can act as an ungrounded physical proxy to a simulated virtual object [325]. Therefore, they can carry haptic props and textures to mimic the haptics of virtual objects perceived or manipulated by VR users.

In this context, we used our *Flyables toolkit* (see Chapter 4) to evaluate flying haptic input devices, which arrange themselves autonomously around the VR users. After that, we investigate ways to land drones on the human body to lay the foundations to understand how we can deploy such drones ubiquitously. For instance, to provide mobile haptic feedback in nomadic VR systems [165].

In this chapter, we answer the following RQ: **How can we deploy flying UIs to provide haptic feedback in VR? (RQ 6)**

11.1 Understanding Flying User Interfaces for VR Using Flyables

We conducted an explorative user study with 12 participants to compare the *Flyables* toolkit to state-of-the-art VR controllers. Specifically, we designed four different VR scenarios to showcase the functionality of *Flyables*. These scenarios could be controlled using *Flyables* or standard VR controllers. We gathered data on performance, usability, and physical movement, as well as qualitative feedback using post-study interviews. Although the *Flyables* toolkit does not outperform standard VR controllers in terms of precision and task completion time in its current state, it can enrich virtual UI elements with appropriate haptic feedback and induce greater body movement. The contribution of this chapter is threefold: We provide the *Flyables* toolkit as open-source software together with the 3D models of our five UI elements. We compared *Flyables* to VR controllers. The results highlight the toolkit's strengths, weaknesses, and future challenges. We outline possible research challenges for improving the *Flyables* toolkit. These include how *Flyables* can be used to provide additional force feedback or can be designed to be repurposed automatically.

11.1.1 Related Work

Traditional VR applications provide haptic feedback through controllers (e.g., by applying vibration to the user's hands). To overcome the limitations of current controllers, drones acting as haptic proxies for virtual objects have become a popular research topic.

Knierim et al. showed how to use drones as physical counterparts to virtual entities [251]. They designed a scenario in which a bumblebee attacks a user in VR. In reality, a drone stings the user with a small stick. They ensured user safety by using a drone that could not harm the user, as it was not powerful enough to pose any risk of injury. Hoppe et al. showed that drones providing haptics for virtual objects resulted in a greater sense of presence in VR [210]. Abtahi et al. later introduced safe-to-touch drones [3]. In a virtual shopping scenario, they evaluated different styles of haptics provided by such a drone. For example, the drone could be equipped with textiles to mimic the texture of virtual garments. Further, the drone could position itself in the room and be picked up by the user to provide haptic feedback. A VR user could reach out for the drone to pick up virtual garments. Through a preliminary study, they could show that their participants successfully interacted with the drone while shopping in VR. Abdullah et al. used drones to simulate the weight and stiffness of virtual objects [1]. Here, a drone applied a downward force matching the weight of a virtual object that a VR user was holding. In contrast, stiffness could be simulated with an upward force. Another approach to enhance VR experiences with drones uses their inherent properties. Yamaguchi et al. investigated using the airflow from a drone to stabilize a paper hanging from it to provide haptics in VR [567]. They could show that the haptic feedback was effective for supporting mid-air drawing. Tsykunov et al. proposed a string-based approach to interact with a drone in VR [508]. Users can pull on a string attached to the drone to interact. Through the string, users experience feedback.

Using specific elements of a drone (e.g., the propellers) to provide haptic feedback has also previously been investigated. Heo et al. created a handheld device that can provide haptic feedback [198]. Six propellers are used to accelerate the device in any direction. In VR, the haptics of different elements can be simulated. For example, when a user places a stick in flowing water in

VR, the device provides the matching force feedback to mimic the resistance of the water. Further, when the user travels to another planet in VR, gravitational forces can be rendered differently through the device. Participants in a preliminary study reported being more immersed in the VR experience when using the device. Je et al. presented a wearable device that provides force feedback to virtual weapons used in VR games [225]. Through propellers, this device can apply force to the wrist of the user. A study showed that the system could increase the enjoyment of VR games. A similar approach to apply forces in VR was introduced by Sasaki et al. [431]. Through propellers attached to a rod, the device applies forces on its user.

In the previously mentioned approaches, it is common that drones are used to create haptics, either to enhance the VR experience or to create a touchable 3D UI in reality that supports known input metaphors (e.g., touch or drag). In this work, we introduce a flying UI toolkit for VR that uses interaction metaphors materialized via 3D-printed haptic props mounted on quadcopters. In contrast to previous work, such as [251, 3, 1], the *Flyables* toolkit aims to provide well-known input elements for arbitrary VR experiences. The goal of *Flyables* is to mimic haptic feedback as accurately as possible and provide generic input capabilities such as controllers, but without requiring the user to constantly have their hands occupied. With further advancements in fabrication, we might be able to create such props within a matter of minutes in the near future [338, 343, 383]. Then, such 3D-printed structures can provide haptic feedback for virtual objects when they are navigated to the right place at the right time using quadcopters.

11.1.2 Evaluation

To evaluate the *Flyables* toolkit, we conducted a user study with 12 participants. We developed four different VR scenes, each scene contained a task to be completed using *Flyables* or VR controllers.

Apparatus

The four different VR scenes, which we will now refer to as SCENES, made up the first independent variable (see Figure 11.1). The second independent variable was INPUT, which was either *Flyables* or *Oculus Rift* controllers. In each SCENE, we integrated two different *Flyables*. We counterbalanced the order of INPUT and SCENE using a Latin Square design. We deployed

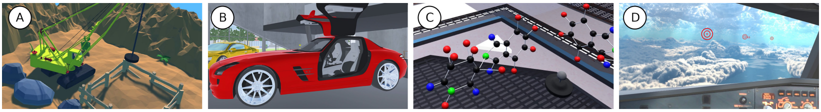


Figure 11.1: (A) the participants controlled a crane with the *joystick* and the *button*. (B) a car could be rotated using the *knob*, or its doors could be opened using the *button*. (C) the participants compared molecules by moving them with the *3D mouse* and rotating them with the *knob*. (D) the participants steered an aircraft with the *joystick* and controlled its speed with the *slider*.

Flyables and the *Oculus* VR system in a $3m \times 3m$ area that was tracked by an *OptiTrack 13W* system. To deploy the physical UI elements, we attached the different 3D-printed elements to off-the-shelf quadcopters (i.e., the *Parrot Mambo*).

Virtual Reality Scenes

We created our four VR scenes in *Unity3D*. In each scenario, we recorded the task completion time and logged the user's movement.

Remote Controlled Crane In this scene, the participants control a crane to stow away three rocks (see Figure 11.1A). The crane could be rotated sideways by tilting the *joystick*. By pressing the *button*, the crane arm could be controlled. Pressing the *button* once made the crane move downwards while pressing it again stopped it. A third press made the arm move upwards. Then the sequence started back at the beginning. The arm was stopped when it hit a rock, and the rock was then attached to the arm. The task was finished when the rocks were brought to the destination area. The scenario could also be controlled using the *Oculus* controllers. Here, the joystick of the right controller was used to turn the crane. The trigger button on the left controller was used to move the arm up and down.

Car Showroom In the *Car Showroom* scene, the participants could use the *Knob* to rotate a car (see Figure 11.1B). The *button* could be pressed to open or close the car doors. The participants had to find three price tags attached around and inside the car. We instructed the participants to verbally indicate when they had found all three price tags. The car could also be turned using the *Oculus* controllers. Here, the joystick of the right controller turned the car. The trigger button on the left controller could be used to open or close the doors.

Molecule Comparison In this scene, the participants had to compare a specific molecule (i.e. *Thalidomide* [506]) to four other molecules (see Figure 11.1C). Two of the other molecules were the same, and two were mirrored. The *Knob* could be used to rotate the molecule, while the *3D mouse* could be used to translate the molecule into 3D space. To complete the task, the participants had to approach the four molecules in the room and compare them to the molecule attached to the *3D mouse*. We recorded the answers and the time to fulfill the task. To move the molecule with the *Oculus* controllers, the participants held down the trigger of the right controller and then moved the controller to translate the molecule. The joystick of the left controller could be used to rotate the molecule.

Aircraft Piloting In this scene, the participants steered an aircraft by using the *Joystick* to steer the aircraft sideways and the *Slider* to control its speed. The participants sat on a chair in the middle of the tracking space. After 30*s*, five targets popped up at the same altitude (see Figure 11.1D). The participant's task was to hit all the targets. To steer the aircraft with the *Oculus* controllers, both joysticks were used. The left joystick was used to steer the aircraft sideways, and the other was used to adjust its speed.

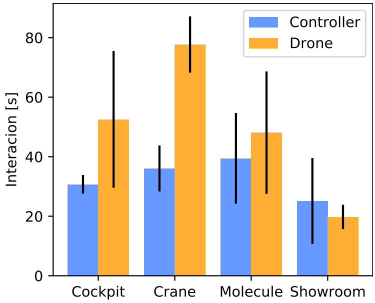
Measurements

As measurements, we use TCT and movements per task. Here, TCT is the time the participants worked on the task, excluding the setup time and breaks. Movement is the distance the participants moved during the task, which we use to measure physical engagement.

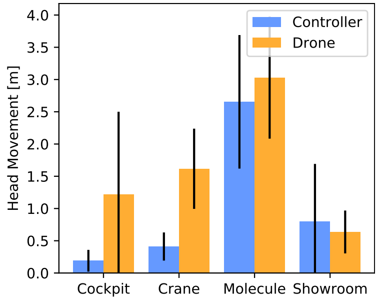
We chose the following questionnaires to obtain a comprehensive understanding of the impact of *Flyables* on users. Specifically, we used the *AttrakDiff* questionnaire [189] for the overall user experience and the SUS [67] for overall usability. We also added five 7-point Likert scale questions on the following properties: Realism, Hardness, Naturalness, Expected Location, and Future Use. In addition, we assessed simulator sickness via the SSQ [238]. Finally, we used the PQ [549] to measure the presence in VR.

Procedure

After welcoming each participant, we explained the purpose of the study and answered any questions they had before having them sign an informed consent form and fill out a demographics form. Next, we introduced them to our study and the *Flyables* toolkit. We explained the general procedure and showed



(a) TCT



(b) Movement

Figure 11.2: (a) Average TCT per condition in seconds. (b) Average head movement per condition in meters.

them the quadcopters equipped with the haptic UI elements. As we used off-the-shelf indoor consumer quadcopters with low power, we ensured that the interaction with them would be risk-free and would not cause injuries like the ones in Knierim et al. [251]. To further ensure the safety of the participants, experimenters were constantly in proximity to disable the quadcopters at any time. After the introduction, the participants were seated in the middle of our tracking space. Then they entered VR, interacted with the scene, and then exited to fill out a SUS questionnaire. At the end of the study, we asked the participants to fill out the *AttrakDiff*, *PQ*, and *SSQ* questionnaires.

Participants

We recruited our participants through our university mailing list. We invited 12 participants to our lab (5 female, 7 male, 0 other). Our participants were aged between 17 and 32 ($M = 24.5$ years, $SD = 5.33$). All participants self-identified as right-handed. Nine participants had used VR before: 2 daily, 1 once a week, and 6 once a month. Two participants owned a VR headset.

11.1.3 Results

For the evaluation, we performed a quantitative analysis of the collected objective and subjective data. For the non-parametric data, we applied the

Aligned Rank Transform (ART) using the ARTool toolkit and applied a paired-sample t-test with Tukey correction, as was suggested by Wobbrock et al. [551]. For all other ANOVAs, we used paired t-tests with Bonferroni correction.

Task Completion Time

As the normality assumption of the Task Completion Time (TCT) was violated ($p < .001$), we performed a non-parametric two-way repeated measures analysis of variance (RMANOVA) equivalent using ART. We determined whether INPUT × SCENE significantly influence the TCT, revealing a significant effect of INPUT ($F_{1,77} = 69.281$, $p < .001$) and SCENE ($F_{3,77} = 50.602$, $p < .001$). Moreover, we found a significant interaction effect for INPUT × SCENE: $F_{3,77} = 28.729$, $p < .001$. Thus, *Controllers* ($M = 33sec$, $SD = 12$) were faster than *Flyables* ($M = 50sec$, $SD = 26$) (see Figure 11.2a).

Body Movement

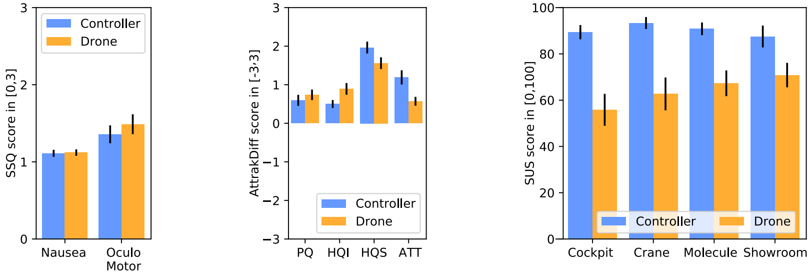
We conducted a two-way ART RMANOVA as the normality assumption was violated ($p < .001$) to determine whether INPUT × SCENE significantly influence the amount of head movement. The analysis revealed a significant effect of INPUT and SCENE ($F_{1,77} = 34.350$, $p < .001$; $F_{7,77} = 51.980$, $p < .001$; respectively). We found a significant interaction effect for INPUT × SCENE, $F_{3,77} = 8.129$, $p < .001$. Thus, participants moved less when using *Controllers* ($M = 1.01m$, $SD = 1.62$) than when using *Flyables* ($M = 1.19m$, $SD = 1.23$) (see Figure 11.2b).

System Usability Scale (SUS)

We conducted a two-way ART RMANOVA (normality assumption violated: $p < .001$) to determine whether INPUT × SCENE significantly influence the SUS [67]. The analysis revealed a significant effect of INPUT: $F_{1,11} = 103.748$, $p < .001$. However, we could not find a statistically significant influence for SCENE ($F_{3,33} = 1.444$, $p > .236$). Moreover, we found no statistically significant interaction effect for INPUT × SCENE ($F_{3,33} = 1.542$, $p > .210$). Thus, using *Controllers* ($M = 90$, $SD = 12$) was rated as better than using *Flyables* ($M = 64.1$, $SD = 22$) (see Figure 11.3c).

Simulator Sickness Questionnaire (SSQ)

For the SSQ [238], we conducted a Wilcoxon signed-rank test (normality assumption violated: $p < .001$), which did not show a statistically significant



(a) SSQ (b) AttrakDiff (c) SUS

Figure 11.3: Average scores for the *Simulator Sickness Questionnaire (SSQ)* (a) and *AttrakDiff* (b) questionnaire scores. Error bars represent the standard error. (c) Average SUS scores.

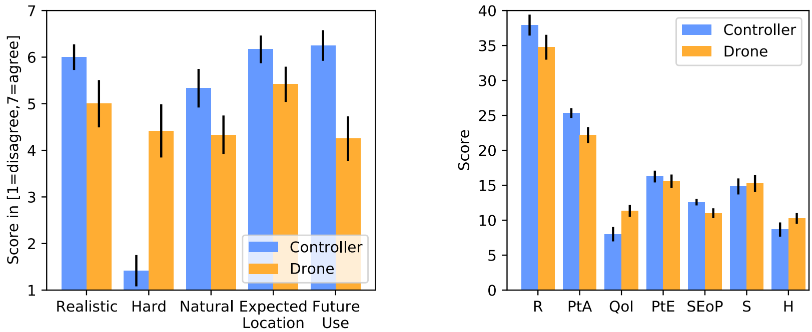
influence of INPUT on *nausea* ($Z = 9.5$, $p > .914$). Thus, *nausea* was similar between conditions, with $M = 1.11$, $SD = .16$ for *Controllers* and $M = 1.12$, $SD = .15$ for *Flyables* (see Figure 11.3a). Furthermore, a second Wilcoxon signed-rank test (normality assumption violated: $p < .001$) did not show a significant influence of INPUT on *oculomotor* ($Z = 5$, $p > .076$). Thus, *oculomotor* was similar between conditions, with $M = 1.36$, $SD = .40$ for *Controllers* and $M = 1.49$, $SD = .45$ for *Flyables* (see Figure 11.3a).

AttrakDiff

Since the normality assumption ($p > .05$) for a paired Student's t-test was met, we performed them on each subscale to investigate the influence of INPUT on PQ (pragmatic quality), HQI (hedonic quality – identification), HQS (hedonic quality – stimulation), and ATT (attractiveness). Our analysis revealed significant differences for HQI, HQS, and ATT ($t(11) = -2.315$, $p < .041$; $t(11) = 2.293$, $p < .043$; and $t(11) = 2.780$, $p < .018$; respectively). However, we could not find significant differences on PQ ($t(11) = -.674$, $p > .513$) (see Figure 11.3b).

Presence Questionnaire

We conducted the presence questionnaire [549] to evaluate the users' experiences in the environment. The results show that the controllers reached higher scores. However, for *Quality of interface* and *Haptics*, *Flyables* scored higher



(a) Additional Questions (b) Presence

Figure 11.4: (a) Average scores for the *Additional Questions*. (b) Average scores of presence questionnaire categories. R = *Realism*, PtA = *Possibility to act*, QoI = *Quality of interface*, PtE = *Possibility to examine*, SEoP = *Self-evaluation of performance*, S = *Sound*, H = *Haptics*.

(see Figure 11.4b). We performed an additional seven Wilcoxon signed-rank tests (normality assumption violated $p < .05$), which showed that *Possibility to act* and *Self-evaluation of performance* are significantly different ($Z = .866$, $< .005$; $Z = .868$, $p < .005$; respectively). For the others, the analyses did not reveal statistically significant differences ($p > .05$).

Additional Questions

We performed an additional five Wilcoxon signed-rank tests (normality assumption violated: $p < .05$), which indicated that there was no significant influence of INPUT on Realistic, Hard, Natural, Expected Location, or Future Use. We could only show significant differences for Hard and Future Use ($Z = 12.5$, $p < .004$; $Z = 59$, $p < .022$; respectively). For all others, $p > .05$ (see Figure 11.4a). For the *Molecule Comparison Task*, all participants solved the molecule comparison task correctly when using *Flyables*, whereas only 10 out of the 12 participants solved it correctly using the controllers.

Interviews

We conducted semi-structured interviews to obtain qualitative feedback from our participants. We combined all interviews from the study sessions for analysis. We transcribed and translated the interviews into English literally without summarizing or transcribing phonetically [57]. Finally, we employed a simplified version of qualitative coding with affinity diagramming [183] for interview analysis.

Pro-Flyables Feedback In general, seven participants enjoyed using the *Flyables* to fulfill the tasks (P1, P3 - P6, P9, P10). As P4 put it, *"you can move around like you would do in everyday life"*. P10 said that, for solving tasks, *Flyables* are more enjoyable. Moreover, the two main positive comments we received about using *Flyables* were that a) the mapping between the VR action and the physical action were in sync, and b) that the haptic feedback from the physical UI element made them feel more immersed in VR. Four participants (P3, P4, P9, P10) enjoyed that the mapping of *Flyables* was in sync with the physical attachments. P10 noted that the mapping of the functionality to the controllers is often arbitrary. Here, P10 sees a benefit in using *Flyables*, as they communicate their functionality. Six participants (P3 - P7, P9) liked that the physical objects felt like the virtual ones. Here, we received praise for the realism that *Flyables* provided. P5 stated *"I had the feeling of being more inside with the drones,"* and P6 said, *"I liked the attachments and their haptics."* Also, P3 said that *"from a haptics point of view it was definitely better than the controllers,"* while P5 pointed out that the haptics could not be achieved by the controllers. Lastly, P7 stated that *"[...] the drones might be more intuitive for people not used to controllers."* and added that the movement with *Flyables* is more natural than with the controllers.

Pro-Controller Feedback In contrast to the comments we got on the positives of using *Flyables*, we also got positive feedback on the use of controllers. Six participants (P2, P4, P6 - P8, P11) stated that controllers are well-known, and therefore, easy to use. P6 said that *"the controllers were better because [...] they are well-known."* P11 concluded that the controllers are easier to use because they are well-known, but that *Flyables* also worked *"surprisingly well."* P10 stated that using controllers *"is clearly easier, but therefore also more boring."* Two participants (P1, P12) argued against using *Flyables*. P1 explained that it was exhausting to grab *Flyables*, so the controllers were easier to operate. P12 generally preferred the controllers over *Flyables* because the control was easier and more intuitive. P12 also pointed out that one did not have to think about the usage: *"I preferred the controllers in every scenario. It was easier and more intuitive because I did not have to think about it. While using the drones, I had to look for where they were all the time. I had to watch to avoid colliding with them."*

Real World Use-Cases Six participants (P2, P8 - P12) liked the idea of using *Flyables* for games. As P10 put it, *"It was fun! It was exciting because* *it was challenging!"* Eight participants (P2, P4, P5, P7 - P12) suggested using such a system for training purposes or simulations, such as surgery training (P5), pilot training (P4), or training for setting up chemical experiments (P11). Supporting design such as CAD or 3D modeling was also suggested (P9).

Improvement Suggestions Two participants wanted more ways to interact with *Flyables*. Suggestions included being able to touch *Flyables* from all sides (P5) or double-tap the button (P12), as well as having *Flyables* that can find their way to the user's hand autonomously (P1). One participant added that future systems could have safety measures for roommates, pets, and house plants (P6).

Scenario Feedback For *comparing molecules*, five participants liked *Flyables* (P1, P2, P7 - P9). Being able to hold things in the hand was perceived positively by P2 while making the molecule comparison: *"The drones were better for the molecule thing because one had to turn and move around while holding the molecule. It was more haptic, which I liked."* P7 stated: *"I found it more intuitive. Using the controllers was monotonous."* P10 liked the way the molecule was rotated via *Flyables*, but at the same time had efficiency concerns. P9 stated: *"I tend to the controllers [...], but for investigating objects and moving them around, the drones also work very well."* Four participants disliked *Flyables* during the molecule comparison (P3 - P5, P7). Three participants had no preference for *Flyables* or the controllers (P1, P8, P11). P11 explained: *"Both are quite similar. The controllers are faster [...]. Moving objects with the 3D mouse and rotating them worked well with both the controllers and the drones"*.

From eight participants, we got feedback that *Flyables* worked well for the *car showroom* (P1 - P4, P7, P9 - P11). Here, P4 said: *"The motion was relatively easy. I could do it quite well by using the drones."* P7 reported a better spacial feeling for the *car showroom* while using *Flyables* to rotate the car, but mentioned that the button could not be pressed very hard because the drone would crash. P9 commented that *"[...] if the task is to investigate an object, the drones work, [as] it feels like I have the object in my hand."*

In the *remote-controlled crane* scenario, two participants (P10, P11) liked *Flyables* for controlling the crane. P11 said that one could properly control the crane with *Flyables*. P6 and P10 noticed the joysticks' resistance: *"The joystick is cool because the drone generates a force against my motion and one pushes against that. That is really cool!"* (P10). P10 added that a joystick for turning the crane is well-known, while the mapping of the functionality to the controllers is quite arbitrary. Still, P10 said they would prefer the controllers in terms of input precision and interaction time. Others experienced difficulties and therefore preferred the controllers (P2, P3, P6, P7).

In the *aircraft piloting* scenario, we found that all participants who themselves own a joystick liked *Flyables* (P4, P7, P9, P10). P4 liked how the aircraft was steered in the piloting scenario but at the same time appreciated the precision of the controllers. P4 said: *"Compared to the controllers, it is more realistic! In reality, you also have a thrust lever." Flyables* were also disliked by three participants (P2, P8, P11). P5 expressed that steering the aircraft was very complex and that the different types of motion were especially challenging (i.e., tilting the joystick from left to right while simultaneously moving the slider back and forth). This was explained as; *"I found the drones very bad for steering the aircraft. I had to move around a lot, and I had to hold on to the drones all the time. However, with the controllers, I could rest my hands"* (P2).

11.1.4 Discussion

We implemented four different VR scenes using five different *Flyables* (i.e., quadcopters) that carry physical UI elements to control VR objects and provide matching haptic feedback. We provided five different UI elements (i.e., a *button*, a *knob*, a *joystick*, a *slider*, and a *3D mouse*). Through our exploration, we uncovered several strengths and weaknesses of *Flyables*. This enables us to guide the future development and investigation of *Flyables*.

Flyable Handling

We observed a significantly higher TCT in the VR scenarios when *Flyables* were used instead of VR controllers. This ranks *Flyables* as worse than controllers for interaction in VR. Further, we observed that in general, the participants rated the drones as *"hard to use."* Participants reported that controllers were easier to operate. In general, users are familiar with controllers, as it is a mature technology. This is a true weakness of the current *Flyables* toolkit. Independent of the toolkit itself, the performance of *Flyables* in our study may be affected by the drone model that we chose for the evaluation. Larger, more stable drones might enable better interaction.

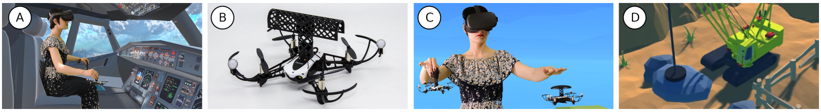


Figure 11.5: Showcases of the *Flyables* toolkit. Here, *Flyables* are used in different scenarios to show their applicability: for flying (A), for instance, using a thrust lever attachment (B) or in a crane scenario (C + D).

Body Movement

We observed an increase in physical movement when *Flyables* were used in contrast to VR controllers. Participants mentioned that interacting with *Flyables* was tiring. However, in specific circumstances, such body movement may be desired. While the participants argued that this is a negative aspect of *Flyables*, it might also provide a benefit. Research on exertion games [342] underlined the positive aspects physical activity can provide to the user. In addition, six participants explicitly mentioned games as a potential use case. Participants enjoyed using *Flyables* as controls because of the matching haptic feedback and the communication of functionality through their design (e.g., using a joystick to control an aircraft). This highlights that, for the gaming context, *Flyables* could be a step towards serving various control elements to players. This might be improved by having drones specifically designed with more precise input capabilities, which is an important step for users to engage with a game [69]. Also, special controlling algorithms could provide active and scenario-dependent force feedback. Together with powerful drones, that could lead to a more sophisticated VR experience.

Usability, UX, & Simulator Sickness

In terms of usability, controllers outperformed *Flyables* in every scenario. This is also reflected in the AttrakDiff results; however, only in terms of the hedonic quality (stimulation) and attractiveness. The pragmatic quality and hedonic quality (identification) are similar between *Flyables* and controllers. We argue that this might be due to the long task completion time when using *Flyables*, but we also argue that the largest factor for reduced usability is the unfamiliarity with using *Flyables* for interaction. We further support our argumentation with the qualitative feedback from the participants, which indicates that the controllers were easier to use. This allows us to contend that, over time, users could become familiar with *Flyables*. Thus, we believe that in the long term *Flyables* could provide an alternative means of interaction in VR. Yet, only a long-term investigation could yield such results. Finally, we observed no significant differences in simulator sickness for *Flyables* or standard VR controllers. We can claim that *Flyables* most likely do not contribute to simulator sickness any more than controllers.

Immersion & Presence

Participants reported feeling more inside VR when using *Flyables*; and thus, felt immersed. Brown and Cairns [69] divided immersion into three levels: engagement, engrossment, and full immersion. Becoming immersed in a game means transiting from engagement to engrossment to full immersion. Usability and control problems might hinder users from engaging with a game. While *Flyables* overall helped participants to feel more immersed, we think that our scenes and especially our tasks were not constructed to fit the gaming context. We suggest investigating *Flyables* in playful scenarios to uncover the suitability for different game genres.

For presence, the controllers received a higher score than *Flyables* in general. However, *Flyables* scored higher in terms of *Quality of Interface* and *Haptics*. Moreover, feedback from the participants confirmed that they liked the drone attachment's haptics. Being able to feel what they saw in VR was especially appreciated by the participants. Again, we argue that the users' lack of familiarity with *Flyables* rendered the results lower on average. When we questioned them in detail, however, we could unveil the positive aspects, which have the potential to provide greater immersion.

While the *Flyables* toolkit is not yet ready to be used in an arbitrary VR scenario, this initial evaluation points to directions for future investigation. Weaknesses of Flyables (e.g., precision) could be addressed to cover a wider range of applications. Technical improvements of quadcopters might also support more use cases.

Limitations

We acknowledge the following limitations of our work. First, for the evaluation, we used consumer drones that were not specifically designed for interaction with humans. Custom drones that are designed to be equipped with the *Flyables*' UI elements may perform differently with regard to stability or precision. The *Flyables* toolkit allows configuring the maximum tilt angle individually for each drone to realize different flight characteristics. In our evaluation, we limited the maximum tilt angle for a drone to move in any direction to 10°. This allowed us to fly precisely in our tracking space. Further, this limited the speed of the drone to further ensure safety. Second, we compared *Flyables* to state-of-the-art controllers that have improved in recent years. These devices had been used by the majority of our participants before. Participants were used to this type of input device and were thus able to solve the tasks more easily. It remains unclear how participants would perform after gaining similar experience with *Flyables*. Finally, drones could crash when they were hit too strongly by the participants. This might subtly influence the participants negatively. *Flyables* could benefit from drones that recover quickly from crashes. We outline how to tackle this in our future research challenges. Finally, we must point out that interacting with drones can be dangerous. In our current version of *Flyables*, we did not include additional blade guards that cover the propellers from above. During our evaluation, several experimenters reduced the injury risk by constantly observing our drones and disarming them in case of an emergency. In a future version of *Flyables*, we plan the integration of safety measures like cages [3] or deformable propellers [366].

11.1.5 Research Challenges

We envision the *Flyables* toolkit more as a starting point for novel interaction prototyping using drones rather than as a framework that supports out-of-the-box flying UI elements. We think that developers, designers, and researchers could use the toolkit to create drone-enhanced interaction in VR without the technical challenges of drone controlling and integration. Therefore, we introduce challenges that could be the subjects of future research endeavors to improve the *Flyables* toolkit and broaden its applicability.

Force Feedback and Anchoring in the Air Similar to previous approaches [198], a new type of specially designed drone could be integrated into the *Flyables* toolkit to provide force feedback that matches the given VR scenario. Especially because drones are not anchored to the environment, rendering realistic counter-forces is challenging. For example, a thrust lever or joystick of an aircraft has mechanical resistance. The pilot needs to overcome this resistance while operating the aircraft. To mimic these haptic properties, we envision that *Flyables* could integrate further matching haptic elements (see Figure 11.5B) to our aircraft scenario (see Figure 11.5A). Through specially designed drones, the matching force feedback could be generated by accelerating horizontally without tilting, similar to accelerating up and down to render weight and stiffness [1]. We envision a drone with additional horizontally mounted rotors. This would enable the drone to induce forces sideways while using the vertical rotors to maintain height and orientation. Besides that, future drones could use the resistance of the air to apply forces to the interacting VR user by adjusting their surface size to render resistance and inertia [584]. Further, we envision that a specifically designed PID controller could enhance the haptic sensation of counter-forces. Such controllers could overtake the controlling of a *Flyable* when the system detects that specific counter-forces must be applied (e.g., if the VR user grabs a thrust lever). While this was out of scope for the current version of *Flyables*, we envision that future research could investigate in this direction. We are confident that such research could lead to improvements in the overall idea of *Flyables* as future drones evolve rapidly due to the mass market. To foster such research, we included a detailed document on how to integrate any kind of remote-controlled drone or quadcopter with *Flyables* with little technical effort.

Autonomic Reuse of Flyables To provide haptics to myriads of objects in VR, *Flyables* could be reusable, similar to haptic retargeting [36]. Here, one haptic prop is used for multiple virtual objects. One *Flyable* could also be used for multiple virtual objects as long as it is present at the position where the user expects the haptic feedback. We imagine using machine learning algorithms to predict the future position of a *Flyable* with regard to where it is most likely needed. Future research could investigate the suitability of different prediction approaches.

A major drawback of using drones for haptic feedback is that drones crash easily. For example, a *Flyable* could crash when the user hits the button too hard (see Figure 11.5C). The button press event would still be valid to the system, but the drone with the physical button would not be available for interaction. We envision that future drones could automatically recover from such crashes without the user noticing. Drones could be designed to restart after they crash, similar to the *Parrot Rolling Spider*. Such drones can simply roll over and restart. We envision that drones specifically designed to automatically restart and get back in position would enable a more reliable and enjoyable *VR* experience, as the user would not need to handle the drones carefully. Thus, future research could investigate how to hide the fact that a drone crashed from the user while preserving the narrative of the VR experience.

Novel Interface Elements Besides the existing five UI elements and the previously envisioned thrust lever (see Figure 11.5B), we imagine new interface elements that can be integrated into *Flyables* to support more use cases in VR. To support narratives in games or enhance realism in, for example, interior design experiences, a pull string to turn on a lamp, open a garage gate, or honk a truck horn could be mounted to a drone, similar to the work of Tsykunov and Tsetserukou [509]. To support more specific elements, such as a door handle, future research could investigate the suitability of drones that are tilted by the user. Here, proper force feedback and anchoring could be the keys to providing a realistic experience.

Further Use Cases Modern VR-HMDs can track the hands of their users, but controllers are still needed or even desired for some interactions. Here, *Flyables* could fill the gap by providing controller devices when they are required without breaking the immersive experience. Users could quickly switch between haptic UI elements brought to them by a drone and free-hand interaction. This would allow the use of bare hands for gestures (for example, in multi-user scenarios such as collaboration [560, 395]) as well as the ability to switch quickly to haptic device input.

11.1.6 Conclusion

We designed, implemented, and evaluated the *Flyables* toolkit, a haptic UI toolkit that uses quadcopters to deliver physical input devices to a VR user. The current toolkit consists of five UI elements (a *button*, a *knob*, a *joystick*, a *slider*, and a *3D mouse*) that resemble fundamental interaction patterns of today's UIs. The results of our study show that *Flyables* can introduce an exciting, realistic, and fun way to interact with virtual content. Participants felt more immersed in the VR environment when using *Flyables*, appreciated the haptics of *Flyables*, and stated that, compared to controllers, *Flyables* communicate their functionality through their affordance. However, state-of-the-art controllers still outperform *Flyables* in terms of input precision and task completion time.

We extracted research challenges to further improve the *Flyables* toolkit. These challenges include additional force feedback through specially designed drones, approaches to reuse a limited set of drones for multiple virtual objects, and the creation and exploration of novel UI elements and interaction opportunities. Addressing these challenges can help to promote *Flyables* as an alternative to controllers in a variety of VR scenarios. Such scenarios could benefit from a richer haptic experience and the communication of functionality through well-known input devices. We also aim to further develop the toolkit to enable researchers and practitioners to explore how *Flyables* can serve as physical UI elements in future VR applications.

11.2 Understanding Drone Landing on the Human Body

In the previous part of this chapter, we showed how future VR systems can benefit from flying UIs. To realize these interfaces, we mounted common UI elements on drones. In the future, such systems could be deployed ubiquitously. For example, we could think of a haptic MR system that supports its users in critical missions (e.g., rescue personnel or ambulance units). In this context, it is important to understand how we can make such systems mobile. This would, for example, require the user to transport the system and to set it up at a target location as well as stow it away when it is not needed anymore. This could be accomplished automatically if the drones start and land autonomously on the user's body. In the following, we introduce fundamental research on autonomous drone landing on the human body. With that, we pave the way for future body-worn drone systems that could be applicable beyond the aforementioned nomadic MR scenarios.

In recent years, it has become common for drones to solve tasks that are outside of the reach of the human (e.g., conducting inspections at large heights). We can expect that the interaction between autonomous flying drones and humans will further increase over time. Drones may be used in a wide range of scenarios, such as controlling crowds in an emergency [437], delivering urgently needed medicine to a patient [552], assisting search and rescue missions by providing an overview [312, 155], for work or sports [341, 266] or even entertainment [404, 438], or to enhance virtual experiences [3, 210, 251]. Further, drones can assist their owners in various tasks, for example, providing navigation aid [252, 34]. They are also widely adopted for photography, filming, or delivery [494].

Drones usually keep their distance from the user and land in the vicinity before they are manually picked up and stored away in boxes. However, this makes their usage cumbersome and limits their use to situations with free hands and no time constraints. In this research, we envision the human body as a base station for one or multiple drones to enable fast landing and take-off.

In HDI research, four major fields have emerged – *Control Modalities*, *Human-Drone Communication*, *Proxemics*, and *Novel Use-Cases* [500]. However, the HDI community lacks an understanding of the user's common themes, as well as if and where users would accept drones landing on their body [32]. This is important since the body is a personal space. People may have different

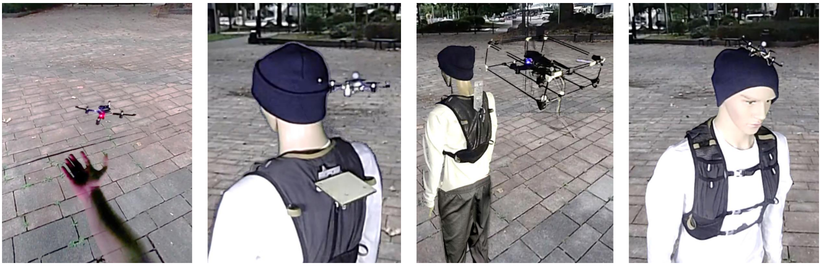


Figure 11.6: The human body allows for fast and autonomous take-off and landing of drones. We conducted an online survey and a follow-up study with 360° VR videos to investigate the landing suitability of various body locations (e.g., hand, back, or head).

opinions about what constitutes an appropriate interaction between drones and their bodies. Further, investigating how a drone must be visually designed to land on the human body is important, as certain designs could negatively influence the perception of a drone [83].

We address these issues by reporting the findings of two user studies. In our findings, we identify common themes and, in particular, investigate the acceptability of autonomous drone landing on the human body. In the first study, we conducted an *Amazon Mechanical Turk* (*MTurk*) survey with 159 participants to understand the preferred landing location and opinions on the visual appearance of drones that land on the body. We contribute body maps showing the acceptability of drone landing during four activities: standing, walking, sitting, and climbing. These body maps can help researchers and practitioners to find well-accepted locations for drone landings. Based on our findings from the survey, we implemented a software framework to enable autonomous drone landing on the human body (see Figure 11.6). With this framework, we recorded 360° videos of drones landing on different human body sites. In particular, we investigated landing on the hand, back, shoulder, and head by building various body-worn landing mechanisms. The software framework supports two drones of different sizes and eases the specification of custom landing maneuvers. We used the software framework to conduct a second study with 12 participants. We aimed to deepen our understanding by investigating six drone-landing maneuvers in 360° videos that can be rendered on VR-HMDs. The videos were created using two autonomous drones steered by our framework that landed on a mannequin. The immersion into the VR landing scenario revealed common themes, metaphors, and preferred approach behaviors for drones landing on the human body. It demonstrated that preferred landing locations are the hand and back, that drones should indicate landing intentions, and they should approach the user in a controlled and precise trajectory. Taken together, our results demonstrate great potential for autonomous drone landing on the human body.

In summary, we present three main contributions: Findings from an *MTurk* survey ($N = 159$) on the suitability of body locations for drone landings and ratings of the visual appearance of drones landing on the body. Further, we contribute body maps that visualize location preferences in four activities, and we derive common themes, including safety, comfort, and visibility. An implementation of different drone landing maneuvers using two drones. We made this software framework open-source[47] to accelerate and ease the development of new drone landing maneuvers. Insights from a VR user study ($N = 12$) in which participants were immersed in six landing scenarios. We contribute results from a questionnaire and a semi-structured interview. We found that the hand and back are particularly well-suited for drone landing. We also obtained suggestions about how drones should carry out landing maneuvers.

11.2.1 Envisioned Application Scenarios

In many scenarios, a drone operator might not have the time, mental focus, or physical space to land and store a drone. For instance, rescue personnel, paramedics, and police officers might need to get an overview of their environment multiple times during a mission. However, they are too occupied with safety-critical tasks, and the terrain might not always be suitable for traditional drone landings, for example, while climbing a mountain or standing in a crowded space. Autonomous drones could return after completing their task and automatically land on a suitable body location without restricting the operator's movements and requiring human intervention. In other scenarios, the drone might land on people who are not the owner or operators of the drone. For example, autonomous or teleoperated medical drones could land on people to perform basic first-aid and vital monitoring to support triage after mass casualty events. Further, in the context of VR or CR systems, the benefits from drone-based interactions could be transferred into these scenarios in future systems. Therefore, we believe that drone landing on the human body is an important and timely research topic.

[47] Drone Landing Framework, `https://github.com/jonasauda/understanding_drone_landing`, last retrieved on August 12, 2022

Finally, our vision extends prior work on nonaerial on-body robots [105]. Drones could interact with the human body while being present on the human body, e.g., by giving tactile feedback. Additionally, they can perform tasks *beyond* the human body while in the air. We believe this will lead to more social drones in the future that can support people during their daily lives [80].

11.2.2 Related Work

This work relates to the domains of collocated HDI and proxemic interactions and takes inspiration from prior VR study methodologies.

Collocated Human-Drone Interaction

Small-sized drones are increasingly present in human environments, used for leisure and professional settings. They are already helping people in a plethora of applications ranging from journalism and agriculture to surveying, scientific work, and even search and rescue missions [450]. As drones become increasingly autonomous, low-level remote control becomes redundant, and collocated interactions prevail [79]. Researchers have proposed different mechanisms for collocated HDI, such as using hand and body gestures [336, 365, 79, 117, 121, 356, 366] or gaze [241]. Recently, researchers have investigated the use of touch [63, 4, 287] where the drone can be interacted with at arm's reach. For example, Lieser et al. let a drone fly specific dance trajectories to electronic music after detecting being touched recurrently on its frame by a user [287]. These trajectories depend on the position of the user's touch on the frame. The intention was to provide a playful bond between humans and drones. Such interaction might become more prominent in the future thanks to new forms and shapes of drones that are now safe to touch [193]. This enables new paradigms of interaction where drones could come all the way to the person's body. Such metaphors have been proposed as potential natural interaction techniques, where drones could land on the forearm using a falconry metaphor [365]. Commercial products have now followed suit, giving the ability for a drone to land on a person's hand [449]. Inspired by Ng and Sharlin [365], we propose that the body could become a platform for the drones to land and take-off from. Yet, much is unknown about how a drone should approach a person and what body locations are suitable to land and take off.

Proxemics

Hall introduced the notion of proxemics [180] as a way to organize interaction spaces and distances in human-to-human communication. It is divided into four zones, from intimate to personal, social, and public. Much research has explored the notion of proxemics in robotics [492, 349, 321], showing how different mechanisms around the design and behavior of robots can mitigate the acceptability of human-robot interaction within different interaction spaces. In HDI, several works have investigated proxemics [572, 114, 553]. Recently, Wojciechowska et al. [553] showed that people prefer for a drone to stop within their personal space and that when the drone enters the *intimate* space, people's comfort levels decrease. This is on par with prior work in ground robotics [216], although it was found that people are more comfortable with flying robots getting closer to them than ground robots [531]. These prior works confirm that getting the drone from the personal to the intimate zone is not straightforward. Since prior works [572, 114, 553] investigated how different factors, including drone shape, speed, movement, position, and approach strategies, influenced human preferences – from the public to the personal spaces. We propose to take the research one step further and investigate the acceptability of drones landing on the body, i.e., entering the intimate space. Our work focuses on both – uncovering suitable body locations for drones to land and take off and identifying characteristics for acceptability. The next section presents research methodologies related to our approach that foster safety while preserving certain aspects of validity.

HDI Research Methodologies Using Simulations in VR

Researching drones that land on the human body can be dangerous for humans. Therefore, we looked for alternative research methods that avoid dangerous exposure to drones while maintaining an acceptable level of realism for the participants to experience. Simulating drones in VR or AR provides medium realism and complexity while reducing the safety risk, according to Wojciechowska et al. [553]. Here VR studies achieve second best realism but real co-located flights achieving the highest realism. Furthermore, using VR or AR to simulate drones fosters reproducibility. Different approaches were employed in prior research to study users' perceptions of a drone and how to communicate the drone's intentions or behavior. To study users' perception and attitude toward a drone companion in a home environment, Karjalainen et al. simulated a virtual home in VR [234]. Prior to the VR study, they designed a virtual drone based on results from questionnaires and workshops. The results from the VR study indicated that the virtual drone matched the expectations of the participants in the context of a home environment. Duncan and Murphy studied HDI using a 2D-CAVE VE [115]. They simulated drones flying at different speeds or with different cyclic flight motions. The results indicate that low flight speed and cyclic flight motion resulted in larger distances between the human and the drone. Both approaches used virtual simulations to research HDI. Common to these approaches is a low safety risk that is of utmost importance in the field. We opted for a similar approach: bringing our drones in VR through pre-recorded 360° videos that can be viewed on an immersive VR-HMD.

11.2.3 Online Survey

We conducted an *MTurk* online survey to understand location preferences and common themes. In total, 159 participants participated in this survey successfully.

11.2.4 Study Procedure and Participants

We conducted the online survey using the *MTurk* platform to crowdsource feedback on suitable spots on the human body for a drone to land. Crowdsourcing platforms like *MTurk* are applied across various research domains, for example, wearables, to obtain a reasonable representation of the population [184]. In total, 210 participants took part in our survey. We excluded 51 participants who did not answer a control question properly in order to eliminate participants that quickly skipped through our survey. In total, 159 participants (100 male, 57 female, 1 non-binary, and 1 unspecified gender) completed the survey successfully. The participants reported an average age of 33.68 years ($SD = 10.42, IQR = 9.0$). In terms of education, 93.01% of the participants had a Bachelor's degree or above.

We asked the participants how often they had used drones in the past. Fifty-three (33.33%) reported having used drones 1–2 times, 41 (25.79%) reported 3–5 times, 12 (7.55%) reported 5–10 times, and 11 (6.92%) reported more than 10 times. A total of 19 (11.95%) participants had never used drones. Of those with experience, 88 (55.3%) participants reported that they had piloted a drone by themselves. We also asked the participants about what kind of drone experience they had. A total of 68 (42.77%) reported that they had used drones in the context of photography or filming, such as at a wedding or for video

Question	Mean	SD	IQR
I have experience with drones or quadcopters	4.75	1.95	2.0
I am interested in new technology	5.84	1.38	2.0
I am using new technology regularly	5.48	1.48	1.0
I would consider myself tech-savvy	5.26	1.64	1.0

Table 11.1: Previous drone experience & technology interest of the 159 participants on a 7-Point-Likert-Scale (1: Strongly disagree – 7: Strongly agree).

Body Location	Mean	SD	Med	Min	Max
Head	54.91 %	16.3 %	59.02 %	15.69 %	69.44 %
Shoulders	77.29 %	13.38 %	80.0 %	50.0 %	100.0 %
Arms	74.06 %	7.98 %	72.7 %	60.5 %	85.6 %
Hands	78.1 %	7.42 %	77.21 %	66.67 %	88.89 %
Upper Torso (front & back)	66.87 %	7.11 %	66.76 %	57.01 %	77.31 %
Lower Torso (front & back)	61.72 %	9.31 %	62.92 %	50.0 %	79.44 %
Legs	61.05 %	9.99 %	60.73 %	46.67 %	75.2 %
Feet	62.33 %	6.48 %	59.8 %	55.0 %	72.22 %

Table 11.2: Drone landing acceptability ratings for different body locations.

shoots. A total of 32 (20.13%) participants reported flying drones as a hobby. Twelve (7.55%) participants stated that they had conducted drone races. Two (1.26%) participants reported that they had stood by while another person flew drones. One (0.63%) participant was building a drone for aerial security. The remaining participants did not specify any particular usage. Further subjective ratings regarding drone experience and technology interest can be seen in Table 11.1.

11.2.5 Acceptance of On-Body Landing Locations

One key aspect that we addressed in the online survey was the acceptability of different landing locations on the body. We asked participants to mark various body parts for one of four activities as either acceptable or unacceptable for a drone to land. Based on this data, we rendered the heat maps in Figure 11.7. Further, we calculated acceptability percentages across all body maps (see Table 11.2). We have chosen activities such as standing, walking, and sitting as they represent everyday activities. In addition, we picked climbing as a

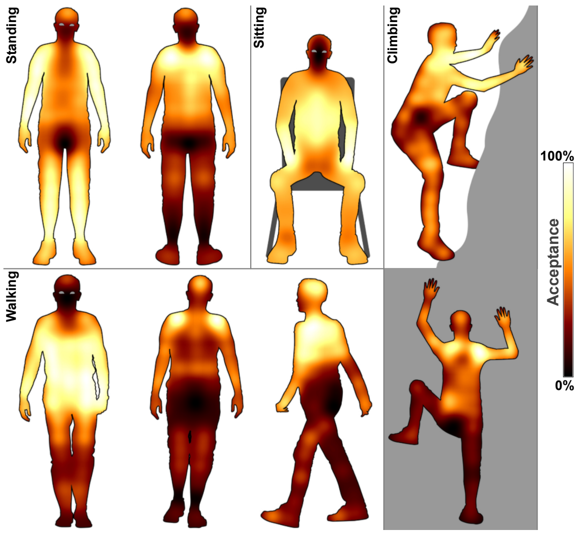


Figure 11.7: Location preferences for drone landings on the human body while standing, sitting, walking, and climbing.

Activity	Mean	SD	Med	Min	Max
Standing	67.0 %	8.56 %	64.5 %	53.0 %	81.0 %
Walking	65.0 %	9.43 %	64.0 %	51.0 %	79.0 %
Sitting	62.87 %	9.66 %	65.0 %	46.0 %	77.0 %

Table 11.3: Drone landing acceptability ratings for different activities.

demanding mobile activity, which is common in search and rescue missions. In the climbing scenario, the drone operator has occupied hands, is located in extreme terrain, and is focused on another task.

Always Acceptable Landing Locations The hands, the shoulders, and the back and front of the arms were rated as most acceptable across all body maps. On average, the hands have the highest acceptability of 78.10%. This is followed by the shoulders with 77.29% and the arms with 74.06%. Next, the upper torso was rated as acceptable for drone landing with a percentage of 66.87%. The feet were rated 62.33%, followed by the lower torso (61.72%). The legs received a percentage of 61.05%. Overall, the head was rated with the lowest acceptability (54.91%).

Figure 11.8: Drones with various designs and their average suitability ratings for landing on the human body (7-point Likert scale). Drone images are taken from prior work on drone design [552].

Activity Differences We compared the acceptance of landing on the front of a participant's body in three activities: sitting, standing, and walking (see Table 11.3). We excluded climbing from our analysis since the body is pressed towards a wall and does not allow for drone landings from the front. Our findings show that participants found, on average, more landing locations acceptable while standing (67.0%). This was followed by walking (65.0%) and sitting (62.87%). It is particularly visible when comparing the lower body of sitting, standing, and walking that the activity influences acceptance. Although participants found the legs and feet to be acceptable landing locations while inactive (e.g., sitting and standing), they were considered unacceptable during movement (e.g., walking). In addition, joint areas such as the knees were rated as less acceptable than flat areas such as the upper or lower legs.

Rating of Drone Design as a Factor for Landing Suitability

The design of drones could be a major factor influencing the suitability of drones to land on the human body. To investigate this, we selected 25 drones (see Figure 11.8) that are commercially available from prior work on drone design [552]. We selected drones from different categories (e.g., appearing *pet-like*, *machine-like*, *intelligent*, or *mature*) based on the classification of Wojciechowska et al. [552]. We asked our participants to rate whether the drone looks suitable for landing on the human body on a 7-Point Likert Scale

(1: Strongly disagree – 7: Strongly agree). We sorted the drones in Figure 11.8 according to their received rating for landing suitability. Afterward, we asked the participants to specify the reasoning behind their ratings for the landing acceptance and suitability of the 25 presented drones.

Shape, Size and Weight The participants explicitly mentioned that the shape of the drone did influence their decision-making. The participants were concerned about spiky parts such as rotors or *"legs"*. Furthermore, size and weight were listed as limiting factors of the landing suitability. The participants mentioned that flat drones seem more suitable for landing on the human body. For example, the *"legs"* of the drones were mentioned frequently (12 times). The participants stated that *"spiky parts"* and *"pointy legs"* seem unsuitable for landing and could pose an injury risk.

Drone Design The design of the drones further influenced the landing acceptability. Some reasons for unsuitability were a militaristic appearance or an insect or spider-like character. A more friendly appearance was required for landing suitability. The color of the drone was also mentioned by the participants, as a dark or black drone was perceived negatively: *"I can let the more colorful drones land on me, as they seem a bit more friendly, and smaller[...]"*.

Risk of Injury As an important decision factor, the risk of injury was mentioned explicitly by 18 participants. Sharp parts were considered to make a drone unsuitable for landing. On the one hand, a larger size was believed to increase the risk of injury: *"[...] some look to be the size of my body, that could crush me and kill me"*. On the other hand, participants welcomed safety features such as a *"strong frame"* and *"blade guards"* to protect the skin.

Use Cases The participants mentioned that the use case influenced their decision-making. For example, they stated it could be acceptable for a drone to land on a human in the case of a medical emergency or in *"[...] risky situations such as natural disasters"*.

Acceptable Use Cases and Situations for Drone Landing

We asked the participants to rate the acceptance of landing a drone on their bodies for different use-cases and situations on a 7-point Likert scale.

Use-Cases The acceptance was rated highest for *rescue purposes* with an average of 4.43 (SD=1.37, Med=5.0, IQR=1.5) followed by *work-related purposes* 4.28 ($SD = 1.49, Med = 5.0, IQR = 2.0$) and *medial emergencies* with 4.02 ($SD = 1.65, Med = 4.0, IQR = 2.0$). Landing a drone for *entertainment purposes* were rated the least with 3.89 ($SD = 1.62, Med = 4.0, IQR = 2.0$).

A Wilcoxon Signed-Ranks test (Bonferroni corrected) indicated that landing drones for *rescue purposes* was rated more *acceptable* than for *entertainment purposes*, ($W = 3269.50, p = .027$). Same for *work purposes* compared to *entertainment purposes* ($W = 2502.00, p = .048$) and for *rescue purposes* compared to *medical emergencies* ($W = 1389.5, p = .017$). Other comparisons did not reveal significant differences.

Situations The acceptance for landing a drone on the body *while being indoors* was rated lowest with an average of 3.82 ($SD = 1.68, Med = 4.0, IQR = 2.0$) followed by landing *while working* with 3.99 ($SD = 1.66, Med = 4.0, IQR = 2.0$) and while doing sports 4.04 ($SD = 1.75, Med = 5.0, IQR = 2.0$). *During free time* received an average rating of 4.14 ($SD = 1.63, Med = 5.0, IQR = 2.0$). Last, *being outdoors* was rated highest with 4.5 ($SD = 1.41, Med = 5.0, IQR = 1.0$). Wilcoxon Signed-Ranks test indicated that landing drones for *while being outdoors* was rated more *acceptable* than *while being indoors* $W = 2686.00, p = .001$, more acceptable than *during sport* ($W = 1467.00, p = .017$), and *while working* ($W = 1836.50, p = .007$). Other comparisons did not reveal significant differences.

Themes

We extracted common themes from the answers to the open-ended questions in our *MTurk* study. Four authors used thematic analysis [97] for the qualitative analysis of this set of data. We coded the free text answers from the *MTurk* study simultaneously by moving and annotating the data on a collaborative whiteboard. From the created clusters, they extracted themes related to the acceptability of landing on different body locations. The whole process was conducted in two sessions and concluded once all researchers agreed on the themes and coding of the data, which took a total of 12 person-hours We found six different categories that the participants used for reasoning about the acceptability of landing on different body locations:

Safety Most statements were related to safety. Participants found places unacceptable that have *"too much risk of getting severely hurt"* and mostly accepted places *"where it would not possibly hurt me"*. Many participants found it *"unsafe to land a drone near the head or face because of the risk of injury from the drone"*. Some were concerned with locations with *"exposed skin or sensitive pain areas"*, which *"might not heal fast and can bleed a lot if the fans cut a person"*, possible *"damage to vital organs"*, and that *"the fan might twist the hair"*. They preferred *"[...]healthy parts which are quite strong[...]"* and that these *"area[s] will be easy to control if at all damage is about to occur"*. One participant positively mentioned *"legs, knees, and feet as good places to land because those are places that can take some impact during sports like soccer."*

Comfort and Appropriateness Participants mentioned comfort as another important factor for their ratings and found places unacceptable that *"cause immediate discomfort"*. For example, one participant states *"any bony areas such as elbows and ankles would not make for a comfortable landing"*. Multiple participants mentioned they prefer less sensitive body locations for drone landing because *"the body doesn't get affected as much"*. Another participant found body locations unacceptable, *"because these areas are very sensitive and not comfortable to land drones"*. Beyond physical comfort, the participants were concerned about the appropriateness of the landing location. One participant found it *"inappropriate [...] to land a drone on the butt, sides, stomach, tights, and face"*. Another participant mentioned *"landing on my bum will be offensive to me"* and another mentioned *"the hip could also be used as a landing spot even though it's sort of awkward"*.

Convenience and Restrictions

Convenience was mentioned as another important factor. For example, landing locations should be *"easily accessible"*. Drones on some body parts might be inconvenient since they impair the balance of the body. Some mentioned *"the legs are not suitable for the drone to land on because the body rested on the leg"*. Further, drones should not restrict the movement of the body. Participants mentioned they prefer locations that *"won't affect the person"* and where a drone is *"not in the immediate way of action"*. These restrictions include not only movement but also other factors like the sight of the person. Participants were also concerned that this would require a certain fitness level and that specific *"areas are moving too much [and] too quickly"*. One participant mentioned that, especially while climbing, *"adding another element makes the risk higher of losing grip and falling to [...] death"*.

Visibility Participants mentioned they would like to be able to see the drone and the landing area. They mentioned that landing on locations with bad visibility (e.g., the back) might be *"too much of a surprise"* and people might *"get panic when the drone suddenly lands"*. This is also reflected in the heat maps in Figure 11.7: Locations in the front of the person have, on average, higher acceptability compared to locations with limited visibility behind them.

Drone Capabilities Although we did not mention any specific landing capabilities of drones during the online survey, many participants mentioned technical considerations as a key factor for their acceptance rating. They accepted landing on body parts that are *"flat"*, and *"horizontal"*, as well as *"remain stable even while walking"*. They also preferred larger spaces to *"ease the landing"* and locations that can *"withstand the drone's weight"*. They found body parts that are *"unstable"*, *"shake"*, or have *"too much movement"* unsuitable for landing.

Participants preferred *"easy places where the drone can land"*. This includes *"top surfaces"* (e.g., *"the top of the head is alright for landing as it is easy for the drone to just sit on the head"*), *"small places"* (e.g., *"landing on the feet or other small body parts would be difficult"*), and *"smooth area[s] to [...] not fall off"*.

Interaction and Control Some participants mentioned they prefer hands and arms since these locations give them the possibility to interact with the drone and a high level of control. People can *"convenient hold the drone"*, *"easily catch the drones"*, *"easily grab it, control it"*, *"convenient to take off the body"*, and *"escape from any accident"*.

11.2.6 Virtual Environment Study

To get a deeper understanding of the insights from the online survey and to further investigate suitable body locations, we used our software framework to precisely steer drones to a specific location on the human body. We incorporated two differently sized drones into the system – a small drone and a larger drone. We prerecorded six 360° VR videos of the two drones. These videos included landing on various body parts, i.e., the back, head, arm, and shoulder. We then showed these videos to the participants using an VR-HMD with stereo headphones and gathered qualitative feedback through questionnaires and semi-structured interviews. In the following, we describe the technical implementation of the software framework we used to record the 360° VR videos.

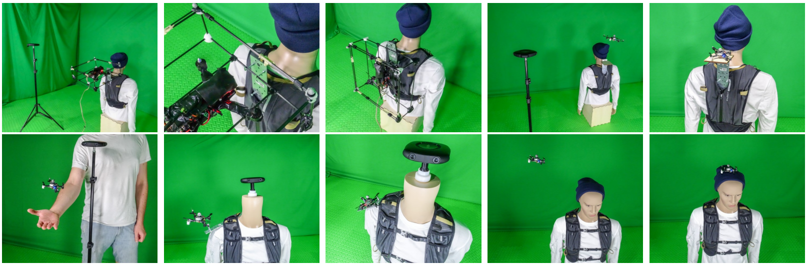


Figure 11.9: We recorded six drone landing maneuvers with a 360° camera. The camera was either mounted on a mannequin to record 1st person-view videos or on a tripod to record from a 3rd person-view.

Drone Control Software Framework

Our software framework consists of two drones, a command and control application, and an optical tracking component. To precisely track the position and orientation of our drones in 3D-space, we used an *OptiTrack 13W* optical tracking system. The spatial data from the *OptiTrack* system was streamed to a control application in real-time using our *VinteR* middleware (see Chapter 3). For the system to see the drones, we equipped them with optical tracking markers. The control server determined yaw, pitch, roll, and throttle for the drone to reach a specific position. To precisely steer the drones, we tuned PID controllers to the given physical properties of the drones until we obtained flight trajectories that diverge by less than $\sim$3 cm from the specified position. The commands were sent by radio to the drones. The code of the complete system is available under MIT license on GitHub[48]. We integrated two drones into our system, which we introduce in the following.

Small Drone As a smaller drone we used an off-the-self *CrazyFlie 2.1*[49]. It measures $9.2 \times 9.2 \times 2.9$ cm with a weight of $27g$. To control the *CrazyFlie*, we used a *Crazyradio PA* Universal Serial Bus (USB) radio dongle attached to a computer running the command and control application.

Large Drone We build a custom *F3 Flight* drone measuring $35 \times 38.5 \times 14.5$ cm with a weight of $750g$. We used a *F3 Flight Con-*

[48] Drone Control Software Framework, https://github.com/jonasauda/understanding_drone_landing, last retrieved on August 12, 2022

[49] CrazyFlie 2.1, https://www.bitcraze.io/products/crazyflie-2-1/, last retrieved on August 12, 2022

troller Acro 6 DOF as the central control unit of the drone. As a frame, we used a *QAV250 250mm Carbon Fiber Quadcopter Frame*. We mounted four motors (*MT2204 2300KV*) controlled by four ESCs (*Emax 12A Simonk ESC*) to the frame. Further, we mounted *5030 propellers* on the motors. We soldered together all the wires between the power distribution board and the components. To receive the radio signal, we added a *NodeMCU* to the drone equipped with an *WayinTop 2pcs NRF24L01+PA+LNA* transceiver. The received signal was forwarded via Pulse-Position Modulation (PPM) from the *NodeMCU* to the flight controller. We attached a *Keywish RF-Nano Arduino Nano V3.0* to the computer running the control application via USB to radio control commands to the drone. For safety, we build a cage out of carbon sticks[50] that surrounds the drone to keep distance between the rotors and humans or obstacles.

Platforms We built three landing platforms to ease the drone landing and to analyze the impact of the landing platform on the acceptability of the user. To land a drone on the shoulder, we used a metal plate with hooks (to prevent a landed drone from falling off) that is attached to one of the user's shoulders (see Figure 11.9). The metal plate juts over the shoulder of the wearing user. For landing a small drone on the back, we attached a horizontal plate to the backpack measuring 10 x 10 cm. To land a large drone, we attached a vertical plate with hooks to the backpack. The drone could use its cage to attach itself to the hooks and then hinge itself down to be worn like a backpack by the user.

360° Recordings of Landing Maneuvers

We used a *Vuze 3D 360 4K VR Camera* to record our drones converging on different body locations. Prior to recording, we covered the walls, floor, and ceiling of our lab with green screens to digitally add another background video in post-production. Therefore, we recorded a video of an urban setting (i.e., an open square with buildings, trees, and cars in the background). As we could not cover the cameras of the tracking system because it was needed to steer the drones, we digitally masked these areas in the 360° video in order to properly edit the cameras out of the video. We recorded seven scenes – six flight maneuvers and one video to familiarize viewers with the situation of having a drone flying in proximity. To avoid injuries while filming, we used a mannequin as a model for the human body (see Figure 11.9). Instead of the head, we mounted the camera to the mannequin to record 1st person-view videos. For landing on the user's hand, an actor reached out with the arm for the

[50] `Safe-to-touchDroneCage,http://www.hirundino.com/beyond-the-force/do-it-yourself`, last retrieved on August 12, 2022

Question	Mean	SD	IQR
I have experience with drones or quadcopters	2.25	1.83	1.75
I am interested in new technology	5.25	1.53	1.0
I am using new technology regularly	4.83	0.9	1.25
I would consider myself tech-savvy	4.83	1.82	2.0

Table 11.4: The average technical affinity of the participants on a 7-point Likert scale.

drone to land on. Landing on the head and back was filmed from a 3rd person-view because otherwise, one could not see the drone approaching or landing. For landing on the shoulder, we attached a platform to the mannequin's right shoulder.

We excluded climbing and other similar sports activities from our VR study since they did not fit the urban context. We elaborate on such activities and further settings for drone landing on the human body in future work.

Participants

We recruited 12 participants (6 female, 6 male, ten right-handed, two left-handed) with an average age of 30.92 years ($SD = 12.41, IQR = 9.75$). We asked the participants what kind of drone experience they have. They reported that they had used drones for fun, filming, or education (programming). One participant reported an encounter with remotely controlled drones in real life. In this situation, the participant wanted to pass by a specific area. Because of a possible crash with the drones, passing by was not possible. Of the 12 participants, 7 reported that they have never used a drone in the past. Three participants used drones for 1–2 times before. One participant for 3–5 times and one more than 10 times. Of the 12 participants, 4 reported that they had piloted a drone by themselves. Further, we asked the participants if they had previous VR experience. Seven out of 12 participants reported that they had used VR once. Two said they use VR on a monthly basis, and two have never used VR before. Finally, we assessed the technical affinity of our participants on a 7-Point-Likert scale (see Table 11.4).

Apparatus and Procedure

We started the study by showing each participant a video of a drone flying in front of them in VR to familiarize them with the setting. Therefore, we handed the participants a HMD (*Oculus Quest*) with attached stereo headphones

Figure 11.10: A participant experiences a drone landing on the hand in a 360° video (staged scene).

(*beyerdynamics Custom One Pro*). In this video, our small drone (*CrazyFlie*) repeatedly flew in front of the user. After the participant reported to have acclimated to the setting, we started with the first landing video. The landing videos were counterbalanced (Latin Square Design). In total, each participant watched six landing videos (see Figure 11.10). The participants could watch each video multiple times. After each video, we asked the participants to rate nine statements on a 7-Point-Likert scale. After each rating, we asked for the reasons why specific values were picked. Then we proceeded with the next video. We instructed the participants to stand still while watching the 360° videos or hold their hands, as seen in the video in which drones were landing on the viewer's hand in VR (see Figure 11.10). Further, as we recorded landing on the head and back from the 3rd person-view, we instructed the participants to empathize with the mannequin on which the drones landed. Otherwise, the participants would not recognize the drone because they would not be able to see nor feel it due to missing haptic feedback in current VR systems. After each participant had seen all six landing videos, we conducted a semi-structured concluding interview about the virtual drone experience.

Results

We asked each participant to rate their virtual drone experience with regards to drone flight behavior, visual appearance, auditory appearance, and experienced safeness. In total, the participants rated nine statements (S1 – S9) on a 7-Point-Likert scale (see Figure 11.11). Wilcoxon Signed-Ranks (Bonferroni corrected) indicate statistically significant differences regarding the different body parts used for drone landing. In the following, we introduce the feedback from our participants gathered in a semi-structured interview. We introduce them clustered into themes:

Landing Platforms We used the landing platform and hook primarily to ease the landing. Surprisingly, participants mentioned positive associations with the landing setup. 58% (7 of 12) of the participants noticed the landing pad and mentioned that it helped them to understand the scenario: *"I saw the square platform, and it was clear what is going on."* [P1]. Some participants mentioned they prefer the hook over the platform. They said the hook is an *"optimal solution for the big drone"* [P4], *"a clever solution"* [P9], and that they *"would accept [the hook] rather than a platform"* [P9].

Drone Localization Auditive feedback played an important role for participants in localizing the drone: *"I tried to localize the drone according to the sound"* [P8]. The sound is especially important if the drone is not visible: *"I would need to trust the sound when the drone is approaching from the back"* [P2]. In addition to the rotor sounds, participants suggested additional audio feedback to signalize the landing: *"Maybe a sound would have helped to signalize that the drone wants to land"* [P7].

Proximity and Control Flying a drone near the head or shoulder was stated to be intimidating or to be an injury risk: *"[...] I fear that the drone gets stuck in my hair"* [P5]. In contrast, landing a drone on the hand induced the feeling of being in control: *"I want to see the drone. I think it is good to land on the hand because I want to be in control and be able to react easily."* [P3]. Further, a controlled behavior was perceived positively: *"I had the feeling of sympathy because it was controlled. I did not feel threatened"* [P6].

Drone Size 75% (9 of 12) of the participants said that the small drone should be even smaller for at least one body location. Most participants wanted a smaller drone on the back (42%), while 25% of participants said the drone should be smaller on other body locations. The large drone was mentioned as too big by 75% of the participants. However, one participant also mentioned that drones should not be smaller than the small drone *"since they would be difficult to notice"* [P4]. One participant compared the small drone to *"a small bird that lands on the hand"* [P8]. This demonstrates more positive associations than the bigger drone, which was seen as *"a bit threatening"* [P6], *"bulky"* [P5], and *"heavy"* [P7].

Other Landing Locations Beyond the implemented landing locations, participants suggested other landing setups. For example, *"a kind of baby sling on the chest could make sense to keep the drone in the field of view"* [P7] and

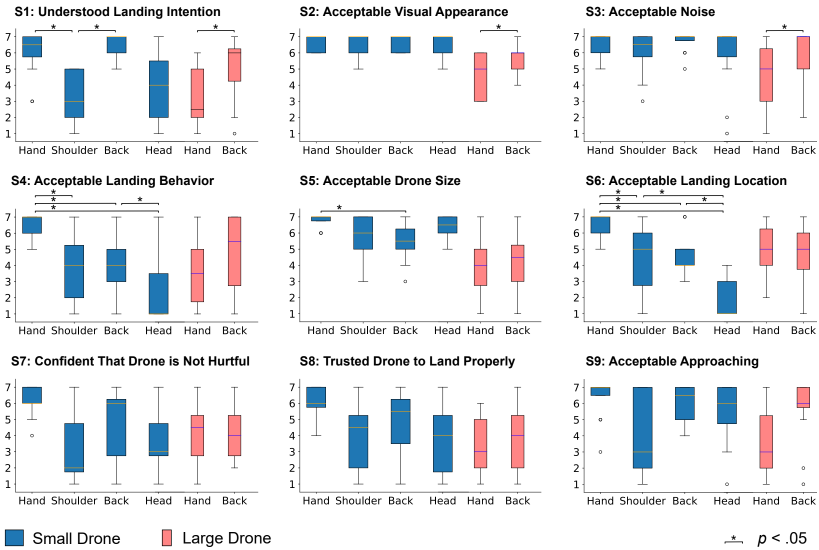


Figure 11.11: Participants 7-Point-Likert ratings of the nine statements.

"a big drone with an integrated hat could bring its own landing place" [P6]. A visible landing setup might also help to improve the bond between human and drone: *"The backpack gives a guarantee that the drone will come back. I feel more connected to the drone"* [P10].

Safety Risk and Trust For the large drone, participants stated that the injury risk is high when it approached from the back: *"I feared that the drone would hurt me because of its size"* [P6]. The participants stated that they had to trust the drone to land properly when they could not see it. *"I could not see the drone, so I had to trust that it lands safely"* [P4].

Drone Approach Positively rated approaches had flight paths that were perceived as *"controlled"*, *"steady"*, and *"target-oriented"*. For low ratings, the most common reasons were that the drones were *"too fast"*, *"difficult to see"*, or *"did not wait"* for the user.

11.2.7 Combined Findings and Takeaways

This section compares the results from the online survey and VR study and discusses their similarities and differences.

Suitable Landing Locations on the Human Body

Through the VR study, we could confirm several findings from the online survey. We could confirm that the hands and the back can be suitable landing locations. This supports prior work on launching and catching drones using the hands [449] but also demonstrates that there are many more possibly acceptable locations for drone landings. In contrast, the shoulders, which were rated acceptable for landing in the online survey, were rated with a low acceptance by the participants of the VR study. Furthermore, we can confirm that the head is not well-suited for drone landing. For these landing locations, participants noted they would not accept the locations due to a high injury risk. This was made more apparent due to the increased immersion in the VE compared to the online survey.

The acceptance in the online surveys was independent of the concrete landing platform. However, the VR study revealed that a good landing platform can help one to understand the drone's intention and can influence the acceptability of the overall system. Hence, the platforms should be carefully designed. While prior wearable design factors should be taken into account (e.g., [145, 580, 255, 116]), future work should investigate different landing mechanisms and their technical feasibility in more depth.

Influence of Drone Design on Landing Acceptability

Despite the relatively neutral acceptance ratings in the *MTurk*, participants found the "traditional" quadcopter form factor highly acceptable when immersed in the VR scenario. This could be biased because participants only experienced two similar form factors. However, both results indicate that there might not be a huge influence of visual appearance on the acceptability of on-body landing. This is particularly interesting since prior work found that aesthetics play an important role for body-worn devices [382]. We believe that, despite the close proximity, our participants saw the drones as external objects rather than as a part of their bodies.

Influence of Activity and Context on Landing Acceptability?

Through the online survey, we could gather first insights into the activity and context for which a user would accept drones landing on the body. We found that landing a drone would be considered more acceptable for work-related activities or in emergency rescue situations than, for example, for entertainment purposes. This highlights the idea that landing a drone on the human body could find application in more serious contexts in which critical tasks must be accomplished, or lives must be saved.

Influence of Flight Path and Landing Behavior

From the VR study, we learned that the participants wished for the drone to be in sight while landing. Further, a steady and controlled approaching procedure was required for the acceptance of landing. Such a procedure should give the user time to prepare for the landing approach. Being in control of the situation and/or being able to react to unforeseen events was stated as a necessity for acceptance by the participants. For example, approaching the user from the back requires the user to trust the system. Therefore, additional modalities, such as auditory feedback, might be of use. Also, the noise of the drone helped the participants to localize it when it was out of view. Together with auditory feedback that might further improve the way people localize drones and therefore increases trust in the landing procedure.

General Findings Regarding VR Studies

We further identified several interesting findings regarding the VR study. On the one hand, a real study with drones can be dangerous for the participants due to the high injury risk. Studying drones in VR comes with limited realism but increases reproducibility [553]. Bringing the drone into the virtual world eliminates safety risks while providing visual and auditory experiences in 3D space. On the other hand, some aspects are not covered by the virtual setting (e.g., haptics and airflow). One participant mentioned that VR was not convincing enough to feel immersed in the virtual setting: *"It was not my hand. I knew that this was not really happening. I could abstract emotionally"* [P1].

In addition, it is difficult to evaluate all aspects of drones (e.g., flight paths and noise) with an online survey. As the contradiction of the landing acceptance on the shoulder in the two studies shows, some aspects need to be investigated with real prototypes or close-to-real systems like VR. Here, we believe that in the online study, the absence of motion and sound led to a higher landing acceptance on the shoulder. In contrast, the VR study revealed that the participants found landing on the shoulder less acceptable due to high injury risks, and the proximity of the drone was found to be intimidating.

11.2.8 Limitations

In the following, we state and discuss the limitations of our research.

Environmental Conditions, Context, and Activity Drones are heavily influenced by environmental conditions such as the weather. The wind has a huge impact on the flying behavior of drones. This might impede proper landing maneuvers and thus might lower the landing acceptability of users. This was not considered in our evaluation. Future research endeavors might investigate weather influence on drone landing capabilities and how users perceive possible risks, for example, through more realism-enhanced simulations that simulate events such as stormy weather conditions and shaky drones. Also, in our VR study, the participants could focus solely on the drone landing on them. In reality, this may differ depending on the context of a user. The acceptance of landing a drone on a user might be lower in specific social contexts, such as being in a crowded place. Further, the task of a person might impact landing procedure and acceptability. For instance, rescue personnel that needs an overview can benefit from drones autonomously starting from them and sending back information. However, when a person is carrying out life-saving measures (e.g., giving CPR), landing a drone on the hand is not acceptable. Therefore, context and activity play an important role for the acceptability of drones landing on the human body.

Studying Drones in Virtual Reality In Wojciechowska et al.'s taxonomy on HDI research methodologies, VR studies achieve second-best reality after co-located flights, resulting in medium realism and complexity while reducing safety risk [553]. This lower realism in VR is due to the lack of full sensory sensations, which are not possible with current VR systems. Because of the missing haptics, results with real drones might differ. However, VR still provides great detail when rendering video and audio. Future research might simulate appropriate haptics along with the VR experience; or, if risk can be eliminated, real specifically designed drones can be tested against our results. Our open source framework can be used to investigate such specifically designed drones for on-body landing.

Drone Design Through the online survey, we obtained ratings on landing acceptability and suitability of differently designed drones. However, showing participants an image of a drone might not result in the same acceptability as experiencing the drone in reality. The proximity, flying speed, or sound could strongly affect acceptance. While our results uncovered initial insights into the acceptance, further landing acceptance factors (e.g., flight behavior, sound, and haptics) require further investigation. In addition, we acknowledge that these drones are available on the market (see Figure 11.8). They are not designed to land on the body. Optimizing the design to land on the body might change the user's perception. Thereby, the drone design and the estimated body location for landing need to match. In the study, participants suggested different metaphors that can inform the design of the drones. This could help to improve users´ perception – particularly with regard to safety. For example, participants mentioned birds as a metaphor to create drones that are more accepted to land on the body (see Section 11.2.6).

11.2.9 Future Work

In the following, we outline possible future research directions.

Further Research Directions Our work presents an initial investigation into suitable locations for a drone to land on the body. We hope it will serve as a foundation for these additional research ideas, which go beyond the scope of this work. Future work should investigate further body locations, such as the front of the body and the legs, along with the long-term effects on the acceptability of on-body drone landings and the implications of real-world environmental conditions, such as wind, visibility, and social context—that arise from a particular user activity (e.g., climbing). Moreover, in-depth studies must be conducted to fine-tune the sound and motion behavior of the drones while approaching the human body for landing.

Safety and Perception of Safety Safety is of utmost importance. In our research, we do not explore safety, but we explore the perception of safety. Thus, our research is a first step towards including users' perceptions in the discussion on safety standards for HDI. With DJI hand-landing system[51], landing drones on the human body has already started. Therefore, we argue that understanding preferences for drone landing on the human body is important and timely. As the technology is not fully developed yet and is limited to

[51] DJI Mini 2, `https://www.dji.com/mini-2`, last retrieved on August 12, 2022

landing on the user's hand, it is important to understand which other body parts seem acceptable for drone landing. We believe that this improves the discussion and future research on this subject. Especially as drones have the potential to bond with humans [287, 121, 266] and become ubiquitous companions [80, 341] in the future. Creating such a bond between humans and drones through their interaction is studied actively in research [287, 121, 266, 341]. Future research could investigate further factors important to creating bonds like those of human-to-human interaction, where different social bonds are related to body regions [490]. On the technical side, there should be more research on the design of drones that promise a lower risk of injury, for example, quadcopters with deformable propellers [366] or suitable emergency handling such as emergency stops which are already integrated into drone controllers. Future emergency stop mechanisms could consider human behavior in the loop.

11.2.10 Conclusion

With our work, we contribute pioneer work that investigates drone landing on the human body. From two user studies, we derived location preferences and common themes for drone landing. Based on an online survey, we visualized the acceptance of different body locations while standing, sitting, walking, and climbing. Future drone designers can make use of these visualizations to find suitable body locations for their supported activities. We identified common themes and appropriate landing locations from open-ended questions and the immersion into VR drone landing videos. Application designers that want to incorporate on-body drone landings should consider that different body locations influence perceived control over the drone and acceptability, that form factors can influence perceived landing suitability, and that contexts of a more serious nature might increase landing acceptability. We hope our work will stimulate future research on drones landing on, starting from, and being worn on the body. We believe this work has the potential to enable novel applications and will lead to a closer connection between humans and drones. To circle back to MR or CR systems, their future use cases, and the possible ubiquitous deployment, we laid out the foundation that could inform future design decisions of systems that integrate drones to enhance the interaction with its users.

Summary and Key Findings

In this part, we enhanced the virtual experience through specifically tailored technology solutions. First, we used passive haptic props to enhance remote VR collaboration. Here, we evaluated methods that allow for taking over the ownership of remote haptic objects to bring knowledge into the collective solution crafting process. Afterward, with the help of our *Flyables* toolkit, we provided VR users with autonomous flying input devices which position themselves autonomously in 3D space. VR users could reach out for the input devices and interact with them in a variety of VR scenarios. We evaluated the toolkit and presented the strengths and weaknesses of drone-mounted haptic input devices in VR. In the following, we present our key findings:

RQ 5: How can we enhance remote collaboration in VR through passive haptic props?

Key Finding I**:** We showed that using haptic props for taking over the ownership of remote objects via well-known methods (i.e., *Copy* and *Cut*) can enhance remote VR collaboration. Through these methods, collaborators felt more decoupled from each other, could work individually, and did not have to wait for the other collaborator. This lowers task completion time.

Key Finding II**:** We showed that using haptic props to create visual instructions reduced verbal communication and provided an easy-to-follow indicator for the correct solution to other collaborators. Nonetheless, this results in higher task completion times.

RQ 6: How can we deploy flying UIs to provide haptic feedback in VR?

***Key Finding III*:** We showed that VR users felt more immersed in the VR environment when using *Flyables*. Further, they appreciated the haptics of *Flyables*. Compared to controllers, *Flyables* communicate their functionality through their affordance.

***Key Finding IV*:** We found that state-of-the-art controllers still outperform *Flyables* in terms of input precision and task completion time. But using *Flyables* induced more body movement by VR users.

Going beyond the deployment of haptic drones in VR scenarios, we investigated drone landing on the human body. In our vision, we believe that drones could be body-worn by their users. For rapid deployment of a haptic MR system, they could start autonomously, be used for interaction, and eventually land on their owner again. In this context, we investigated drone landing on the human body. In essence, we distilled the following key findings:

***Key Finding V*:** We found that for landing drones on the human body, the hands and the back can be suitable landing locations. Further, a steady and controlled approaching procedure was required for the acceptance of landing. Further, drones should give the user time to prepare for the landing approach. Being in control of the situation and/or being able to react to unforeseen events is a necessity for landing acceptance.

***Key Finding VI*:** We found that the context (e.g., the environment and activity) influences the landing acceptance. Users will more likely accept a drone landing on their body during work-related activities or emergencies than, for example, for entertainment purposes.

We can answer **RQ 5** with *Key Finding I + II*. We showed that the implementation of different methods for managing the ownership of virtual objects in remote VR collaboration scenarios through haptic props impacts the underlying workflow. It depends on the collaborators and their expertise on which methods should be used to shape the solution collectively. Experts with domain knowledge can use methods like *copying* or *cutting* (i.e., transferring the ownership) of virtual objects to work decoupled from each other, which results in faster workflows. Novices that need expert guidance can rely on instructions that indicate the steps they need to fulfill to solve the underlying task. As they are easy to follow, they can help novices gather experience from experts through the help of VR even if they are remotely located. In sum, we could enrich the virtual collaboration experience through the integration of passive haptic props, even if these props can not be influenced directly by the remotely located collaborators.

We can answer **RQ 6** with the remaining key findings. Through *Key Finding III + IV*, we showed that using drones to position matching haptic input devices around the VR users can enhance the virtual experience. We realized that in a variety of VR scenes using our *Flyables Toolkit*. Through that, we provided a higher immersion and more convincing haptic sensation compared to state-of-the-art VR controllers. Further, *Flyables* communicated their affordance and therefore indicate their functionality through their appearance. On the contrary, state-of-the-art controllers are more precise than *Flyables*. Therefore, we suggest that our toolkit needs further development to broaden its applicability. When we consider the deployment process of drones, we introduced the first results in the field of landing drones on the human body. Our *Key Findings V + VI* are not only applicable in the field of VR but can inform the design and development of future, drone-based VR or even various systems on the MR spectrum. In this context, we envision drone-supported MR systems that offer more natural input modalities, haptic feedback, and, to circle back to drone landing on the human body, fast and reliable deployment processes. Through that, these systems can become ubiquitously available in the future.

VI

Conclusion

Chapter 12

Conclusion

In this thesis, we investigated novel interaction opportunities for VR with the goal of improving the applicability of future VR experiences, increasing immersion, and broadening the user's interaction space. We structured our research along three particular research themes, which guided us throughout the research process. Our themes also helped us to answer questions about how to *avoid conflicts with the real world* while immersed in VR (see Part III), how to *integrate the real world* into VR experiences (see Part IV), and how we can *enhance the virtual world* through novel technology solutions (see Part V). Within each theme, we posed two RQs. To answer them, we developed tools and frameworks to support our research process, thus enabling us to conduct a wide range of evaluations. Thereby, we generated our contribution of knowledge for each of our three research themes.

We began with a brief look into the history of VR. Thereafter, we reflected on the fundamental knowledge that is needed to understand how humans perceive and interact with digitally-created worlds. We followed up with an extensive literature review on CR systems to understand the interplay of reality and virtuality. Here, we highlighted the relationship between physical reality and VR or other virtually enhanced or simulated environments. With that, we paved the way for our three themes, which form our main research contributions from a theoretical point of view.

Next, we introduced our tools and frameworks, which formed our research infrastructure. Here, we introduced *VinteR*, our tracking and streaming system that allows the integration of various data sources from both the real world and VEs. Therefore, it acted as a middleware for our research prototypes. Next, we introduced the *Flyables Toolkit*. Through this toolkit, we could use drones that steer themselves autonomously and position themselves around a VR user. We equipped the drones with 3D-printed input devices (e.g., a *button* or *joystick*), which served as haptic input devices. VR users could use these devices to interact with the VE. The last system in our repertoire of tools is the *VRception* toolkit. Through that toolkit, designers and developers of CR systems can develop their prototype entirely in VR. This eliminates certain real-world restrictions (e.g., challenging integration of hardware or extensive fabrication), but it also allows for a first impression of the anticipated interaction of the prototype. We published all these systems and toolkits along with their source codes and documentation to foster future research (see Part II).

In the main parts of this thesis, we introduced three different research themes. For each of these themes, we developed several research prototypes following a design-driven and technology-focused approach [550]. We used these prototypes to conduct a wide array of evaluations. From the results, we distilled key findings that can support future VR designers and developers with the implementation of highly immersive and interactive VR experiences.

12.1 Summary of Research Contributions

In the following, we summarize our research contributions. We begin with insights from our review on CR systems and follow that with our artifact contributions (i.e., the tools and frameworks that formed our research infrastructure). After that, we recapitulate the contributions from our three integral research parts. Three main themes contextualize these contributions. For each theme, we proposed two RQs. With the answers to these questions, we discuss implications for VR.

12.1.1 Immersive Technologies and Cross-Reality Systems

We presented a literature survey on CR systems (see Chapter 2). CR systems have recently been at the forefront of research because they provide interaction beyond one specific manifestation from the Reality-Virtuality Continuum, such as AR or VR. This can help users to obtain different perspectives on the underlying task [289]. Along with our survey, we defined three types of CR systems to structure corresponding research. *Type 1* refers to systems in which subjects transitioning on the continuum experiencing a changing actuality (e.g., a user starts in physical reality, joins AR, and then shifts to VR [421]). *Type 2* systems involve subjects interacting with objects that are repurposed for the subject's actuality (e.g., a VR user interacting with a physical keyboard that is integrated into the VR experience [317]). *Type 3* systems involve multiple subjects experiencing different actualities (e.g., one user experiences VR and a bystander is integrated into the VR experience to allow awareness or communication [317, 546]). We analyzed the literature according to our definitions and identified publications that presented a CR system. We then extracted a comprehensive set of properties from the presented systems, including but not limited to the research scenario, involved technologies and manifestations, subjects, integrated objects, and potential transitions along the Reality-Virtuality Continuum. From our findings, we derived nine golden rules for CR system design and development. These rules guide CR system design according to our definitions of CR systems. Thus, they inform on important aspects that should be considered during the development of novel CR experiences.

12.1.2 Tools and Frameworks

In the second part of this thesis, we introduced the research tools and frameworks together with corresponding artifacts that we used to conduct our research.

VinteR

First, we introduced the *VinteR* system (see Chapter 3). *VinteR* served as our main streaming application and allowed us to unify data streams from different input sources (e.g., *OptiTrack* or *Kinect*) within one canonical data format. Through that, we accelerated the integration of technical infrastructure into our research prototypes. We constantly integrated new features into *VinteR* throughout the scope of this thesis. In the end, the *VinteR* system evolved into a distributed, real-time streaming application that can connect remote locations in VR. It synchronizes the data of any endpoints that implement the canonical data model. Further, it can stream data from any input source that is integrated through a software adapter in *VinteR*'s input layer. In the final version of the *VinteR* system, we also integrated VoIP capabilities to allow VR users to communicate while joining VR sessions.

Flyables Toolkit

Based on *VinteR*, we developed the *Flyables* toolkit [31] (see Chapter 4). With the help of this toolkit, we can steer drones autonomously to position haptic input devices around VR users. Here, *VinteR* tracks the positions and orientations of the drones and continuously streams the data to the *Flyables* toolkit. The toolkit calculates the flight commands for the drones based on the data from *VinteR* and the corresponding setpoint from the VR application using PID controllers [380]. With this controlling loop, we can position our drones around the users with respect to the input from the underlying VR application. As haptic input devices, we designed and 3D-printed five well-known input devices that can be mounted on drones: a *button*, *knob*, *joystick*, *slider*, and *3D mouse*).

VRception

Finally, we introduced the *VRception* toolkit [162] (see Chapter 5). Through *VRception*, one can simulate CR prototypes entirely in VR. One can build prototypes in *Unity3D* or, with the help of WYSIWYG building blocks, directly in VR. With this, CR designers, developers, and researchers can rapidly gain first impressions of the anticipated system design. In *VRception*, users can transition seamlessly from simulated reality to simulated AR and AV to simulated VR. This allows them to inspect their prototype and corresponding CR interaction from different manifestations of the Reality-Virtuality Continuum [328, 329, 329]. To work jointly on a CR prototype, we integrated networking capabilities that allow for remote collaboration in VR.

We open-sourced all these systems, corresponding artifacts, and toolkits for others to use. The links to the resources can be found in the corresponding chapters of Part II.

12.1.3 Research Questions

In the three research parts of this thesis, we answered the six RQs that were introduced in Chapter 1. In the following, we reflect on each RQ and contextualize our findings within each of the three themes.

Avoiding Conflicts with the Real World

In Part III, we investigated approaches for avoiding unintentional encounters with the real world to improve VR experiences. Therefore, we introduced approaches to enhance natural locomotion. In this context, VR suffers from physical constraints and space limitations. These constraints hinder the VR users from freely exploring potentially infinite virtual worlds. Hence, there is a need to either confine natural locomotion to limited physical space or use the available space more efficiently. Here, we proposed the following RQs:

RQ 1: How can we reduce the physical space needed for natural locomotion in VR? To unlock the full potential of VR, we introduced enhancements for *redirected walking* to reduce the physical space required for exploring significantly larger virtual worlds by foot (see Chapter 6). Here, we introduce our approach for enhancing natural locomotion through redirected walking via EMS-based actuation of the VR user. We conclude that we can enhance redirected walking through the actuation of the user's leg via EMS. Our approach can help to prevent encounters with limiting obstacles such as walls, thus preserving immersion. Through EMS, we can steer VR users away from physical obstacles to avoid possible encounters that would conflict with the virtual experience.

RQ 2: How can we use the available physical space more efficiently for natural locomotion in VR? To answer this RQ, we investigated the influence of immersion on the perception of non-Euclidean spaces in VR (see Chapter 7). Such environments allow for more efficient utilization of physical space because they overlap virtually. In particular, we investigated how users perceive self-overlapping VEs and determined which factors allow users to recognize the virtual overlap. To shift the users' attention away from this, we employed a distractor in the form of a minimap to provide a move believable illusion. Thereby, we use the physical space available in a more efficient way. This distraction can help to bolster the created illusion of non-overlapping virtual spaces since the attention of VR users is diverted. Through this distraction, we can use the physical space more efficiently through the deployment of larger self-overlapping architectures.

With this, we can conclude the first research part of this thesis – *Avoiding Conflicts with the Real World*. Taken together, our approaches for natural locomotion can be used to reduce the conflicts between the virtual and the real world; thus, they form a step towards increased autonomy of VR users that can explore possibly infinite virtual worlds.

Integrating the Real World

In Part IV, we investigated the integration of real-world objects and physiological responses of the VR user into VR experiences. This can help one to overcome certain limitations of VR. For instance, current VR controllers lack matching haptic feedback to differently-shaped virtual objects. Further, integrating real-world objects that are familiar to users can offer benefits for certain tasks. For instance, integrating a pen for sketching in VR may make the experience more natural. Tending towards the users, VR can benefit from integrating physiological data sources. Additional integration of such sources (e.g., EEG) allows for the utilization of novel interaction modalities. Integrating these sources can provide an additional interaction channel for VR users. We approached this integration from two directions: one direction toward the environment and its objects and one toward VR users and their physiological responses. Here, we proposed the following RQs:

RQ 3: How can we enhance the user's virtual experience by manipulating the appearance of real-world objects in VR? Tending towards the environment, mixing in objects from the user's environment can support users in serious VR application by providing haptic feedback or boost task performance by overcoming real-world restrictions (see Chapter 8). We integrated real-world objects into the VE to allow haptic experiences and applied different levels of transparency to allow a better view of the underlying task in VR. We observed that transparency did not foster a better view of the task in every case. Therefore, we suggest that it may be beneficial to adapt transparency dynamically, based on the underlying scenario and given circumstances. In addition to applying transparency to certain virtual objects, we create illusions by manipulating the apparent size of the integrated objects and investigate the degree to which VR users believe such illusions. Through that, we can reduce the number of haptic props that are needed to mimic matching haptics for a larger quantity of virtual objects. In conclusion, we can state that respecting such thresholds can help developers and designers to drastically reduce the number of physical objects required to serve as haptic props for virtual objects. Overall, we can conclude that through VR, we have the possibility to bypass physical constraints such as occlusion, which is an inevitable restriction in reality. Future VR experiences can benefit not only from mimicking the real world as closely as possible, but also from the consideration of whether certain constraints from the real world can be circumvented to benefit VR users.

RQ 4: How can we integrate BCI-based sensing to provide additional interaction modalities in VR? Tending towards the user, we could show that VR experiences that make use of SSVEP-based interaction can be enhanced by blending stimuli (see Chapter 9). This allows for the integration of less disruptive or artificially appearing stimuli. Hence, we can focus on providing an immersive narrative and still be able to use the SSVEP interaction paradigm in a more subtle manner. Of utmost importance here is the trade-off between the performance and the appearance of our stimuli. Therefore, we recommend that VR designers and developers consider this trade-off when integrating SSVEP stimuli in VR. If a robust interaction in terms of classification accuracy is required, a *flickering* stimulus is well-suited. If visual fidelity is important, we suggest using a stimuli that blends with the VE. Here, matching animations and form-factors can enhance the VR experiences.

With this, we can conclude the second research part of this thesis – *Integrating the Real World*. All in all, mixing in real-world objects and sensing cortical data from the VR users allows us to provide more realistic and interactive VR experiences.

Enriching the Virtual World

In Part V, we introduced novel approaches that can broaden interaction possibilities in VR. Specifically, we focused on two research areas. First, we enhanced remote collaboration through passive haptics and thereby enabled haptic interaction beyond a single location. Second, we provided haptics to virtual UIs through flying haptic proxies using drones. In essence, we enriched the virtual world in two ways – through passive haptic props and flying haptic UIs. With that, we tackled the following two RQs:

RQ 5: How can we enhance remote collaboration in VR through passive haptic props? We showed that remote collaboration can benefit from haptic props when one needs to overtake ownership of an object of interest (see Chapter 10). In particular, we showed that using haptic props that implement different methods for managing the ownership of virtual objects can have different implications for the underlying workflow. The choice of method depends on the collaborators and their expertise. In particular, we found that methods such as *copying* or *cutting* (i.e., transferring the ownership) of virtual objects resulted in faster and decoupled collaboration workflows. For novices to a task, we found that experts can provide guidance via instructions through haptic props. These instructions can indicate the necessary steps for fulfilling the underlying task. This results in different implications for the collaboration. Designers and developers of VR-based collaboration applications should consider their users and corresponding expertise to provide suitable interaction methods.

RQ 6: How can we deploy flying UIs to provide haptic feedback in VR? To answer this RQ, we deployed flying haptic input devices in VR (see Chapter 11). We envision that future VR systems could integrate *Flyables* to provide a wide array of haptic input possibilities to VR users. This would enrich virtual experiences through an interactive haptic sensation that is autonomously deployed where users expect to feel virtual content. We showed such an enrichment possibility using our *Flyables Toolkit*. In particular, we used drones to position haptic input devices in 3D space around VR users. We found that our users felt more immersed into the VR scenario when using *Flyables* than when they used state-of-the-art VR controllers. Further, using *Flyables* resulted in increased physical movement of VR users compared to VR controllers. Therefore, we believe that flying haptic input devices can not only provide a more intuitive way for interacting with VE, but can also foster physical activity. Nonetheless, controllers are more precise than *Flyables*. Here, we derived future challenges that can improve *Flyables* and thereby broadening their application space. Along with that, we introduced pioneering work in the field of drone landing on the human body. At first glance, this is not closely related to drone-enhanced VR experiences, but we believe that future VR or even several kinds of MR systems can benefit from drone-based input modalities. Therefore, we believe that our results can inform the design and development of novel MR systems that are mobile and ubiquitously applicable.

With this, we can conclude the last research part of this thesis – *Enriching the Virtual World*. We introduced approaches that allow one to enrich VR experiences with haptics beyond a single location. Further, we showed how drones can autonomously deploy interactive haptic end effectors around the VR user.

With our work, we aimed to provide a solid contribution towards the vision of VR – creating a system that allows one to enter a completely computer generated world that is so advanced that there is no distinction between the fidelity of this world and physical reality – similar to the *ultimate display* as imagined by Ivan Sutherland [488]. Since 1960, research has been steadily approaching this vision. As part of this, we contribute a wide array of research insights to enhance interaction with virtual worlds. In the following sections, we summarize our findings, reflect on the answers to our RQs, and derive future research challenges with the potential to guide VR research towards its ultimate goal.

12.2 Future Work

Throughout this thesis, we identified various research challenges distributed across a wide array of VR-related fields. We discovered these challenges through the development and evaluation of our research prototypes as well as through the theoretical analysis of the literature. In the following, we propose various promising future research challenges based on our own research endeavors and corresponding findings. We ordered these challenges according to our estimation of their complexity.

12.2.1 Adaptive Methods for Natural Locomotion

In Part III, we reduced the number of conflicts between the real world and VR. In particular, we reduced encounters with physical obstacles such as walls by using the physical space more efficiently. Therefore, we developed and evaluated two different methods, each of which can enhance natural locomotion in VR. Through the EMS-based actuation of the VR user's leg (see Chapter 6), our system decoupled physical from virtual locomotion. We did this with every step. Future work could investigate a more adaptive approach similar to previous work in the field of redirected walking. Here, the redirection occurred when specific conditions were met (e.g., reorientating the VE during eye blinks of the VR users using change blindness [271]). In particular, EMS-based actuation could be applied during specific situations within the VR experience. This approach could be combined with previous approaches for dynamic layout generation [517, 307, 90] to allow the most efficient use of the available physical space. We strongly believe that the situational combination of these approaches yields the best results, as our own approach in Chapter 6 indicates. Additionally, future research could investigate the adaptive appearance of visual distractors like our minimap distractor (see Chapter 7). During the redirection of VR users, critical situations arise. Such situations have great potential to disrupt the virtual experience, as they may increase the chance of collision with an obstacle. To mitigate these adverse effects, future research could investigate the application of distractors that appear during the occurrence of such situations or even before to shift the VR users focus. Here, we believe that occupying the user's focus could further help to disguise the underlying redirection methods. In this context, previous work showed that there is great potential in using task-driven distractions [96].

12.2.2 Awareness for Reality

In Part IV, we showed that the integration of the real world can enhance virtual experiences. For example, one bringing a useful, physical tool into a virtually enhanced environment can improve the experience [317, 106]. As experts in the field of MR and CR systems believe that future devices will allow seamless shifting between different degrees of virtuality [464], the integration of such real-world objects into the possibly changing actualities (see Section 2.2.2) of users becomes more challenging. In the past, research introduced approaches that allow for seamless integration of real world objects or environments to enhance the experience for users in VR [307, 454, 90] or AR [202]. Here, most research focuses on a particular manifestation on the Reality-Virtuality Continuum [328]. Nonetheless, there are only a few early works that allow users to transition between different manifestations that integrate real-world objects into these transitions [53, 54, 421, 420]. Less is known about the versatility of integrated objects for a given task that is approached by users that can change their actuality (e.g., starting on a task in AR and then switching to VR). Research introduced a bulk of work for collaboration investigating scenarios in which users work together while they experience a specific manifestation within the MR spectrum that does not change during the workflow. Such studies have mainly focused on AR and VR (e.g., [85, 394, 499, 240, 181, 576]), other configurations using projections [166, 533, 224, 187, 422], or 2D displays [495, 332, 565, 98]. We also found a small number of systems that investigate collaboration using transitional interfaces [157, 289, 446, 248, 503]. Transitional interfaces in particular offer a dynamic view of the underlying task and corresponding objects. Therefore, we suggest that future research could investigate transitional interfaces that allow the integration of real-world objects in various manifestations. This could allow one to obtain an adaptive view on a task and its objects. Here, users could work on task and could switch, for example, to VR to use similar approaches to our application of transparency to real-world objects in a VE (see Chapter 8). In such scenarios, VR can provide a lot of potential improvements by enhancing the senses of its users. Future research could investigate the dynamic applicability of VR as a part of transitional experiences in a wide range of scenarios (e.g., architecture, engineering tasks, or surgery training). A device class that allows us to transition between manifestations could act as a driver for these future research endeavors. We can expect such devices to be available in the next few years [464]. In essence, we suggest that these future MR systems can benefit from enhanced awareness of the physical reality [370]. Therefore, we propose that these systems should not only provide means to transition between different manifestations, but should also be able to sense, recognize and understand their surroundings and context autonomously [591]. Users of such systems should be able to interact with virtual and real-world content from the most suitable manifestation while having the option to switch to another if necessary.

12.2.3 Towards Ubiquitous Cross-Reality Systems

Due to the rise of CR technology, we need to think of novel ways to interact with VR systems that can be deployed ubiquitously. With regard to the vision of Sutherland's *ultimate display*, future VR systems will be able to control matter and thereby form a room in which the computer creates all kinds of haptic encounters. We see VR not as something isolated from physical reality, but more like a type of simulation that can be visited by its users. It may be useful, for example, when the underlying task can be solved more easily through the manipulation of certain human senses (e.g., applying transparency to solid objects) or when we want to change our surrounding environment to our liking [454, 90]. Further, users might transition to or out of VR during different stages of interaction with virtual or physical objects. Additionally, VR users may be surrounded by bystanders or, when we think of future CR technology, might immerse themselves in VR in public, which can have social implications [448]. Here, we cannot use drones that allow realistic haptic feedback, as this could harm bystanders. In the same sense, we cannot allow the manipulation of matter in every place (e.g., creating a weapon in public). We need to develop a framework of suitable guidelines that preserves a symbiosis of physical reality and simulation that is in the best interest of persons that are immersed with a certain degree in a simulated environment (e.g., AR or VR) and persons that just experience physical reality. Such a framework must ensure that future VR experiences do not absorb their users in certain contexts in which it is important to be aware of the surrounding events and environment (e.g., virtually walking through the forest when one really walks on a busy city street). It should choose and provide appropriate means of stimulation (e.g., not starting flying haptic end effectors in public or crowded spaces). Such a framework must also prevent totally immersed users from becoming victims of malicious attacks that mimic virtual situations. In other words, it should not allow VR users to be tricked into doing things that are not in their interest (e.g., attacking others in a virtual game while in reality physically attacking peaceful bystanders). In addition, such a framework must consider privacy, as future CR devices could acquire a wide range of sensitive data, such as physiological properties or information from the user's brain via BCIs [528]. Further, when future simulations become indistinguishable from physical reality, we should think of ways to ensure that users are aware of the current degree of immersion. Sutherland's *ultimate display* is something that will need careful consideration in the future. As technology matures and VR and related technology classes become more manipulative, we must consider them carefully when we aim for a ubiquitous application of such technologies. Therefore, we suggest that future research in this field should be interdisciplinary, as we face technical, social, philosophical and ethical, as well as security and safety challenges. In line with this, we propose approaching VR and related technology jointly, bringing in the expertise of a multitude of disciplines to design future systems in the best interests of their users.

12.3 Concluding Remarks

In this thesis, we introduced a wide array of enhancements for interaction with virtual worlds. As the future of VR systems lies beyond interaction through dedicated VR controllers or the experience of visual and audio content, we introduced research that provides enhanced interaction channels that have not yet been implemented in standard VR technology. Therefore, we introduced, evaluated, and discussed our own approaches to tackle crucial open research challenges. We structured our research into three themes – *"Avoiding Conflicts with the Real World," "Integrating the Real World,"* and *"Enriching the Virtual World."* In the first theme, we improved natural locomotion in VR. Through that, we increased the autonomy of VR users when exploring VEs. Thereafter, we approached the integration of the real world into the virtual experience to allow beneficial combinations of physical reality and virtuality. Lastly, we enhanced the interaction with VR. Here, we introduced methods for the remote manipulation of haptic objects to enhance VR-supported collaboration of individuals that are physically distant. Further, we deployed flying haptic input devices that allow interaction beyond the experiences that can be offered via state-of-the-art VR controllers.

All these enhancements not only form incremental steps towards the ultimate form of VR, but also show that virtual experiences can be closely intertwined with reality. Therefore, one should not consider virtual experiences as something that should stand on its own, but rather as something that can benefit its users through interaction beyond the virtual space.

VII

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VIII

Appendix

List of Figures

List of Tables

List of Acronyms

ANOVA	Analysis of Variance
BCI	Brain Computer Interface
EEG	Electroencephalography
EMS	Electrical Muscle Stimulation
GUI	Graphical User Interface
HCI	Human-Computer Interaction
HMD	Head-Mounted Display
HUD	Head-Up Display
LED	Light Emitting Diode
PC	personal computer
SDK	Software Developer Kit
SUS	System Usability Scale
TCT	Task Completion Time
TLX	Task Load Index
UI	User Interface
UX	User Experience
MR	Mixed Reality
AV	Augmented Virtuality
AR	Augmented Reality
VR	Virtual Reality
VE	Virtual Environment
DE	Desktop Environment
HMD	Head Mounted Display
OCR	Optical Character Recognition
ART	Aligned Rank Transform
RMANOVA	repeated measures analysis of variance
SSVEP	Steady State Visually Evoked Potential
FFT	Fast-Fourier-Transform
FIFO	First In First Out
PID	Proportional-Integral-Derivative
SVM	Support-Vector Machine
RQ	Research Question
RW	Real World
UML	Unified Modeling Language
HDI	Human-Drone Interaction
CR	Cross-Reality
PQ	Presence Questionnaire
SSQ	Simulator Sickness Questionnaire
UEQ	User Experience Questionnaire
IPQ	Igroup Presence Questionnaire
FoV	Field of View
CPD	Cycles per Degree
GDPR	General Data Protection Regulation
IP	Internet Protocol

UDP	Unified Datagram Protocol
GSS	Grow Shrink Stimulus
CGI	Computer-generated imagery
VoIP	Voice over Internet Protocol
WYSIWYG	What You See Is What You Get
GCS	Global Coordinate System
CSV	Comma-separated values
IK	Inverse Kinematic
3D	3 dimensional
2D	2 dimensional
URL	Uniform Resource Locator
VRI	VinteR Resource Identifier
CCD	Cyclic Coordinate Descent
LIDAR	Light Detection and Ranging
PPM	Pulse-Position Modulation
USB	Universal Serial Bus
DOF	Degrees of freedom
JSON	JavaScript Object Notation
PRCS	Pattern-Reversal Checkerboard Stimulus
OSC	Open Sound Control

ADDITIONAL DOCUMENTS

Provide a descriptive list of items you attach here.

- Consent form used for EMS-based research.
- Statement of my contributions for the presented publications.
- Declaration.

Universität Duisburg-Essen

Mensch-Computer Interaktion
Prof. Dr. Stefan Schneegaß

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I was informed about the study "**Walking in Virtual Reality"** and its procedure in writing. I consent that I would be subjected to electric muscle stimulation on my body. Especially on my legs. I confirm that I don't have any of the following conditions:

- High fever
- Cardiac Arrhythmia or other heart conditions
- Seizure disorder (e.g., epilepsy)
- Pregnancy
- Cancer
- After operations where intensified muscle contractions can disturb the healing process
- Skin diseases
- After alcohol or drug consumption

If I have had any questions to this study, the experimenter has answered them completely and satisfactorily

I agree with the described recording and processing of my data. Storage and analysis of my data will take place in a pseudonymous manner at University Duisburg-Essen, by means of a number and without my name. There is a coding list on paper, which related my name with this number. Only the experimenter and the project leader have access to this list, i.e., only these people can relate my name with the recorded data. From this point onwards, my data will be anonymous. This means, it is no longer possible for anyone to relate my data to my name. I am aware that I can withdraw my consent for the storage of my data at any time without reprisal. I was informed that I could request the deletion of my data at all times.

I have had enough time for a decision and I am ready to participate in the study. I am aware that participating is voluntarily and that I can stop participating at any time, without the need to give reasons for doing so.

I have received printouts of the general information for participating in this study. The information sheets are part of this consent form.

PICTURE DATA: (select one)

- ○ Please **do not publish** the pictures recorded during my participation of study.
- ○ I allow you to **publish** the pictures recorded during my participation of study.
- ○ I allow you to **publish** the **anonymous** pictures recorded during my participation of study.

Place, date and signature of the participant: ______________________

Name of the participant in block letters: ______________________

Place, date and signature of the experimenter: ______________________

Name of the experimenter in block letters: ______________________

CONTRIBUTING PUBLICATIONS

This thesis is based on a range of publications that went through the peer-review process of international venues. For all publications except one, I was the lead researcher and author. For the one exception, I worked closely with the first author and was responsible for essential parts of the corresponding research process. I describe these responsibilities at the end of this section. I collaborated closely with my co-authors for the remaining publications and primarily led the writing process. For the following publications, I was in charge of their preparation. Therefore, I envisioned essential parts of the concept, implemented the prototype (if applicable), conducted the evaluation (if applicable), and wrote essential parts the manuscript.

[30] Jonas Auda, Max Pascher, and Stefan Schneegass. "Around the (Virtual) World: Infinite Walking in Virtual Reality Using Electrical Muscle Stimulation". In: *Proceedings of the 2019 CHI Conference on Human Factors in Computing Systems*. Glasgow, Scotland UK, 2019. URL: `https://dl.acm.org/doi/10.1145/3290605.3300661`

[25] Jonas Auda, Uwe Gruenefeld, and Stefan Schneegass. "Enabling Reusable Haptic Props for Virtual Reality by Hand Displacement". In: *Mensch und Computer*. Ingolstadt, Germany, 2021. URL: `https://dl.acm.org/doi/10.1145/3473856.3474000`

[33] Jonas Auda, Martin Weigel, Jessica R. Cauchard, and Stefan Schneegass. "Understanding Drone Landing on the Human Body". In: *Proceedings of the 23rd International Conference on Mobile Human-Computer Interaction*. Toulouse & Virtual, France, 2021. URL: `https://dl.acm.org/doi/abs/10.1145/3447526.3472031`

[31] Jonas Auda, Nils Verheynen, Sven Mayer, and Stefan Schneegass. "Flyables: Haptic Input Devices for Virtual Reality using Quadcopters". In: *Proceedings of the 27th ACM Symposium on Virtual Reality Software and Technology*. Osaka, Japan, 2021. URL: `https://dl.acm.org/doi/10.1145/3489849.3489855`

[23] Jonas Auda, Uwe Gruenefeld, Thomas Kosch, and Stefan Schneegass. "The Butterfly Effect: Novel Opportunities for Steady-State Visually-Evoked Potential Stimuli in Virtual Reality". In: *Augmented Humans*. Kashiwa, Chiba, Japan, 2022. URL: `https://dl.acm.org/doi/10.1145/3519391.3519397`

– Jonas Auda, Uwe Gruenefeld, Thomas Kosch, and Stefan Schneegass. “The Butterfly Effect: A Showcase Study”. In: *To be submitted*.

– Jonas Auda, Uwe Gruenefeld, Sarah Faltaous, Sven Mayer, and Stefan Schneegass. “The Actuality-Time Continuum: Visualizing Interactions and Transitions Taking Place in Cross-Reality Systems”. In: *Submitted to MUM 2022*.

– Jonas Auda, Uwe Gruenefeld, Sarah Faltaous, Sven Mayer, and Stefan Schneegass. “A Scoping Survey on Cross-Reality Systems”. In: *Submitted to ACM Computing Surveys (CSUR)*. 2022.

The following publications are based on student work that I have supervised. Here, I envisioned essential parts of the concept and supported the implementation process, evaluation planning, and execution. Further, I led the manuscript preparation.

[22] Jonas Auda, Leon Busse, Ken Pfeuffer, Uwe Gruenefeld, Radiah Rivu, Florian Alt, and Stefan Schneegass. “I’m in Control! Transferring Object Ownership Between Remote Users with Haptic Props in Virtual Reality”. In: *Symposium on Spatial User Interaction*. Virtual Event, USA, 2021. URL: https://doi.org/10.1145/3485279.3485287

[27] Jonas Auda, Roman Heger, Uwe Gruenefeld, and Stefan Schneegass. “VRSketch: Investigating 2D Sketching in Virtual Reality with Different Levels of Hand and Pen Transparency”. In: *INTERACT 2021*. Bari, Italy, 2021. URL: https://link.springer.com/chapter/10.1007/978-3-030-85607-6_14

[26] Jonas Auda, Uwe Gruenefeld, and Stefan Schneegass. “If The Map Fits! Exploring Minimaps as Distractors from Non-Euclidean Spaces in Virtual Reality”. In: *Extended Abstracts of the 2022 CHI Conference on Human Factors in Computing Systems*. New Orleans, LA, USA, 2022. URL: https://dl.acm.org/doi/10.1145/3491101.3519621

For the following publication, I jointly worked with my co-authors on the concept of *VRception*. In particular, I supported the design process of *VRception*, contributing new ideas and thereby essentially influencing the research outcome. Additionally, I co-implemented the prototype. In particular, I implemented essential features (i.e., networking and data logging capabilities, among others) and supported the development process through creative ideas and eliminating software bugs and errors. During the evaluation, I was in charge of the technical supervision of the implemented system to allow for smooth and error-free study execution. My tasks included remote management of user sessions in VR, database management and data integrity verification, as well as on-demand support of the experimenter. Further, I helped to analyze the gathered data and supported the writing and media creation process to a great extent.

[162] Uwe Gruenefeld, Jonas Auda, Florian Mathis, Stefan Schneegass, Mohamed Khamis, Jan Gugenheimer, and Sven Mayer. "VRception: Rapid Prototyping of Cross-Reality Systems in Virtual Reality". In: *CHI Conference on Human Factors in Computing Systems*. New Orleans, LA, USA, 2022. URL: `https://doi.org/10.1145/3491102.3501821`

DECLARATION

Ich gebe folgende eidesstattliche Erklärung ab:

Ich erkläre hiermit, dass ich die vorliegende Arbeit selbständig ohne unzulässige Hilfe Dritter verfasst, keine anderen als die angegebenen Quellen und Hilfsmittel benutzt und alle wörtlich oder inhaltlich übernommenen Stellen unter der Angabe der Quelle als solche gekennzeichnet habe.

Die Grundsätze für die Sicherung guter wissenschaftlicher Praxis an der Universität Duisburg-Essen sind beachtet worden.

Ich habe die Arbeit keiner anderen Stelle zu Prüfungszwecken vorgelegt.

Essen, den 12. August 2022

Jonas Auda