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PHYSICAL AND VIRTUAL WORLDS:

Towards Interaction in Distinct Realities

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Physical and Virtual Worlds: Towards Interaction in Distinct Realities

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Für
Birgit, Felix und Emilea

ABSTRACT

Virtual Reality (VR) has found its way into the households of end users and into many areas of industry. Current VR headsets as well as control devices are tracked by sensors in three-dimensional space and movements are transmitted into the virtual world in real time. This way, users can move freely and interact naturally with the digital world. However, the interaction always takes place in both worlds. However, each action performed by the user for the virtual world also has an effect on the real world. For example, every step a user takes in the virtual world is also executed in reality. But reality and virtuality are usually not the same. While the dimensions of the virtual world can be arbitrarily large, the space in reality is mostly limited by walls or other objects. Therefore, virtual objects are not physically present and real objects do not find a visual counterpart in the virtual world.

This leads to challenges in the areas of locomotion and haptics. On the one hand, a conceptually endless virtual world is to be explored within the physical boundaries of the real world. On the other hand, virtual objects without corresponding hardware lose their physical properties because they have no physical counterpart.

In this dissertation, a model of interaction in virtual worlds is presented, which takes into account both human perception and the real world. Furthermore, a continuum for input and output is derived, which considers in five categories from real to virtual different levels of abstraction from reality. A special category is the abstract real one, which is oriented towards reality, but deviates noticeably from it. Own works from the fields of locomotion and haptics, as well as an example of a purely virtual output modality are described under consideration of the presented continuum.

The aim of this work is to show a decoupling of reality and virtuality as an elementary component of interaction in virtual worlds. The proposed continuum, as well as the presented abstract real interaction category should serve as an orientation aid to create interactions in VR.

ZUSAMMENFASSUNG

Virtual Reality (VR) hat ihren Weg in die Haushalte der Endverbraucher sowie in viele Bereiche der Industrie gefunden. Aktuelle VR-Headsets als auch Steuergeräte werden von Sensoren verfolgt und im dreidimensionalen Raum getrackt und Bewegungen in Echtzeit in die virtuelle Welt übertragen. Auf diese Weise können sich die Benutzer frei bewegen und auf natürliche Weise mit der digitalen Welt interagieren. Jedoch findet die Interaktion stets in beiden Welten statt. Jede Aktion die vom Benutzer für die virtuelle Welt vorgesehen ausführt, wirkt sich jedoch auch auf die reale Welt aus. So wird beispielsweise jeder Schritt den ein Benutzer in der virtuellen Welt tätigt logischerweise auch in der Realität ausgeführt. Doch Realität und Virtualität sind meistens nicht übereinstimmend. Während die Dimensionen der virtuellen Welt beliebig groß sein kann, ist der Platz in der Realität meistens durch Wände oder andere Objekte beschränkt. Virtuelle Objekte sind physisch nicht vorhanden und reale Objekte finden kein visuelles Gegenstück in der virtuellen Welt.

Dies führt zu Herausforderungen in den Bereichen der Fortbewegung und Haptik. Zum einen soll eine konzeptuell endlose virtuelle Welt innerhalb der physikalischen Grenzen der realen Welt erkundet werden. Auf der anderen Seite verlieren virtuelle Objekte ohne entsprechende Hardware ihre physikalischen Eigenschaften verlieren, da diese kein physikalisches Gegenstück haben.

In dieser Dissertation wird ein Modell der Interaktion in virtuellen Welten aufgestellt, welches sowohl die menschliche Wahrnehmung, als auch die reale Welt in die Betrachtungen aufnimmt. Des weiteren wird daraus ein Kontinuum für Ein- und Ausgabe abgeleitet, welches in fünf Kategorien von real bis virtuell verschiedene Abstraktionsebenen von der Realität betrachtet. Eine besondere Kategorie ist die abstrakt reale, welche sich an der Realität orientiert, jedoch merklich von dieser abweicht. Eigene Arbeiten aus den Feldern der Fortbewegung und Haptik, sowie ein Beispiel für eine rein virtuelle Ausgabemodalität werden unter den Gesichtspunkten des vorgestellten Kontinuums beschrieben.

Ziel dieser Arbeit ist es eine Entkopplung von Realität und Virtualität als elementaren Bestandteil der Interaktion in virtuellen Welten aufzuzeigen.

Das vorgeschlagene Kontinuum, als auch die vorgestellte abstrakt reale Interaktionskategorie sollen als Orientierungshilfe Interaktionen in VR zu kreieren dienen.

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ACRONYMS

2AFC	Two-Alternative Forced-Choice
3D	Three-Dimensional
6DOF	Six degrees of freedom
ANOVA	Analysis of Variance
AR	Augmented Reality
AT	Acceptance Threshold
AV	Augmented Virtuality
DT	Detection Threshold
EMG	Electromyography
EMS	Electrical muscle stimulation

HMD Head Mounted Display
HCI Human-Computer Interaction
MR Mixed Reality
MS Motion Sickness
PQ Presence Questionnaire
RDW Redirected Walking
SUS Slater, Usoh, Steed’s presence questionnaire
UCD User Centered Design
UX User Experience
VR Virtual Reality
XR Cross Reality

LIST OF PUBLICATIONS

This cumulative dissertation is based on the following publications. The respective works can be found in the appendix of this thesis and are described in part iv.

[R1] Michael Rietzler, Florian Geiselhart, and Enrico Rukzio. “The Matrix Has You: Realizing Slow Motion in Full-body Virtual Reality.” In: *Proceedings of the 23rd ACM Symposium on Virtual Reality Software and Technology*. VRST ’17. Gothenburg, Sweden: ACM, 2017, 2:1–2:10. ISBN: 978-1-4503-5548-3. DOI: `10.1145/3139131.3139145`. URL: `http://doi.acm.org/10.1145/3139131.3139145`.

[R2] Michael Rietzler, Katrin Plaumann, Taras Kränzle, Marcel Erath, Alexander Stahl, and Enrico Rukzio. “VaiR: Simulating 3D Airflows in Virtual Reality.” In: *Proceedings of the 2017 CHI Conference on Human Factors in Computing Systems*. CHI ’17. Denver, Colorado, USA: ACM, 2017, pp. 5669–5677. ISBN: 978-1-4503-4655-9. DOI: `10.1145/3025453.3026009`. URL: `http://doi.acm.org/10.1145/3025453.3026009`.

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[R4] Michael Rietzler, Florian Geiselhart, Julian Frommel, and Enrico Rukzio. “Conveying the Perception of Kinesthetic Feedback in Virtual Reality Using State-of-the-Art Hardware.” In: *Proceedings of the 2018 CHI Conference on Human Factors in Computing Systems*. CHI ’18. Montreal QC, Canada: ACM, 2018, 460:1–460:13. ISBN: 978-1-4503-5620-6. DOI: `10.1145/3173574.3174034`. URL: `http://doi.acm.org/10.1145/3173574.3174034`.

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[R8] Michael Rietzler, Gabriel Haas, Thomas Dreja, Florian Geiselhart, and Enrico Rukzio. “Virtual Muscle Force: Communicating Kinesthetic Forces Through Pseudo-Haptic Feedback and Muscle Input.” In: *Proceedings of the 32nd Annual ACM Symposium on User Interface Software and Technology*. UIST ’19. New Orleans, LA, USA: Association for Computing Machinery, 2019, pp. 913–922. ISBN: 9781450368162. DOI: `10.1145/3332165.3347871`. URL: `https://doi.org/10.1145/3332165.3347871`.

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[R9] Michael Rietzler, Florian Geiselhart, Janek Thomas, and Enrico Rukzio. “FusionKit: A Generic Toolkit for Skeleton, Marker and Rigid-body Tracking.” In: *Proceedings of the 8th ACM SIGCHI Symposium on Engineering Interactive Computing Systems*. EICS ’16. Brussels, Belgium: ACM, 2016, pp. 73–84. ISBN: 978-1-4503-4322-0. DOI: `10.1145/2933242.2933263`. URL: `http://doi.acm.org/10.1145/2933242.2933263`.

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[R11] Michael M. Otto, Philipp Agethen, Florian Geiselhart, Michael Rietzler, Felix Gaisbauer, and Enrico Rukzio. “Presenting a Holistic Framework for Scalable, Marker-less Motion Capturing: Skeletal Tracking Performance Analysis, Sensor Fusion Algorithms and Usage in Automotive Industry.” In: *Journal of Virtual Reality and Broadcasting* 13(2016).3 (2017). ISSN: 1860-2037. DOI: `10.20385/1860-2037/13.2016.3`.

[R12] Julia Brich, Marcel Walch, Michael Rietzler, Michael Weber, and Florian Schaub. “Exploring End User Programming Needs in Home Automation.” In: *ACM Trans. Comput.-Hum. Interact.* 24.2 (Apr. 2017), 11:1–11:35. ISSN: 1073-0516. DOI: `10.1145/3057858`. URL: `http://doi.acm.org/10.1145/3057858`.

[R13] M. Rietzler, F. Geiselhart, J. Brich, and E. Rukzio. “Demo of the Matrix Has You: Realizing Slow Motion in Full-Body Virtual Reality.” In: *2018 IEEE Conference on Virtual Reality and 3D User Interfaces (VR)*. Mar. 2018, pp. 773–774. DOI: `10.1109/VR.2018.8446136`. URL: `http://doi.org/10.1109/VR.2018.8446136`.

[R14] Thomas Dreja, Michael Rietzler, Teresa Hirzle, Jan Gugenheimer, Julian Frommel, and Enrico Rukzio. “A Demonstration of VRSpinning: Exploring the Design Space of a 1D Rotation Platform to Increase the Perception of Self-Motion in VR.” In: *The 31st Annual ACM Symposium on User Interface Software and Technology Adjunct Proceedings*. UIST ’18 Adjunct. Berlin, Germany: ACM, 2018, pp. 185–187. ISBN: 978-1-4503-5949-8. DOI: `10.1145/3266037.3271645`. URL: `http://doi.acm.org/10.1145/3266037.3271645`.

[R15] Evgeny Stemasov, Gabriel Haas, Michael Rietzler, and Enrico Rukzio. "Augmenting Human Hearing Through Interactive Auditory Mediated Reality." In: *The 31st Annual ACM Symposium on User Interface Software and Technology Adjunct Proceedings*. UIST '18 Adjunct. Berlin, Germany: ACM, 2018, pp. 69–71. ISBN: 978-1-4503-5949-8. DOI: `10.1145/3266037.3266104`. URL: `http://doi.acm.org/10.1145/3266037.3266104`.

Part I

MISMATCH OF PHYSICAL AND VIRTUAL WORLD

1

INTRODUCTION

1.1 VIRTUAL REALITY – FROM PAST TO PRESENT

The vision of Evan Sutherland of an *Ultimate Display* [1], *'[...] a room within which the computer can control the existence of matter'* is seen as the birth of virtual reality. In 1968 Sutherland et al. proposed a first head mounted display (HMD) [2]. Images were rendered and displaying for each eye separately and the user's head was tracked in 3D space to update the visual output accordingly. Now, 50 years later, virtual reality (VR) has made its way to the homes of end users as well as into many domains of industry. Current VR headsets are still tracked by sensors and create an illusion of a 3D world by displaying distinct and perspective adjusted images per eye.

The basic concept of such hardware is to create a substitutional reality in which every information and perception the user experiences arises from the digital and virtual world. Accordingly, the current state of the art of VR hardware foresees a sensory substitute for various senses. While it is easy to fully override visual information via a head mounted display (HMD), or the auditory ones using headphones with active noise cancelling, there are other senses, that cannot be overridden as easy. Light, being electromagnetic radiation, and sound, being a wave, are stimuli a user can be shielded from. Other human senses cannot be shielded by a simple hardware device. When a user reaches out his hands to tactilely capture the world around him, he will be able to touch and feel every real object in his immediate vicinity. This problem arises by the physical mismatch of the real and virtual world. While the virtual world can potentially display worlds beyond limitations, the physical world is always limited with a certain space which may contain obstacles and objects depending on the room in which the VR setup is assembled.

1.2 THE DISCREPANCY BETWEEN REAL AND VIRTUAL WORLD

One of the greatest challenges posed by the discrepancy between the real and virtual world is the area of human haptics. Haptic feedback includes various modalities, such as those that are measured by the skin, like pressure or temperature. But haptic feedback also refers to the perception of weight or kinesthetics (directional forces) in general.

The current state-of-the-art of most VR systems is the use of controllers to interact with the virtual environment. Most of the available controllers are tracked with six degrees of freedom (position and orientation; short: 6DoF). Examples can be found in the most popular VR systems like the Oculus Rift's Touch or the HTC Vive's controller. Some controllers, though, only utilize a three degrees of freedom tracking where only the rotation of a controller is tracked and displayed. This is the case, for example, with the mobile Oculus Go. Most 6DoF controllers aim at providing a more natural interaction that is oriented towards the way we interact in reality. The controllers become substitutes of the users hands and button presses are utilized to perform actions like grabbing. In contrast to vision and audio, that are each sensed by two definite sensory organs (eyes and ears), haptic perception arises on a more distributed sensory system. Temperature or pressure can be measured by the human skin, which covers the whole body. Kinesthetic forces are mainly sensed by mechanoreceptors in muscles. They measure information about the static length of muscles, the rate at which muscle lengths change, and the forces muscles generate [3]. Considering these distinct aspects of haptic sensation, even a simple action, such as lifting an object, becomes very complex if the desire is to provide a realistic sensation. The texture of the object has to be rendered on the user's hands, the temperature has to adjust to the object's properties, the pressure the skin would measure when grabbing the object needs to be displayed and the weight of the object has to be present and sensed by the muscles. The current state-of-the-art of haptic feedback, though, only consists of a controller that is capable of providing vibration feedback. The controller itself can be interpreted as passive haptic feedback device (a physical object that is used as substitute for a virtual one) that at least communicates touch in a certain way. The use of a simple vibration, though, is in most cases without reference to the expected perception of touching an object. Therefore, the virtual object loses most of its physical properties like its weight, shape and texture.

However, this senosry feedback is not the only aspect that changes if feedback is missing. Considering haptics, object properties may also influence the way we interact with them. Depending on the object's weight or size, a user might either use one or two hands to lift it. As long as there is no feedback about the weight of virtual objects, it makes no difference to the user whether he lifts a feather or a car. Both can be lifted with one hand without any challenge if the application does not restrict such actions by making certain objects static.

Besides haptics, there is a second great challenge that has to be faced when implementing VR applications that arise by the mismatch of real and virtual world. While the virtual world can be for example be a representation of a seemingly endless landscape, the physical world remains limited by the boundaries of the tracking space or by the physical boundaries of a room. To be able to naturally walk through a virtual world without constraints, the space available in the virtual world needs to be adjusted to the real world or vice versa to avoid unintentional collisions.

1.3 THE COUPLING OF REALITIES

The aim of recreating a virtual world as close as possible to the real world therefore comes with high demands – either on the design of the virtual world or on the requirements the real world has to fulfill. These high requirements will be referred to in the following as reality coupling. I define reality coupling as the degree of dependency between the real and the virtual world. It is dependent on the chosen form of interaction. With regard to the already mentioned areas of haptics and locomotion, passive haptic feedback and natural walking would be examples of forms of interaction with a high degree of reality coupling. Passive haptics requires either the real world to provide props similar to virtual objects or the virtual world to only consist of objects matching the ones available in reality. Natural walking, as already described, requires the boundaries of real and virtual world to be the same.

Current VR applications and hardware avoid this coupling by either omitting certain stimuli and thus properties of the virtual world (as is the case with haptic feedback) or through the introduction of new interaction techniques that replace the reality of known forms of interaction. The latter can be found, for example, in the most commonly used mode of navigation in VR: teleportation. Instead of walking through a virtual world, the user typically selects a spot by pointing with a controller and pressing a button to confirm the selection. The user then instantly changes the location without changing the position inside the real world.

1.3.1 *Experiencing a Virtual World*

The way a user interacts in virtual environments using an HMD and controllers is a step towards mimicking reality. Compared to the conventional use of external displays, mouse and keyboard the respective VR interaction may raise expectations of consumers. HMD and 6DOF controllers provide a feeling of virtual body ownership [4, 5], an illusion that gives the user the feeling that the body of the virtual avatar is their own. If the virtual avatar is seen as a substitute of the real body and if users interact with their own hands, they may tend much more to expect feedback as they are used to get in the real world. In the far future, it may be possible to recreate virtual worlds that cannot be distinguished from reality, but given the current hard- and software, users always are aware of being inside an artificial world and have to accept that some feedback is perceived as artificial or even completely missing. The effect that a VR application has on the user is often described as the feeling of presence. Presence is most of all defined as the feeling of *being there* (e.g. [6–8]). It refers to how much the user feels like being in the virtual world. It was shown, that multi-sensory feedback enhances this feeling [9]. But such an inclusion of additional stimuli usually requires a whole new set of additional hardware or a higher reality coupling.

The previous explanations mainly considered the system-side implementation of VR applications (consisting of hardware and software). The second important factor of VR is the user himself and above all the process of perception. Perception is the process and result of information processing and interpretation of the human brain. The information from the variety of senses have to be processed and combined to understand the surrounding world. This process is far from perfect and involves an potential error-prone interpretation of the sensory data which more or less equals an educated guess. This circumstance can be exploited for the development of virtual realities. There are already some examples from the field of research where human perception is consciously played with in order to generate a certain perception or to decouple virtuality more strongly from reality. An example of this is Redirected Walking (RDW), in which the user is presented with a subtle and unnoticed manipulation of the orientation of the environment. In order to compensate for this reorientation, the user begins to reorient himself and therefore walks on a circular path in reality to walk a straight line in the virtual world. Such subtle manipulations of the user's perception though come along with smaller effects and therefore the example of RDW still requires a very large physical space to allow the user to walk within an endless virtual world without limitations.

I argue that the interaction in virtual realities does not always have to resemble reality and that not every user action or system feedback has to be adapted as close to reality as possible. As already mentioned, given the possibilities of hardware and software, a user will always be aware of being in the real world and not in the virtual one. Manipulations such as those used for RDW could be used to a greater extent and in a perceptible way. In such a case, the user notices the manipulation, but the higher abstraction also allows a stronger decoupling from reality.

In contrast to the aim of most of the past research in the field of VR, the focus of this work is not on implementing and designing feedback that is indistinguishable from the real world. In order to reduce the coupling between the real and virtual worlds while retaining the feedback modalities, approaches for the two problem areas of haptics and locomotion are presented, which were implemented mainly without additional hardware.

2

BASICS OF PERCEIVING AND INTERACTING

2.1 THE PROCESS OF SENSING AND PERCEIVING

The following section provides basic insights on how humans perceive the world that surrounds them and is oriented towards Goldstein's and Brockmole's book *sensation and perception* [10].

The process of experiencing the world around us is long and complex. Goldstein and Brockmole propose a simple model of the whole perceptual process (see also figure 2.1). Put simply, this process can be divided into two basic steps: Sensation and perception. While sensation is often considered as the detection of elementary properties, perception in contrast involves higher brain functions and includes interpretations of what is happening around us [11, 12], though both terms cannot be distinguished that easily and actual research most of all excludes the term sensation and only refers to perception. Though, to make it easy, I will refer to sensation and perception following the simple distinction as described above.

Goldstein describes the sensory and perceptual process using the vision as an example. The first two steps of the sensory process are distal and proximal stimuli. A distal stimulus is a stimulus that comes from outside (from a certain distance) – like the light of an object that is observed. The visual receptors' proximal stimulus is then the image on the retina. The next step in this process is called transduction. It involves sensory receptors, cells that respond to the environment. Humans have various receptors for measuring different aspects of the world (e.g. light, sound, taste, etc.). These receptors transform the environmental information to an electrical one. This electrical energy is then forwarded through a network of neurons where the signal is processed (neural processing) and arrive at a primary receiving area which later creates the perception and may differ between the senses (e.g. the occipital lobe for vision, or temporal lobe for audio).

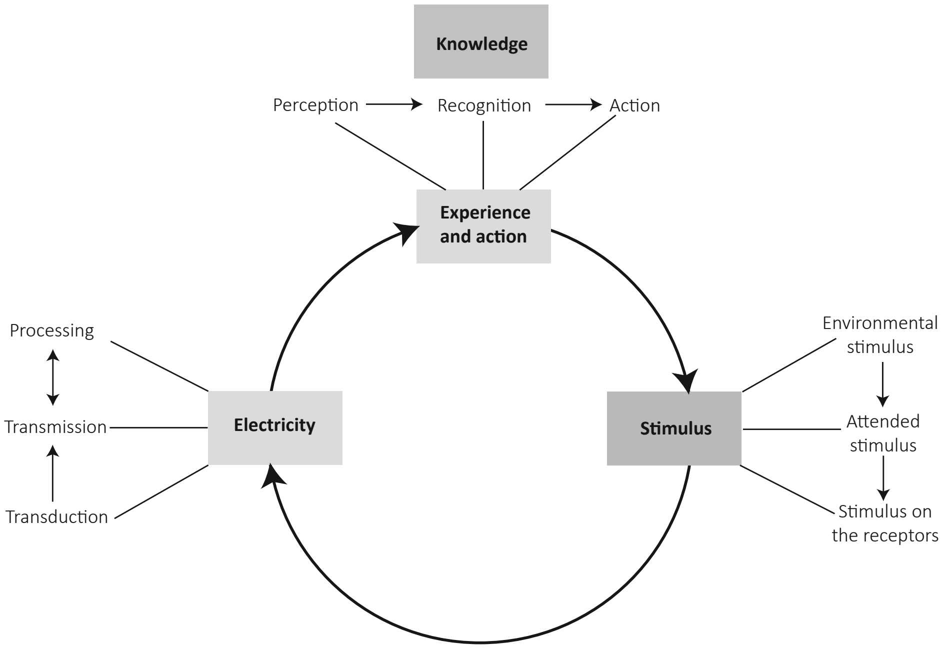

Figure 2.1: Goldstein's model of the process of sensation and perception (based on [10]).

The process of perception (or behavioral responses) has the aim to transform the electrical signals into a conscious experience. Goldstein calls this step of the whole process as the most miraculous one. The perception does not only refer to a single modality but may be cross-modal [13]. The identification and understanding of how such multi-modal perception processes work is challenging and still part of research [14]. Several models have been proposed to show how distinct information is merged to a unified *percept* [15, 16]. Rock and Victor [17] investigated the influence of visual information on the perceived size objects. They found that seeing could have an even greater influence on the perception of size than haptics. Ernst and Banks [18] proposed a statistical model of visio-haptic integration, which states that the influence of each sense depends on the actual performance of the individual sense. As a visual stimulus, they used a point stereogram as a background surface, with the points being shifted to add noise to the visual sense. The influence of the visual information on the perceived magnitude depended on the noise applied. Overall, it is assumed that a Bayesian fusion process combines several sensory signals depending on their reliability to obtain a coherent image of the surrounding world.

As the perception leads to a conscious experience, the respective information can be further interpreted and recognized. In this process prior knowledge is used. This knowledge can be both: acquired a long time ago or just recently. As the last behavioral response, Goldstein defines actions that include motor activities.

2.2 BASICS OF INTERACTION

2.2.1 *Interacting with Computers*

Interaction with computers is mostly based on metaphors. From the early times of HCI on, these metaphors were grounded in the real world, like e.g. the desktop or folder structure a operating system offers [19]. Don Norman [20] presented several models of how humans interact with computer systems based on cognitive processes. He further defines six concepts to be essential for HCI: affordances, signifiers, constraints, mappings, feedback and the conceptual model of a system. Applying these concepts should allow interaction with unknown objects intuitively. While affordances describe a relation to known properties that determine what actions are possible, signifiers communicate the location of action. Constraints work the other way round. They communicate what cannot be done and limit the user's actions. Mappings refer to the relation between the controls, the actions, and the intended result – which should be intuitive. Feedback is required in order to recognize that an action was noticed by the system. It therefore has to be intuitive and informative. Conceptual models, as a last point, are required to provide a simplified understanding of how the interaction works. Norman lists the desktop metaphor or the term *in the cloud* (as a model of not being stored on the local machine) as examples.

These principles have been applied to a wide range of the HCI research and have become the fundamentals of designing intuitive and usable hardware and software.

2.2.2 *Interacting in VR*

The interaction in VR can on one hand be compared with the described principles of interacting with computers, but on the other hand with interacting with the reality. Most often the virtual world mimics the behaviour of our known reality, but it also allows novel ways of interaction and manipulations Mark Mine [21] defines three ways of manipulations in VR: (1) **Direct user control** (gestures that mimic real world interactions, (2) **Physical control** (devices that can be touched), and (3) **virtual control** (interfaces that are fully virtual and cannot be touched), while Sherman et al. [22] add a fourth category, being (4) **agent control**, which they define as commands to an entity in the virtual world. This fundamental categorization of input devices can still be applied nowadays. The current state of the art is the use of physical hand-held controllers that allow a direct interaction with virtual objects (direct control). For navigation, the interaction with such controllers (like the most common way of navigating: teleportation), would be classified as hand directed (an equivalent of direct control).

But there are other attributes that should be considered when implementing interaction techniques in virtual reality. One of them is the **naturalness**. Often naturalness is considered in terms of interacting in 3D space since they involve natural motions. Here Bowman et al. [23] distinguish between **natural** and **hyper-natural** interactions. They suggest to categorize navigation as an example to be either **natural** (mimicking the real world locomotion match one to one), **magic** (e.g. steering), or **manipulation-based** (combining natural and magic techniques). They argue that there is no obvious better way to realize interaction. All of the mentioned strategies to realize interaction have both, advantages and disadvantages. While natural input is easy to learn since they are already common for interaction in the physical world (e.g. we do not need to learn how to walk again), they may also be less efficient than their magic counterparts. Real walking will never be as fast as teleportation. Magic, or hyper-natural interaction therefore has the potential of enhancing actions, giving super powers to users and therefore perform better considering efficiency compared to their natural counterparts.

3

METHODOLOGY AND APPROACH

In HCI, usually an *User-Centered-Design* (UCD) approach is applied. This process is standardized under the norm ISO 9241-210 [24]. It is an iterative process with a strong focus on the user being the main source of requirements. The main goal is the greatest possible usability of a system. The main three steps can be summarized as requirement engineering, prototyping and evaluation. To determine the requirements, the context of use, as well as the users are the main focus. The goal is to understand both, user and context and to identify limitations to bring this knowledge into the next step of prototype design. Since the aim of UCD is not on implementing a final solution in one iteration, the next step is to design a prototypical implementation which is then evaluated. This evaluation again strongly focuses on the user. Data (qualitative or quantitative) is collected of a user interacting with the prototype. The gathered insights can then be used to further improve the design of a system.

Requirements: For the artifacts that were created during my Ph.D., I applied several UCD methods to cover distinct domains of VR interaction (most of all in the field of haptics and navigation). To get insights on the requirements, I conducted focus group interviews for first iterations and post-experience interviews and questionnaires for refining solutions in further iterations. Further, literature reviews were done on building on prior insights in the respective domains and to identify challenges and possible solutions.

Prototyping: The solutions that were created are both, software-only and hardware prototypes. In several iterations, these prototypes were designed and refined. Most of all horizontal prototypes were created. Such prototypes are considered to implement the basic concept of interaction and not an in-depth exploration of how a final implementation can be designed and implemented. The artifacts also aim at being a measurement instrument, since they provide a first implementation of a concept that can be used to determine the scope and possibilities as well as limitations of a certain interaction technique when being applied in a final product.

Evaluation: Many of the investigated interaction approaches rely on the human perception with a focus on perceivable manipulations. It was therefore a major goal to determine at which point a manipulation can be perceived and on the other hand how far a manipulation can go until it becomes inapplicable or unpleasent for users. These are user centered constraints of an interaction technique, but they also influence the system design. My aim was to reduce the physical requirements of a system by abstracting interaction from the way interaction is done in the real world. Since in VR, a user interacts in both worlds (the real and the virtual one), both are considered to be part of the system.

Depending how strong manipulations can be applied, a different abstraction from real world interaction can be achieved. Usually, the requirements for the physical system decreases with the amount of abstraction. Therefore, prototypes were designed and analyzed to determine the maximum of such abstractions to provide guidelines on how to design VR applications.

The main goal of the evaluation part of the UCD in general is to get an understanding of the user experience (UX). UX typically refers to a persons's emotion about a product and is a main part of HCI. The ISO 9241-210 norm [24] defines UX as '*a person's perceptions and responses that result from the use or anticipated use of a product, system or service*'. This includes the utility, ease of use and efficiency of a system. In VR research, the feeling of presence is often used as reference of the quality of an application. The term *presence* is defined as the feeling of *being there* [6–8]. Depending on the literature, different characteristics of a system can contribute to this feeling. In particular, questionnaires are used to make the feeling of presence comparable and more objective. The questions of these questionnaires aim at generating a quantitative representation of the subjective feeling of presence. This quantification should then allow to compare a subjective perception as objectively as possible. A related term is immersion: immersion in another world. The definitions and views of this term range, however, from technical specifications for the exclusion of the real world [25] over the immersion in the action of a virtual world [26], up to definitions, which are very similar to those of the presence and refer to the feeling to be in the virtual world [8]. Presence as well as immersion can therefore be seen as factors of UX and respective questionnaires were often used to evaluate the developed artifacts. Several questionnaires to determine the feeling of presence were proposed, like Witmer and Singer's PQ [8], Slater, Usoh and Steed's presence questionnaire (SUS) [27], or the E^2I questionnaire proposed by Lin et al. [28]. The latter questionnaire (E^2I) additionally assesses the feeling of enjoyment, which is as well an important factor for the quality of interaction in many experience-based VR applications.

Since the named questionnaires aim at providing insights about the whole experience but most of all are focused on vision and audio, it is hard to find differences regarding the score for specific features or sensations out of the questionnaires' scope (like haptics). Therefore, I often needed to additionally use Likert scale single item questions to assess the subjective ratings of a certain aspect of interaction (e.g. whether the participants felt to be able to judge the weight of an object).

It is valid to apply tests for parametric data on questionnaire scores, while usually a normal distributed data is required. Such tests include for instance an Analysis of Variance (ANOVA). Likert scale data instead is considered as ordinal data. Such data can be compared with statistical methods like Friedman's ANOVA and Wilcoxon signed-rank post-hoc tests. Both methods are considered to be more conservative. For most analyzes Friedman's ANOVA with Wilcoxon signed-rank post-hoc tests were applied, since either no normal distribution was found or Likert scale data was compared.

To measure the detection of manipulations, two-alternative forced-choice (2AFC) tasks were used. This methodology is often used for cognitive studies that aim at getting insights on the probability of detecting or distinguishing a stimulus. I applied such a 2AFC task to get insights on the probability of detecting a manipulation. To do this, the participants were presented two stimuli after another. While one was without any manipulation, the other was with a certain amount of manipulation. The participants had to decide in which condition they were manipulated. Every comparison is repeated several times (the more repetitions, the reliable the resulting probability). If a participant is not able to detect the manipulation they will guess. If repeated often enough, this will result in a probability of detection of 50%. A detection rate of 75% is often considered to be no longer coincidence and is regarded as detection. All participants have their own probability of detection for each tested intensity. If all participants are considered together, a curve can be fitted into the set of intensities of a stimulus (or the strength of manipulations) and its corresponding probability. This curve is called psychometric function. The intensity at which

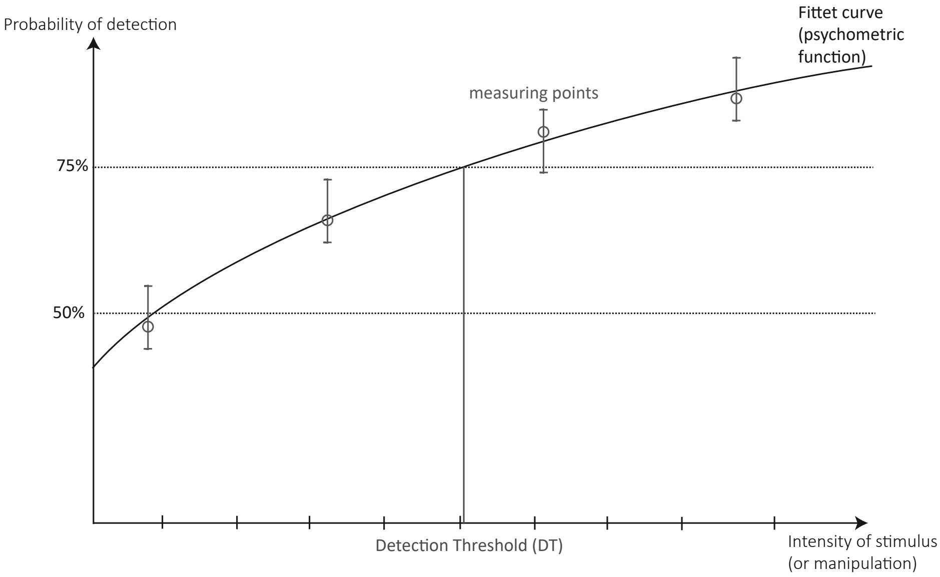

Figure 3.1: Example of a psychometric function. A curve is fitted through the probability of detecting a stimulus of all participants. Usually the spot at which the curve exceeds the probability of 75% is considered as the detection threshold.

the curve exceeds the 75% threshold is called the detection threshold (DT). An example to illustrate the concept of psychometric functions and DTs is shown in figure 3.1.

4

THESIS STRUCTURE

This dissertation is divided into five parts, which are composed as follows:

- **Part I** was divided in three sections including a motivation and introduction, a basic overview of the basics of perception and interaction and the description of method and approach.
- **Part II** starts with the introduction of an own perception-based model for VR interaction (**chapter 5**). Based on this model, several aspects that have to be considered for designing VR interaction are discussed in **chapter 6**. The following **chapter 7** combines the proposed model and discussions of **chapter 6** and suggests the categorization of VR interaction on a continuum.
- **Part III** discusses prior works and is split in two main parts which were chosen based on the focus of this thesis. The related works are categorized using the proposed design space as presented in **chapter 7**. **Chapter 8** presents work in the field of tactile and kinesthetic feedback. **Chapter 9** has a focus on navigation in VR. Here, interaction techniques as well as basics of motion perception and motion sickness is discussed.
- **Part IV** is split in three chapters. The first, **chapter 10** describes the research questions. The following **chapter 11** is split in three sections all cover one area of research. Section 11.1 discusses the difference between realistic and unrealistic VR interaction. Section 11.2 discusses works on pseudo-haptic feedback and embed them into the already mentioned interaction continuum. In section 11.3 own works on navigation in VR are discussed. It is split into the topic of controller based and room-scale navigation. The topics are further discussed in **chapter 12**.

- **Part V** includes three chapters. The thesis will be summarized in short in **chapter 13**. **Chapter 14** discusses the abstraction of feedback from reality and proposes some guidelines on how to design virtual rules. Finally, in **chapter 15**, some thoughts on how the proposed interaction continuum can be utilized for VR interaction are stated.

Part II

MODELS OF VR INTERACTION

5

A PERCEPTION-BASED INTERACTION MODEL FOR VR

5.1 UNDERSTANDING THE DIGITAL WORLD

Humans have learned to understand the world that surrounds them. This understanding comes from various senses, that measure stimuli from the real world. Since, as already described, this information is far too much for the human brain to handle, sensory information is filtered, interpreted and connected with prior knowledge. The result of this process is perception. What we perceive as reality is a filtered interpretation of a subset of measurable stimuli of our surrounding. But humans do not have senses for digital information. We need a physical stimulus that matches our senses' specifications. This is why we use displays or headphones to make the artificial and virtual data perceptible. Thus, VR could be interpreted as a specific kind of making digital information available and perceptible for a user. While common computer systems integrate virtual information in the user's surrounding (like an external screen), VR aims to provide information about a whole virtual world in a way similar to the perception of the reality. This includes all the information that we need to understand this artificial world. The process of perceiving a virtual reality should therefore be the same as for the *real* reality, but with all sensory measures matching the virtual world.

5.2 COMPONENTS OF THE INTERACTION MODEL

I divide the process of interacting in virtual worlds in two parts as shown in figure 5.1. The process presented is an adaptation of Goldstein's model of perception. It links the basics of perception with the concepts of interaction with computers and has a special focus on parallel interaction in two worlds (real and virtual).

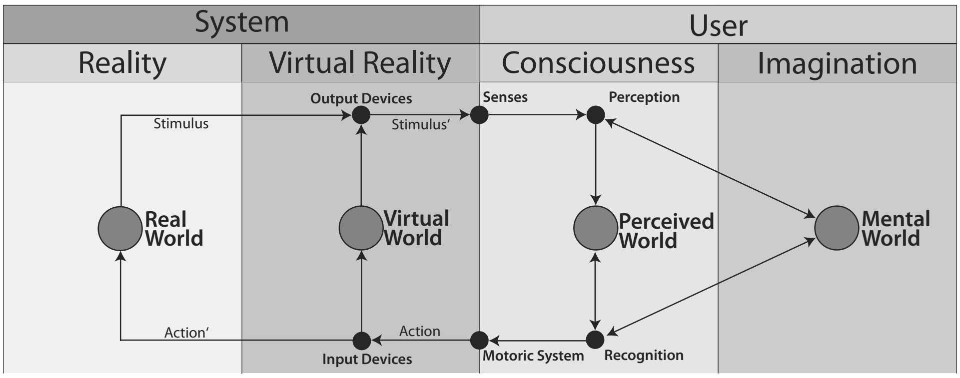

Figure 5.1: A conceptual interaction cycle illustrating the concept of interacting in two distinct realities. On the left: The system that consists of the two information sources (real and virtual world). While the real world is capable of providing stimuli on their own, the virtual world requires output devices to transform the digital information into measurable stimuli for human beings. On the right: The user, divided in two main parts, the perceived world and the mental world. While the perceived world stands for the perception of current stimuli, the mental world stands for a consistent representation of information that is conceptually independent from the immediate sensory inputs.

5.2.1 *The System*

The first part of the model is the **system**, consisting of the **real world** and the digital information of the **virtual world** as well as the interface **devices** (such as an HMD) to convert the digital information into a format that is measurable for the human senses. While the real world's information is defined by the set of physical stimuli directly originating from real world matter that our senses can measure, the virtual information have their origin and description on a computer running a VR application. To allow the human senses to measure these information, an interface is needed to convert the digital information into measurable signals.

On the other hand, actions of a user also have to be converted into signals the computer can measure and interpret in order to let the virtual world react on the user's actions (**input devices**). These input and output devices therefore function as a kind of middle-ware that should be hidden from the user. However, they serve a second purpose, namely to ensure that the actions intended by the user affect only the world for which they are addressed. If locomotion in virtual worlds is taken as an example, then it is the user's intention to move from one place to another within that particular world. Since the physical and virtual world do not need to have the same dimensions, a user may reach the limits of the physical world while actually perceiving a larger room in VR. Walls or other objects that are only part of the real world influence the interaction in the virtual world and can lead to unconscious reactions. The way locomotion – and of course other interaction techniques – is realized should therefore ensure that the physical world does not influence the intentions of a user to navigate through (or interact with) the virtual world.

Therefore, an input technique may translate the intended action in the virtual world into an image of this action in the real world – the performed *action* within the virtual world becomes an **action'** for the real world. A treadmill, for example, converts walking into walking in place, teleportation converts a translation from point A to point B within the virtual world to selecting a spot and pressing a button and redirected walking converts walking a straight line into walking on a circle.

5.2.2 *The User*

The second big entity that is shown in figure 5.1 is the user. The user is connected to the system via two interfaces. The first is the sum of all **senses** that measure the stimuli of the real and virtual world. The second one is the **motoric system**, that performs the intended motions and conceptually influences both worlds. The senses measure a subset of the presented information. Due to the nature of the human senses, not the whole reality (or even virtual reality) can be sensed. For example, humans are capable to hear or see within a given spectrum, but not beyond.

Along with the discussed model of Goldstein, the information that is measured by the senses is then filtered, merged, interpreted and recognized into a sum of percepts. To optimize the filtering process and to allow a valid interpretation of sensory data, the human brain uses prior knowledge coming from the mental world. The result is the perceived world, that is a volatile image of the world that surrounds us. In contrast, the **mental world** stands for the persistent information memory but as well for the imagination (which is most of all based on what was learned or experienced priorly) or other aspects that are not directly dependent on the current information stream of the senses (like e.g. social aspects). The exchange of information between perception and mental world is bidirectional, since the knowledge of new percepts is stored inside the mental layer but as well used for the process of perception and recognition.

5.3 SOURCES OF VIRTUAL INFORMATION

The described model of interaction in virtual environments shows that users interact in the two distinct realities of the real and the virtual world. Respectively, a user may perceive a mismatch of information due to sensory information coming from the real world the user is not able to connect to the virtual world. While some input and output devices are capable of overwriting the whole real world information (e.g. wearing an HMD), others are not (most of all those that directly handle with the physical real world – like haptics). Though, the existence of two possible sources of information (the real and the virtual world) can be seen as both: advantage and disadvantage. As long as the real world information can be logically connected to the virtual one, a user may be able to integrate real world information into the virtual experience. One example to this is the already mentioned passive haptic feedback (e.g. [29]). To allow a perceptual integration of real and virtual information sources, both have to match in a certain way. The example of passive haptic feedback requires a physical object with around the same size at around the same physical position as it is displayed in the virtual world. If there is no direct match, the requirements can be lowered by playing with and manipulating the user's perception. The spatial requirements for passive haptic feedback can for example be lowered by redirecting the user's motions (e.g. [30]). Such interactions can be compared to the proposed category of manipulation-based interaction by Bowman et al. [23]. But such manipulations can even go farther. The example of pseudo-haptic feedback shows, that the visual sense can be utilized to create haptic percepts. Based on these properties, I derive the following three sources of information for virtually perceived information.

The first, and most obvious, one is **hardware** that is constructed to translate digital information into stimuli the human senses are capable to measure. In the example of the proposed model of VR interaction, this would be to utilize the virtual world.

The second way of making the virtual world perceptible for a user is to use the **real world** (as the example of passive haptic feedback shows).

The third way is to use the perceived or the mental world by using **manipulations** (further on also referred to as illusions). The example of using manipulations (redirecting the user's motions) to enhance passive haptic feedback also shows, that is possible to combine information sources (in

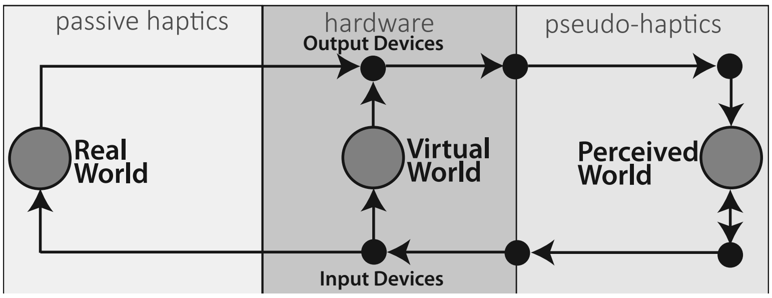

Figure 5.2: Utilizing different sources to display haptic feedback. Passive haptic feedback (using real world props to create haptic feedback), hardware devices (such as a haptic glove or exo-skeleton) or pseudo haptic feedback (using the visual channel to create haptic perceptions as result of the perception process which interprets the visual input as haptic feedback)

this special case real and perceived world). This concept is illustrated for the field of haptic feedback in figure 5.2.

All information sources will be described in more detail in the following.

5.3.1 *Utilizing the Physical World*

Though it might sound illogical, the physical *real* world can be utilized to communicate virtual properties. Since the process of perception aims at integrating the various sensory information, it is possible to link the real world to match the virtual world. This may be done for haptic information when a user touches a real object but sees a similar virtual one (called passive haptic feedback). But similar effects could be utilized for other sensory information, like sound. A user might hear a real bird singing but standing in a virtual forest. As long as the information of real and virtual world match, the real world can become part of the virtual one. The negative aspect of utilizing the physical world are the high demands on the real and virtual world, since at least basic properties have to be the same. For passive haptic feedback, for example, physical objects with a similar size and shape have to be placed at a similar position as they can be found in the virtual world. The positive aspect of such information sources is the potential of delivering feedback close or even equal to the expectations of a user.

5.3.2 *Utilizing Hardware*

Output devices are part of the virtual world and, as described, aim at translating the real world information to match the virtual ones or to hide them completely from the user. In most cases the process of translating real world information into virtual ones is done in two steps. The first one being the exclusion of real world stimuli and the second one being the inclusion of virtual information. The most common VR hardware includes an HMD, headphones and controllers. An HMD is placed in front of the user's eyes to exclude real world visual stimuli. The integrated display simulates a three-dimensional world by displaying an adjusted view of the virtual world for each eye. For audio, the process of excluding real world auditory stimuli can be achieved by noise cancelling technology. This can either be achieved passively (by physically shielding the ears from external sound) or actively (by emitting an audio wave with the same amplitude, but the opposite phase of the sound hitting the ear from the real world). Though the most popular VR headsets (such as Oculus Rift, or HTC Vive pro) include headphones, they by now do not include noise cancelling. Therefore by now only audio is added to the one of the physical world without excluding it. If haptic feedback is considered as an example, there is no feedback about haptic properties of virtual objects without special hardware. The mentioned controllers (as part of the current state-of-the-art hardware) are utilized as both, in- and output devices. Considering the output side, they on one hand provide passive tactile feedback in the shape of the controller (which not necessarily matches with the virtual information), as well as vibration feedback. Since such simple feedback does not suffice to communicate complex haptic properties of the virtual world, hardware was proposed to make these properties measurable for humans. Usually, such devices make it possible to communicate virtual information about haptic properties, but not to remove the respective information coming from the physical world. Once real objects are within the user's reach, they can provide haptic feedback, which in turn leads to unintended reactions. The exclusion of haptic feedback from the real world is therefore typically realized by using an empty physical space without obstacles within the area used for VR.

5.3.3 *Utilizing Illusions*

Virtual Reality is a playground of human perception. It provides the possibility to stage a whole reality and to have full control over the human senses – at least conceptually. A user is tricked to perceive the digital information as real world information by designing hard- and software in a way it mimics real world behavior. Instead of having a fixed display, it is mounted on the user's head, reacting to every movement made and sending different information to each eye to create the illusion of a three-dimensional world. The real world, in contrast, is fully suppressed and the respective information is overridden by virtual ones. But the virtual visual information is still distinguishable from real world information due to a limited field-of-view, resolution, and most of all due to performance reasons that limit the quality of the rendered images – limitations that will most likely be solved in the future with the increase of technical possibilities. The aim of technically increasing the field-of-view and resolution of head mounted displays indicates an effort to make the virtual world indistinguishable from the real world.

As for visual feedback, the same principles can be applied to other feedback as well as input techniques. But the human perception is no faultless measurement tool. It collects as much sensory information as possible, filters and interprets the respective data to understand the world measured by our senses. What we perceive as reality therefore always is an interpretation – a simplified illustration – of the reality. VR in general is a great example for these interpretations. Instead of pixels consisting of red, green and blue light emitters, humans interpret a whole visual world.

Such sensory misinterpretations could be interpreted as illusions. The oxford dictionary defines the term illusion as „*an instance of a wrong or misinterpreted perception of a sensory experience.*“A quite similar definition is given by Richard Gregory, who defines an illusion as „*It may be the departure from reality, or from truth*“[31], adding that the next problem would be to exactly define the terms of reality and truth. Following such definitions of illusions, virtual reality as a whole concept would be an illusion. The pixels a user senses visually are being misinterpreted into perceiving objects and a whole new world. The stereoscopic presentation of different but matching pixels for each eye is interpreted as a three dimensional construct. The same principle applies for the other human senses, too. The human brain is tricked into believing the perception of a virtual reality. For the longest time of a VR experience a user will however be aware of this illusion. She will, when thinking about it, know that what she sees is not a real world around her. If one takes the term illusion very narrowly, even the entire human perception would be an illusion. Our perception is based on interpreting the information of our senses and putting

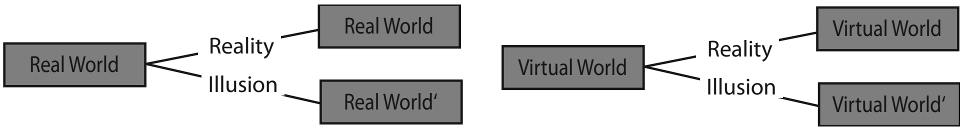

Figure 5.3: The concept of illusions in VR: The perception of the virtual reality as it is, is defined as being no illusion, but the misinterpretation (whether wanted by the application or not) is defined as illusion.

it into context. If one takes the term even more narrowly, one could even assume that even the information that our senses can measure do not correspond to reality, since they can only capture parts of reality (e.g. the small spectrum of the range of electromagnetic waves measurable by the eyes).

If we look at the field of VR, it is not the perception of reality, but that of an artificial reality. In this case one could claim that an illusion in VR is not the misinterpretation of real information, but the misinterpretation of virtual information. Therefore, the interpretation of pixels as a 3D image of a virtual reality could be interpreted as a kind of real perception.

In the following, the term *illusion* is used in the context of VR in such a way that the perception of the virtual world is not an illusion, but the correct perception of virtual reality (see figure 5.3). Manipulations, on the other hand, such as the redirected walking or pseudo-haptic feedback described above, are interpreted as illusions because they go beyond regular perception based on the human senses. The effects achieved are based on the inaccuracy and scope of interpretation of human perception and can therefore be described as illusions.

Illusions are one way of how interaction in VR can be designed. Tricking the human perception to either perceive feedback differently as it is displayed (e.g. as it is done for pseudo-haptic feedback where visual cues are used to provide haptic feedback), or to change the way a user interacts with the virtual world by imperceptibly manipulate the behaviour of a user (e.g. redirected walking).

Illusions therefore are an additional way to communicate virtual properties or to design interaction techniques in VR. They arise in the perceived world by misinterpreting information.

6

REALIZING INTERACTION IN VIRTUAL REALITY

6.1 REALITY DECOUPLING

As shown in figure 5.1 and already discussed, interaction in VR is usually also an interaction inside the reality, since both worlds are coupled. Every action that is performed inside the virtual world in some way influences the real one – if intended or not. I will refer to these interactions between real and virtual world as *reality coupling*. In the following I will discuss the consequences of high reality coupling and further discuss possibilities how this coupling can be minimized (*reality decoupling*).

One major goal of VR input and output devices and techniques is to hide the reality from the users. Figure 5.1 illustrates this concept by letting output devices transform a real world stimulus into another one (called stimulus' in figure 5.1) – an image of this stimulus or even a completely independent new stimulus that replaces a real one. On the input side of a VR system, the illustration shows how input devices can transform an action into an image of this action (action'). This interface is an elementary component of reality decoupling. The more independence from the real world can be achieved in this step, the less both realities are coupled to each other.

The aim of reality decoupling is so to say to achieve a loose coupling of real and virtual world. The stronger both realities are coupled, the more requirements come along that either limit the real or the virtual world. If, for example, the only way of getting from one place to another is by walking, we have a high coupling regarding the physical space in the real word and the space available in the virtual world, since both would have to match. On one hand this could be solved by making high demands on the physical space which would have to have the same boundaries as the virtual world. On the other hand, the strong coupling could also be solved by restricting the virtual world by, for example, displaying a virtual world with the same boundaries as the real world. A third way of dealing with such high coupling is to restrict the user. For walking within a limited physical but greater virtual world, this could be done by letting users only explore parts of the virtual world. A completely different way of dealing with high reality coupling is to reduce it through an alternative interaction technique. In the example of navigation, this could be the replacement of walking by teleportation (as it is realized in common VR applications). In this case, the user no longer physically moves from one place to another, but can move through the virtual world while not changing his position in the real world. The example of reality coupling for navigation in VR is shown in figure 6.1.

However, reality decoupling not only aims at reducing the demands on the real and virtual world, but can also be viewed from a user-oriented perspective where only the perceived world of the user and not the system side is considered. From this perspective, reality decoupling should lead to the real world remaining hidden from the user. For example, if a real object is touched (as is often the case with passive haptic feedback), but the object is perceived as a virtual object, reality is still considered hidden from the user. If the touched object does not have a virtual counterpart, the user will be reminded of the being in the real world. Another example is hearing. When a sound comes from the real world but coincides with the virtual world, the virtual world remains decoupled as long as the user interprets the sound as part of the virtual world.

Reality decoupling therefore aims at lowering the demands on the virtual and real world (lower the prerequisites on real and virtual world to deploy and run a VR setup) and at providing a coherent view of the virtual world by decreasing the influence of the reality on the user's perception.

As described, the virtual world and the interaction within can be realized in various ways. Not only input and output devices (hardware) can be utilized to achieve a loose coupling of realities and to provide information about the virtual world. The virtual environment is also based on the implementation of input and output techniques. While for example the hardware of implementing redirected walking is the same as for implementing real walking, their implementations though differ. While for real walking, any physical move is displayed as a one to one correspondence in the virtual world, RDW additionally includes manipulations that translate the physical move of a user into a slightly different one in the virtual world. Since both, the implementation and the hardware, define how interaction is realized, they will be discussed as one and referred to as **interaction technique**.

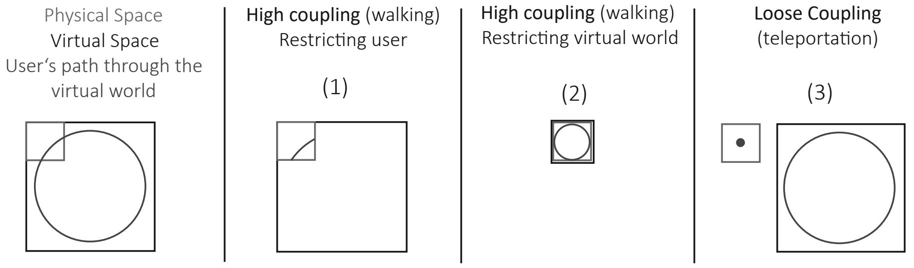

Figure 6.1: The concept of reality coupling. The example shows a virtual world larger then the available physical space and a user traveling on a circular path through the virtual world. Walking (examples 1 and 2) comes with a high coupling of real and virtual world. In (1) the user will be reminded of the real world every time the physical boundary is reached. In (2) the virtual world is restricted to match the available physical space. In (3) teleportation, another navigation technique, is chosen in which the user may remain on the same physical spot to travel through the virtual world. In this case, both realities are loosely coupled an neither the virtual, nor the real world have to be restricted (but with an interaction that no longer resembles reality).

6.2 INTERACTION AS A SET OF RULES

I argue that every interaction technique can be described by a set of atomic (in terms of indivisible) rules. In VR, rules can either be based on the real world or the virtual one. An interaction technique could therefore be described by a set of real and virtual rules.

Such rules can be interpreted as physical rules (for example the physics engine of the virtual world), input rules (e.g. the ability to get from one place to another by pointing on a spot – teleportation) or output rules (e.g. if an object is touched there is a vibration felt).

A simple example could be walking to change the location. Step by step, the user changes the physical location and the virtual camera changes the virtual position accordingly. The real rule would be that the virtual camera moves with the head of a user – and this in exactly the same dimensions. When regarding redirected walking, one or more additional rules are included into the process of walking. Curvature gains, for example, are rules that state: *if the user travels a certain distance, the world around her will be rotated by n degrees.* The n is the strength of the gain and also the strength of this respective virtual rule.

Real rules, in most cases, lead to a higher coupling of real and virtual world, while virtual rules typically loose this coupling. On the other hand, real rules do not have to be learned or accustomed. Often real rules are considered to be natural, while behaviour that differs from the learned is considered to be unnatural.

6.3 THE TERM NATURAL

6.3.1 *Unnatural Real World Interaction*

The term **natural** is often associated to a realistic behaviour. Actions that are performed according to the way they would be realized in reality are assumed to be natural. But what is the actual virtual counterpart? I argue, that – similar to real world knowledge – a user is able to learn about the behaviour of a virtual world. Unnatural interactions may be perceived as natural after a longer experience. The human brain is able to adapt to novel situations. It can even adjust our whole perception if a sense changes the way it transmits information. When, for example, goggles vertically mirror what the eyes measure, the brain adjusts the perception and re-inverts the sensed image again after a certain amount of time [32]. Another example for actions is to float through a world by pushing oneself away with one's hands to float weightlessly through space. This would probably be described by most people as unnatural. But astronauts adjust the way they move through the world or how they interact with object to be able to live in a zero-gravity world.

Humans have the ability to learn and to accustom to new rules the world that surrounds them offers. The same can be said about interaction in VR. Even if some action or feedback mechanisms are realized in a way different from what we know from reality, we can learn how to interact given the novel rules the virtual world offers. This can be compared to the described magic interactions of Bowman et al. [23].

But do such interactions have to be considered as *unnatural*?

6.3.2 *Natural as Independent from Reality*

Unnatural may be not the best way of describing interactions that differ from the common way we interact in the real world. A major requirement, though, is some sort of logic, which I refer to as following understandable rules. These can be compared to Don Norman's conceptual model of a system [20]. If one refers to the entire virtual reality as a system that reproduces a perceptible world and lets this system reproduce a world without the limits of reality, then new rules result. These rules are initially unknown to the user and the interaction based on these rules must first be learned. Similar to an astronaut who has to find his way in an environment without gravity for the first time, the user of such a VR system first has to adapt to the new rules. While these interactions may initially be perceived as unnatural, they may become more natural over time.

In a study I conducted on the Telewalk locomotion approach (which will be described in more detail later on), participants were asked to rate the perceived naturalness of Teleportation [R7]. There were several participants rating Teleportation to be natural, though having obviously no reference to any experience of the real world. Another study I conducted, aiming at displaying slow motion in VR used a single Likert scale question to ask for the perceived realism of the experience [R1]. While in one condition, slow-motion only affected the virtual environment, there were several conditions that also affected the maximal velocity the participants could move their virtual body. Again, though there is no reference to the real world, participants stated that the manipulation of their visual velocity lead to an increased realism.

Therefore, I argue that there must be a virtual counterpart to realism. I will call this virtualism in the following and define it as follows: Everything that is perceived in the virtual world follows rules that can either be learned anew or are already known from reality. As the subjective feeling of realism is the consistency of an experience with what is already known from reality, virtualism is a kind of expectation conformity that enables intuitive and natural interaction in virtual worlds beyond necessarily referencing the real world.

While in VR, most of the interaction is designed as close as possible to what is known from reality (and therefore in a realistic way), some interactions though are hard to be realized fully realistic. One of such examples is the already mentioned navigation by teleportation. It is a great example of how virtual rules can become intuitive and even natural. Since close to all applications design teleportation in the same way (selecting a spot and pressing a button), users can get used to moving through a world in this way. Teleportation has become virtualistic and natural.

7

A DESIGN SPACE OF VR INTERACTION

Before I delve into the design space of VR Interaktion, I will summarize the previously discussed parts and put them into context.

Summary
When designing interaction in VR, there are in most cases two worlds to consider. It is difficult to design interaction in VR in such a way that only the virtual world is influenced, since all actions performed by a user are also performed within the real world. This leads in many cases to the circumstance that one must restrict either the real or the virtual world. These restrictions are conditions attached to certain interactions and are the product of a strong reality coupling. One example for this trade-off is walking in virtual worlds. If interaction is designed in a highly coupled way, in most cases either the real or the virtual world has to be restricted.

Such trade-offs do not apply on interaction that is realized in a reality decoupled way. Taken again the navigation in virtual realities as an example, the most commonly used technique is teleportation. By only selecting a spot and pressing a button a user may change the virtual position without doing so in reality. Therefore teleportation only influences the virtual world, while the real one remains untouched and is therefore an example of a highly reality decoupled interaction technique. When defining interaction as a set of rules that may either be based on the reality or on the virtuality, walking is a technique that follows real rules. Real rules often lead to higher couplings then their virtual counterparts. Teleportation, for example, uses only virtual rules, since neither the input (in the form of destination selection and button press to change the position), nor the feedback (which is a sudden change of the virtual position without motion feedback) exist in reality. Redirected walking combines both types of rules, since it utilizes a real rule (walking) and combines it with one or more virtual ones (gains).

But feedback and the perception associated with it is often more complex. It is not only about getting from A to B, but also about how it feels to get there. These are expectations of feedback that we have gotten used to from the real world. If taking the locomotion in VR via a controller as example (be it a joystick or a steering wheel with accelerator pedal). In this case a visual movement is perceived, but at the same time we expect a matching vestibular stimulus. The result is that the feedback of the movement does not feel like it is actually happening. Another example is the grabbing of objects. Even if the passive feedback of a controller whose buttons are pressed is considered as tactile feedback, there are so many more attributes of objects associated with haptics that are expected to be felt in the moment of grabbing, like texture, hardness, temperature and weight [33]. Given the complexity of feedback that is needed to convey a fully realistic feedback of a virtual object, feedback devices would have to be that complex, too.

To design interaction in VR, a multitude of influencing factors have to be weighed against each other. On the one hand, there are user-centered aspects, such as the experience or the already mentioned feeling of being present in the virtual world, as well as the freedom to act without restrictions in the virtual world. On the other hand, there are often limitations. Often the available hardware is too simple to provide the desired feedback or allow unrestricted interactions. In addition, the level and implications of the reality coupling must be considered. Often interactions and feedback that are very close to reality are accompanied by a higher coupling. This, in turn, can lead to increased demands on the physical world or the need to restrict the virtual world.

The following section looks at and describes various possibilities to realize interaction in VR and also draws on the information sources already discussed (real world, hardware and illusions).

7.1 CATEGORIZING VR INTERACTION

Related work proposes several categories to subdivide the distinct forms of how interaction can be realized in VR. Bowman et al. [23] propose to distinguish between natural, magic and manipulation-based interaction. With a similar meaning but distinct wording it was also proposed to distinguish between natural, hyper-natural and super-natural interaction [34]. Natural interaction is considered to mimic the real world as close as possible, while magic or super-natural interaction is considered to give the user super powers that are highly abstracted from or even unrelated to the real world. Manipulation-based or hyper-natural interaction on the other side is a combination of both. This abstraction from the way we interact in the real world was also referred to as lower interaction fidelity by McMahan et al. [35]. They propose to apply the term fidelity for sensory experiences as well as actions and equal fidelity with realism.

As discussed in the previous sections, I argue that the notion of naturalness for interaction in VR should be expanded. Not only can worlds be represented that are identical with reality, but conceptually worlds that go beyond the limits of our reality. Also the interaction with these virtual worlds can differ from the interaction with the real world. I suggested to use the term virtualistic as a counterpart to realistic. While realistic can be described as *everything that happens follows the rules of the real world*, virtualistic describes the circumstance that *everything that happens in VR follows the corresponding logical rules of the virtual world*. The concept of naturalness would then no longer necessarily be linked to the real rules, but could also be applied to virtualistic situations. However, since we may be not yet familiar with the rules of a virtual world, these new rules must first be learned. After a certain period of getting used to the new rules, they may seem natural though they are not related to reality (as the example of teleportation shows). I therefore propose a categorization of interaction techniques in VR that does not immediately describe unrealistic interactions as not natural.

7.2 A CATEGORIZATION WITHOUT REFERENCING NATURALNESS

As proposed by the mentioned prior works, interaction can be designed realistic as well as virtualistic. The latter, though, has to redefine rules known from the reality and has to be learned by the users. The priorly stated categories though indicate that only realistic interaction leads to naturalness, or that virtual interaction has a lower fidelity. I argue, that if such a virtualistic interaction is designed well, the new rules of the virtual world do not necessarily negatively influence the naturalness of interaction. Here too, teleportation is a good example. VR users have learned the new rules of a virtual world, that they can get from one point to another by just pointing on the desired spot and pressing a button. Since there is no motion feedback as known from the real world, users do not expect to feel the respective cues (such as vestibular motion feedback). The use of a controller to smoothly navigate through a virtual world, in contrast, is not fully virtual and raises some expectations on the way we navigate through the real world. There are still visual motion cues that remind the user of moving. As result, the user's expect to have additional cues of motion as known from the reality.

While real and virtual interactions describe two ways of realizing interaction in VR, there are also in in-between solutions that arise by combining real and virtual rules. I propose five categories of VR interaction which can be summarized as follows:

(1) Real interactions (which only use real rules),

(2) subjective real interactions (that include virtual rules in a way the user does not perceive them),

(3) abstracted real interactions (that include perceivable virtual rules),

(4) abstracted virtual interactions (where the major rule of interaction is a virtual one, but still real rules affect the interaction) and

(5) virtual interactions (in which only virtual rules are applied).

All of these categories will be described an discussed in the following sections.

7.2.1 *Real Interaction*

Real interaction is a one-to-one correspondence of the virtual world to the real one. All rules that determine the interaction are real ones. Examples of such an interaction would be the use of passive haptic feedback, where the object that is physically touched has the exact same properties as the virtual one. Unmodified walking in contrast would be an example for real locomotion. In practice, this category is hard or even impossible to realize. It may be simple for walking (at least for the few meters that are commonly available but much harder for other interaction techniques. The common way to realize real interaction is therefore to adapt the virtual world to the real one or vice versa.

Real interactions most commonly lead to the highest reality coupling, since the real world is often utilized as input or output device.

7.2.2 *Subjective Real Interaction*

From a user's perspective, real and subjective real interactions are the same, since any virtual rule that is included is designed in a way the user is unable to perceive the difference. When regarding subjective real interactions from a developer perspective, there is much more freedom, since virtual rules may be included and adjusted. In subjective real interactions, virtual rules are most of all designed as illusions that trick the perception.

Subjective real interactions also lead to a lower coupling of realities. While an equality of realities is assumed for a real interaction, it can be abstracted from it for subjective real interaction. Through this unobtrusive and unnoticed abstraction, however, a first form of decoupling from reality can already be realized, as the following examples show.

Examples for subjective real interactions include more abstract passive haptic feedback (such as it was commonly applied). Also subtle manipulations that redirect the human hands to map a virtual position of an object to a real one would be part of this category. Subjective real haptic feedback can also be realized by complex and fine tuned hardware (e.g. for touch there would be a rendering of every possible material available).

For the field of navigation, redirected walking is a good example for subjective real interactions. As long as only in imperceptible gains are presented, the user is unable to distinguish between real and redirected walking.

7.2.3 *Abstracted Real Interaction*

Abstracted real interaction offers much more freedom compared to its subjective real counterpart. Virtual rules that are recognized may be included and the interaction can be abstracted from what is known from reality. Though, the main mechanism of such an interaction has to be based on what is known from reality. Parts of the interaction that was proposed as magic interaction by Bowman et al. [23] could also be part of this category.

Abstracted real interaction therefore may be a a more powerful version of subjective real interactions. One example for such an interaction is the Go-Go technique [36]. Here the virtual arm can be extended to reach objects that are farther away. It therefore allows to touch, select or grab objects that would not be in reach when the interaction would have been implemented as subjective real.

Abstracted real interactions can also be used to achieve a higher reality decoupling compared to subjective real interactions. An example for this coming from the field of navigation is the use of treadmills. Treadmills allow endless walking within a very limited space. Compared to real walking, the spatial requirements for the physical tracking space is therefore highly reduced and both virtual and real world become decoupled. The main mechanism or rule that realizes getting from one place to another is by walking (real rule). But there is also a perceptible virtual rule of such a treadmill. This is because the user is always moved towards the center of the treadmill and therefore does not physically move forward as the visual perception based on in the virtual world suggests.

A third reason why abstracted real interaction could be chosen over a more realistic representation is the availability of hardware or the required simplicity of realizing certain interactions. Using a controller as representation of the human hands and pressing a button is an example of such an interaction. It is much more complex to track the exact motions of the human hands or to realize a real grabbing of virtual objects compared to the use of a controller. The main mechanism of such an interaction uses the hands, which are moved as they would be in the reality (real rule). The grabbing part (pressing a button) is still based on what is done in reality, but abstracted and also perceived as differing from reality (virtual rule).

As the examples show, such abstracted real interactions can (as well as the remaining categories) be realized using the real world, hardware or illusions (or by a combination). Abstracted real interactions, however, provide a different view on illusions which are typically designed to be imperceptible, but in the case of abstracted real interactions are designed in a perceptible way. As I will show later on, illusions that were presented and used in an imperceptible way can also be applied in a perceptible way to further decrease reality coupling. This way, I proposed to apply gains from redirected walking in a exaggerated and perceptible way to achieve a higher reality decoupling by reducing the required physical space. The illusions provided by pseudo-haptic feedback (as an example of haptic interaction) can also be exaggerated and displayed in a perceivable way to allow for a greater design space of the respective feedback.

7.2.4 *Abstracted Virtual Interaction*

Abstracted Virtual interaction has a different focus compared to the prior described ones. While they are designed in a way based on or even indistinguishable from reality, the main mechanism of abstracted virtual interaction is a virtual rule that is unrelated to the real world. Most often, abstracted virtual interactions realize a higher reality decoupling by providing interactions beyond the restrictions of the physical world.

An example coming from the field of navigation could be arm swinging techniques in which a user navigates through a virtual world by swinging her arms. While the main mechanism that controls the movement has nothing to do with reality (arm swinging) is a virtual rule, the technique is nevertheless oriented towards reality. A swing with the hand, for example, is mapped to a step and every step moves the virtual character forward (real rule).

For haptic feedback, the vibration feedback of a controller, for example, could be interpreted as a virtual rule that states touch is felt as vibration (both are tactile cues).

7.2.5 *Virtual Interaction*

Virtual interactions are completely based on virtual rules without any reference to the real world. Such interactions in most cases lead to the highest amount of reality decoupling. Similar to the real interaction category, the virtual one also was seldom implemented since most applications and techniques aim at orientating towards certain aspects known from reality.

But there are very well known virtual interactions that are most often used in VR applications, with teleportation being one of them. When navigating through a virtual world by teleporting, there is no baseline of how such a mechanism would feel like, since teleportation is not possible in reality. In this case, the input (selecting a target and pressing a button) is unrelated to reality and therefore is a virtual rule. The output (changing the location without visually moving) is unrelated to reality as well and therefore also utilizes a virtual rule.

There are only fiew examples of virtual interactions in the field of haptic feedback. What could be considered as virtual interactions and also is part of common VR applications is the missing haptic feedback. When objects loose properties they would have in reality (e.g. objects do not have any

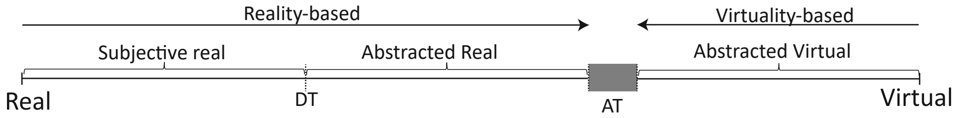

Figure 7.1: The proposed categories of VR interaction can be placed on a continuum with the extrema being real and virtual interaction. The continuum is split in two parts: reading from left to right there is reality-based interaction, in which the main rule of interaction mimics the real world. Reading from right to left there is virtuality-based interaction in which the main rule is a virtual one.

weight), this would be a virtual rule. If the users hand may penetrate virtual objects as if they would have not matter, this is also some kind of virtual feedback.

7.3 A VR INTERACTION CONTINUUM

Milgram and Kishino's Taxanomy for MR Displays

Paul Milgram and Fumio Kishino proposed a taxonomy for mixed reality displays [37]. They describe a continuum having the extrema of a *real environment* and a *virtual environment*. The area between those extrema is called mixed reality (MR), while displays that mainly present real world information but are enriched with virtual ones are called *augmented reality* (AR) displays and displays with a focus on virtual information enriched with real world ones are called *augmented virtuality* (AV) displays. With the increase of technological advantage this continuum may become partially obsolete. Displays may not only be developed for a single purpose such as VR or AR, but be able to display the whole continuum. The HTC Vive Pro for example includes two cameras to render real world images within the VR glasses. It could therefore be seen as a VR or AR device, depending on what is displayed. The term XR (cross reality) was introduced for such hardware that allows the presentation of the whole continuum.

However, the view and idea of creating a continuum between reality and virtuality also offers a wide range of possibilities beyond display technology. One of them is described in the following and refers to the presented categories of VR interaction on such a continuum.

VR Interaction on a Continuum

Since, as described, the interaction in VR is not only consisting of virtual parts and the real world still plays a major role, I propose to apply a similar continuum for interaction in VR. The described ways of realizing interaction in VR can be placed on such a continuum.

The two extrema have already been mentioned: being the *real* and the *virtual* interactions. *Real* means, that a user's interaction is completely the same as for reality and only consists of real rules. The other extreme, being *virtual*, would be an interaction having no reference in reality by only consisting of virtual rules.

A third concrete and measurable point of the interaction continuum is the detection of an interaction being not the same as in reality and is called detection threshold (DT). A DT can be measures using 2AFC task as described in section 3.

The region between real interaction and the DT spans the third category: the described *subjective real* interactions. Such interactions cover the field of abstracting interaction by including virtual rules until the point users recognize to be manipulated. From this point on, interaction increasingly becomes metaphorical and more abstracted from the way known from reality.

I further propose a second threshold besides the detection which I call acceptance threshold (AT). While the DT defines a spot on the continuum on which on the user will be aware of an illusion or of any other difference between what is virtually perceived and expected from reality, the AT defines the spot at which the user does no longer accept an illusion or a given difference. I therefore argue that the blending of real and virtual rules has its own maximum. The area starting with the DT and ending with the AT spans the category of *abstracted real* interaction, in which perceptible illusions or variations from reality are utilized. An interaction in this category is though not being perceived as real still considered as usable.

As long as the major rule that defines the respective interaction is based on the reality, the interaction is still considered to be reality-based, while an interaction with focus on virtual rules is considered to be virtuality-based. The described categories of real, subjective real and abstracted real are therefore considered to be reality-based, while the remaining categories being abstracted virtual and virtual are considered to be virtuality-based.

This subdivision in reality-based and virtuality-based interaction also subdivides the proposed continuum. I argue, that there are these two directions of implementing interaction in VR, while both can be mixed up with rules coming from the respective opponent side. I further hypothesize that abstracted virtual interaction, similar to abstracted real interaction, has an acceptence threshold that defines the spot on which virtuality-based interaction should no longer be enriched with real rules. The area between these ATs marks interaction techniques that are not accepted by users.

The proposed interaction continuum as illustrated in figure 7.1 shows the described concept. It arranges the proposed classes of interaction on a continuum with the extrema real and virtual and shows a colored area of rules that should not be applied, since the user's will not accept them to be part of the virtual world. The following example aims at clarifying the concept of the proposed continuum.

Example: Different Navigation Approaches on the Continuum
When navigation in VR is realized by unmanipulated walking, the interaction is real since having no difference to the same interaction in reality. The other extreme would be the use of teleportation, where the user has no reference from the real world. Teleportation is a metaphor for getting from one place to another – it is a virtual interaction. Real navigation, though, has some drawbacks. To be able to walk through the virtual world, the boundaries of real and virtual world have to be the same to avoid walking against obstacles being only placed inside the real world. The solution would on one hand be a very large physical space or on the other hand a virtual world being designed similar to the real world (as it was e.g. done by Shapira et al. [38]). Teleportation, in contrast, has other drawbacks. While it can be realized without restricting the real or the virtual world, navigation with teleport is often considered to lead to a loss of spatial awareness or a decrease of the feeling of presence [39–42].

But there are also works that can be arranged between both extrema. To overcome the very strict limitations the real walking comes with, the already mentioned idea of redirected walking (RDW) was presented [43, 44], where a user is manipulated in a way to map the conceptually unlimited virtual world's space to a limited real world space. Redirected walking introduces one or more virtual rules like for example that the virtual path is scaled by a certain factor compared to the real one (translation gains) or that the world around the user is rotated during walking (curvature gains). RDW techniques are most of all evaluated in means of psychometric functions and by measuring detection thresholds [45, 46]. This detection threshold provides insights on how far a manipulation can go before a user starts to recognize being manipulated. RDW therefore tries to approach the *subjective real* category on the continuum.

In my work on RDW [R5], I investigated how far curvature gains can go beyond the level of detection, but under consideration of general acceptance of a locomotion technique (acceptance threshold). Though the user is aware of being manipulated, I could show that much higher gains can be applied under consideration of the AT instead of the DT. This would be an example of abstracted real interactions in terms of RDW. In such a case, the main mechanism or rule that is used to navigate through the virtual world is still a real one (walking), but the curvature gains (being a virtual rule) are designed in a perceptible way and therefore noticeably abstract from the way we walk in reality. When too high gains are presented, the user will no longer accept this virtual rule and the red colored area of the continuum is reached.

Real walking and redirected walking (whether with, or without perceptible gains) are examples of reality-based navigation. Teleportation in contrast is a virtual navigation approach and therefore part of the virtuality-based side of the continuum. An example for the remaining virtuality-based category (abstracted virtual) is the proposed way to navigate through a virtual world by swinging the arms instead of making steps (e.g. [47]). In this case, the main mechanism that controls movement is a virtual rule, but it still aims to mimic real world behaviour, since arm swings are matched to making steps. The feedback a user gets is therefore based on reality, since the virtual character moves as he would be walking through the virtual world. A second example that builds upon navigation by teleportation was recently presented by Liu et al. [48]. They present an approach in which the teleportation is no longer triggered by pressing a button, but by walking through a portal. The walking part of this technique can be considered as a real rule and therefore the virtual navigation approach of teleportation is coupled with a reality-based part. The results of the presented user study show a trend towards less acceptance of such an approach, since subjective ratings (such as likeability) decreased compared to common point and click teleportation. This could be an indication that, as previously claimed, the inclusion of real rules in a virtual interaction technique also has a maximum in the form of an AT.

These examples show how navigation can be realized on different parts of the proposed interaction continuum. From real walking over undetected and detected RDW gains to virtuality-based locomotion like arm-swinging or teleportation.

Part III

CLASSIFICATION OF PRIOR WORKS

8

HAPTIC FEEDBACK AND INPUT

The following summary of related research does not claim to be exhaustive, as the fields of haptic feedback and interaction, as well as those of locomotion and motion feedback, were considered very comprehensively by researchers. The works presented in the following therefore concentrate on topics that are most closely related to my own work.

The presented works will be categorized based on the five suggested categories (*real*, *subjective real*, *abstracted real*, *abstracted virtual* and *virtual*). Since in most of the described works neither detection nor applicability thresholds were measured, the categorization is based on the intend of the researchers to create respective stimuli and experiences.

Haptic feedback is a collective term for various feedback modalities, such as pressure, temperature, size, weight or kinesthetic feedback in general. Researchers have presented solutions for each modality ranging from hardware over passive to software-only solutions. Since my own works were focused on the perception of weight, kinesthetic feedback in general and tactile (wind) cues, the following sections are also focused on these specific feedback modalities.

8.1 TACTILE

Real tactile Feedback requires the same shape and texture of real and virtual object. Some passive haptic solutions aim at comparing real passive haptic feedback to subjective real ones (e.g. Simeone et al. [29]). Investigating the effects of varying shape and texture on the physical counterpart, they present two studies. One of them is concentrating on factors that affect the users' suspension of disbelief and ease of use by altering the virtual representation of a physical object and a second study where the physical representation of a virtual object was altered. Though variations of tactile feedback, temperature and weight were present, higher deviations were accepted by participants and minor were not even noticed. The area of subjective real tactile feedback was therefore regarded in more detail.

Subjective real passive haptic feedback (**using the real world**) is most of all realized as subjective real feedback where the real and the virtual objects differ in their tactile properties without the user noticing it. Variations, though, may not only be presented on the physical properties, but also by manipulations of the user (illusions). Various manipulations were suggested to match the position of an object in VR to that of a real object. The location of the hands can be adjusted in a subtle way during grabbing or touching an object [30, 49] or to match a surface [50], or even redirect the walking path of a user to match one object to another [51].

But tactile feedback in consumer **hardware** is mainly communicated by vibration, as the corresponding actuators are small and light enough to fit into all kinds of controllers and have also found their way into common, modern hardware (e.g. HTC Vive or Oculus Touch). There are works on recreating tactile cues as close as possible to the ones perceived in the real world to communicate tactile feedback in VR (e.g. [52–54]). Such works aim at using vibration as tactile feedback that mimics the real texture as close as possible.

Most of the available vibration feedback is however classified as abstracted real or even on the virtual side of the continuum since the resolution and nature of vibration does not fit the specifications of real objects.

Many prototypes aim at delivering the most realistic tactile feedback but do not investigate the indistinguishability from reality. Though it can be questioned whether they provide feedback in a way it is perceived as real, they are classified as subjective real due to their aim at providing respective feedback. Examples for such tactile feedback can be found in skin stretching approaches (e.g. [55, 56]) or other finger mounted feedback devices such as [57–63] or similar but hand mounted approaches [64]. Handheld or static physical shape displacement displays (e.g. [65]) can also be used to provide tactile feedback. Such tactile displays allow to adjust their shape to match the surface of virtual objects. Due to limitations regarding resolution and reaction time Abtahi et al. [66] suggested several imperceptible manipulations of the hand and fingers to overcome these limitations.

A different kind of tactile feedback, which is not focused on the hand regions is airflow (e.g. [67]). Airflow was proposed to be applied by an external stationary device. This can be a fan in front of a user [68] (in this case for a scooter application). But also multiple fans can be used to increase the resolution of airflow. Examples of this are Verlinden et al.'s [69] sailing simulator or the cave setup by Hüllsmann et al. [70]. The WindCube by Moon et al. [71]) used such a construction for 3D airflow simulation as well. They found that participants could not distinguish between wind sources with less offset than 45°. Pluijms et al. [72] measured how good humans can distinguish different directions and strengths stating that directions can be recognized more precisely for frontal sources then from behind. Both results suggest that for the direction of airflow, high deviations from the real world can be applied while still remaining indistinguishable from the real world. The display of airflow in VR can therefore be highly abstracted from the real world while still being subjective real.

But not only fans were used to deliver tactile airflow feedback. Kulkarni et al. [73] used vortices of airflow which were also integrated into the Tread-Port Active Wind Tunnel [74].

Besides these described stationary approaches, there are also examples of head mounted airflow sources, like the helmet proposed by Kojima et al. [75]. It consists of four audio speakers whose airflow is forwarded by tubes towards the user's ears. Lehmann et al. [76] compared stationary and head mounted airflow sources and state that participants preferred the mobile over the stationary set-up.

Pseudo-haptic feedback (**illusions**) is the generic term for haptic feedback that is delivered without actually using a haptic sensory channel. It usually applies illusions and distortions on haptic perception using vision [77]. Using a desktop environment it was shown, that vision has an influence on the perception of friction [78, 79] or stiffness [80]. But not only the own body may be manipulated to enhance the feeling of touch, but also the virtual object may be deformed when being pressed (e.g. [81]). Since such manipulations are carried out very discreetly and with the aim of the user not recognizing the manipulation and only perceives a deviation of the respective stimulus, such manipulations are classified as subjectively real.

Abstracted Real: Vibration, as abstract feedback, was even applied to enable full-body haptic feedback. Lindeman et al. [82] applied vibration motors on a vest to allow either impulse and continuous vibration feedback. Yano et al.'s vibration suite included 12 motors on the forehead, palms, elbows, knees, thighs, abdomen and back. They used the actuators to communicate collisions while walking through a virtual world [83]. The proposed works do not aim at providing realistic and indistinguishable feedback but aim at using vibration to enable feedback where priorly none existed.

Abstracted Virtual and Virtual tactile feedback is hardly found in the field of VR research. It could be argued that the current state-of-the-art of missing tactile feedback is some sort of virtual feedback, but to the best of my knowledge there are no works on such a topic.

8.2 KINESTHETIC FEEDBACK

Real: The only way of displaying real kinesthetic feedback is to physically recreate the virtual world or vice versa. A similar idea is the passive haptic feedback or haptic representation of virtual objects by similarly shaped and weighted objects. [84]. It could be argued, that recreating a virtual world based on the physical boundaries and objects of the real world would lead to a real kinesthetic feedback, as it was done in the reality skins project [38].

Subjective Real: In most cases passive haptic feedback is though realized as subjective real feedback, since the real and virtual objects are chosen to be similar, but not equal. As discussed for tactile feedback, passive haptic feedback provides kinesthetic feedback as well. The suggested visual redirection of users' movements to match the virtual world with real world counterparts for surfaces (e.g. [38, 49]) or objects [30] are an example for this. It was also proposed to provide passive haptic feedback with the help of robots (e.g. [85–87]) or even by other humans [88].

Eva-Lotta Sallnäs [89] investigated the effects of haptic force (kinesthetic) feedback on collaborative works in virtual environments and found it to be contributing to presence and enhanced the collaboration. They used a PHANToM device which offers a huge design space for interaction with virtual objects [90]. Similar to the PHANToM based interactions, exoskeletons are used to design kinesthetic feedback with the aim of being as realistic as possible. Since most kinesthetic feedback arises from outside the human body but exoskeletons typically are mounted on the users body, it is still hard to design a exoskeleton that provides kinesthetic feedback that cannot be be distinguished from its real counterpart. Exoskeletons were designed to either provide respective feedback on the hands [91–94], an whole arm (e.g. [95]) or just attached between two body parts (e.g. [96]). It was also shown that kinesthetic feedback of exoskeletons can be combined with tactile feedback (e.g. [97]).

The already mentioned pseudo-haptic effects can also be applied to simulate directional forces [98, 99]. Such experiments were though done in a desktop environment and therefore without involving the feeling of body ownership or proprioception as it is usually achieved by VR applications.

In VR, the subtle resistance of airflow ([100, 101]) or weight [102] were investigated using pseudo-haptics. While the airflow application had no real world counterpart, the weight perception experiment slightly changed the perception of an already weighted object. It was also proposed to combine passive haptics with pseudo-haptics [103].

Abstracted Real: Directional forces can be displayed by using tethers, which can be held (e.g. [104]), mounted on a user [105] or stationary mounted around the user (e.g. [106]). Such interaction can obviously be distinguished from real kinesthetic feedback, since the applied forces always increase the same way and independent of the object properties due to the use of the same tether for every object. Further, it is not possible to display unmovable static objects due to the nature of tethers which are not capable of displaying a hard barrier.

Another way to display directional forces is the use of electrical muscle stimulation (EMS) (e.g. [107–111]). EMS strives to stimulate single or groups of muscles to trigger body movement. Lopes et al. used this approach to simulate kinesthetic forces by actuating opposing muscles [112]. Using this approach the own muscles unintentionally work against the muscles that are actuated willingly to move an object.

Weber et al. evaluated different ways of communicating collisions by visual, vibration and force feedback from a robot arm [113]. This could be interpreted as comparing subjective real feedback using a robotic arm to abstracted real feedback using visual and vibration feedback. They observed that substituting force feedback with vibro-tactile cues may increase cognitive load, while visual feedback may be perceived as less ambiguous but could increased the time needed to complete the task.

Abstracted Virtual kinesthetic feedback is also rarely considered in VR research. Works like the GyroVR prototype [114] or HangerOVER [115] include kinesthetic forces in a way unrelated to the real world. While GyroVR utilizes the gyroscopic effect on the head of a user to apply kinesthetic forces that aggravate head rotations, HangOVER utilizes the Hanger Reflex to display forces on the head.

Virtual kinesthetic feedback could be seen – similar to tactile feedback – in the lack of such feedback in the current state-of-the-art. Here, the lack of kinesthetic feedback leads to hands penetrating virtual objects as long as the respective objects cannot be moved. For movable objects, the absence of kinesthetic feedback causes virtual objects to lose their physical properties because they can be lifted and moved as if they had no weight. Such clipping effects as well as the direct interaction with seemingly weightless objects could be interpreted as examples of virtual feedback.

9

NAVIGATION

Navigation in general is a challenge and part of VR research. It consists of the cognitive way-finding and the physical (active or passive) travel [116]. Way-finding can be defined as the spatial-cognitive process of finding a route to get from one place to another. Travel in contrast can be interpreted as the actual movement. This movement can be passive (i.e. using a joystick), or active (the user moving physically: often also called locomotion). A third aspect that needs to be considered for virtual navigation is the motion feedback, which is most of all important for passive navigation, since there typically exists no motion feedback beyond the visual motion cues.

The following summery is subdivided in the two categories of travel and motion feedback. Since my research did not touch the field of way-finding, this aspect is left out for this discussion.

9.1 TRAVEL

Walking is considered to be most natural [117] way of navigation in VR. Though, it has some drawbacks with the physical space restrictions being the most important one. Other locomotion techniques were introduced [118] to overcome these limitations. These techniques were categorized by Boletsis et. al [119], who group them into four categories (motion-based, roomscale-based, controller-based, teleportation-based). Their categorization is based on factors such as physical or artificial interaction, continuous or non-continuous motion, and virtual interaction space limitations. In the following, only non-vehicle travel is discussed.

Real travel (in the form of walking) is realized in most of the common VR application as an additional feature to teleportation. While larger distances can be bridged by teleportation, smaller distances can be travelled by walking. Walking freely without any additional help (e.g. teleportation) is seldom realized due to spacial limitations of the physical world.

Subjective real Redirected Walking (RDW) is a way of overcoming the strict limitations imposed by physically available space. The idea of RDW is to compensate the restricted space for tracking by manipulating the orientation, position or other characteristics of the user. While the walking part can be interpreted as the main rule of such an interaction (which is a real one), additional virtual rules are included, such as manipulating the user's orientation after walking a certain distance (curvature gains). Curvature gains make a user walk on a circle in reality while walking straight ahead in the virtual world [43]. RDW was primarily studied as subjective real travel, i.e. the virtual rules or gains are small enough not to be noticed by the user. Therefore, in previous work, detection thresholds were usually specified to cover the design space of a particular RDW technique. For curvature gains, Razzaque [120] reported that a manipulation of less then $1°/s$ is not detected by a user. Their view of curvature gains suggests applying the reorientation of the world around the user regardless of the distance travelled, and applying it consistently over time. In other experiments curvature gains were defined as being dependant on distance (expressed by the unit $°/m$ instead of $°/s$). Steinicke et al. suggest that curvature gains should not exceed the proposed DT of $2.6°/m$ [45]. Such a gain leads to a circular path with a diameter of 44m to go infinitely straight ahead. Grechkin et al. [46] investigated the influence of applying translation gains while also manipulating the user with curvature gains. They found that the detection thresholds of curvature gains were not significantly influenced by translation gains, but propose a DT of around $4.9°/m$. Such gains would still require an available space of 24m x 24m for infinite straight walking. Further, it was proposed, that the DTs of curvature gains are influenced by several factors, like the presence of cognitive tasks [121], the velocity of walking [122], or the presence of passive haptic feedback [123].

But there are several types of gains that have been proposed besides curvature gains. These gains include the scaling of the user's velocity (translation gains) [45], or the rotation of the virtual world while standing on a spot and looking around (rotation gains) [45, 124]. Suma et al. [125] introduced a taxonomy of different redirection and reorientation methods. Their taxonomy ranges from discrete to continuous and from subtle to overt.

The gains presented above provide the basis for a dynamic adjustment of the user path to keep them within a limited physical space. Such strategies were presented by Razzque [120]: Steer-to-center, steer-to-orbit, and steer-to-multiple-targets. Another algorithm to realize unperceived redirections while walking on very large spaces, i. e., 45m× 45m was proposed by Hodgson et al. [126].

Depending on the available space, a user may still collide with the physical boundaries. In such cases, escape strategies such as instant reorientations or distractors (to apply instant corrections) were proposed [127]. Though such reorientation mechanisms are perceived by a user and therefore should be classified as *abstracted real*, they are listed here, since the aim of distractors is to hide the manipulation from the user and since they are only applied if the main locomotion technique (RDW) fails to keep the user within the given space.

To reduce the required physical spaces, it was also proposed to restrict the way a user walks through the virtual world in addition to apply RDW gains. Langbehn et al. [128] propose to force the user to walk on already curved virtual paths. This curvature of the virtual path adds to additionally applied curvature gains and therefore leading to less space requirements. Special designs of the virtual worlds in which virtual spaces (e.g. two rooms) may overlap each other were presented by Suma et al. [129]. When a virtual world is realized so that its spaces can physically overlap, the physical available space can be used to display larger virtual worlds.

Besides RDW, there were other approaches on how to realize walking within limited spaces. These include omni-directional treadmills (e.g., [130, 131]) or even robot controlled moving floor parts [132].

Abstracted real The seven league boots presented by Interrante et al. propose to apply translation gains known from RDW research in a perceptible way [133]. To increase the comfort of higher translation gains, they propose to scale the walking path in the direction of actual movement, while not scaling other directions (e.g. up and down). Since the approach presented uses noticeable gains, they call it a metaphor of walking.

Abstracted virtual: The use of controllers to walk through a virtual world by for example using a joystick can be considered as abstracted virtual. The main rule that controls movement is a virtual one (e.g. pressing a button), but the feedback is still oriented to the real world, because the virtual character moves step by step through the world. A similar implementation is flying through a virtual world by using indirect controls (e.g. joystick) [134]. Such techniques may cause motion sickness symptoms, which are assumed to arise due to sensory conflicts of the visual and vestibular system. Motion sickness will be discussed in more detail in the following sections.

Furthermore, walking-in-place techniques (e.g., [135, 136]) can be considered to be abstracted virtual interaction techniques. Here users only move their arms, head or legs up and down like to navigate through the virtual world without actually moving forward in reality. The techniques translate the respective movement into a virtual forward motion. Similar to this, so called arm swinging approaches utilize the swinging of arms to move the user in the direction they are looking [47, 137]. Walking in place approaches were shown to be preferred over virtual flight but not over actual walking [117].

Teleportation (as discussed in the next paragraph), was tried to be implemented in a more real way by including walking [48]. Though, the technique was rated worse than common teleportation, the authors show that it is possible to combine teleportation with walking and that the physical space is utilized more extensively.

Virtual Navigation does not necessarily require feedback oriented towards the real world. One goal of virtual navigation is therefore to avoid the sensory conflict that can lead to motion sickness. The best example for such a technique is the already discussed Teleportation. The most common implementation is the so-called point and teleport technique, where a user selects a spot in 3D space and confirms the selection by pressing a button [138]. The feedback side of teleportation as well is virtual, since typically no kind of motion is presented. Thusly, teleportation does not suffer from motion sickness [138]. Disadvantages to such an instant location change were soon presented by several researcher as they might negatively influence spatial awareness and presence in virtual world [39–42]. Bowman et al.[116] found that teleportation may cause spatial disorientation, while Christou et al. [139] suggest the overall impact of disorientation on the experience to be negligible. They also report on the potential of missing elements along the route to be potential disadvantage of teleportation.

9.2 MOTION FEEDBACK

Humans perceive movement by interpreting information from their visual, auditory, vestibular and kinesthetic sensory systems [**berthoz2000 brain**,

harris2002simulate]. In VR, typically only the visual system provides information about self-motion. Movement feedback seeks to provide multisensory cues for such movements. The following sections provide an overview of vection and motion sickness. Since these are not interaction techniques, the proposed categorization does not split the respective parts.

9.2.1 *Vection*

Vection has been defined as a *conscious subjective experience of self-motion* that includes both perceptions and feelings of self-motion [140, 141]. It is mainly induced by optokinetic (visual movement signals) stimulation, but can also be influenced by other sensory systems such as the vestibular.

Vection was investigated for rotation (e.g. [142]) as well as for forward motion (e.g. [143]). One of the major source of vection is that the vestibular system only detects accelerations. Constant velocity is therefore not detected nor expected to be detected by the vestibular system. Accordingly, sensory conflicts (and therefore motion sickness, which will be discussed in the next paragraph) do not occur during a constant optokinetic stimulus. Vection therefore can increase after a certain amount of time, which is called onset latency. The feeling of self-motion can be induced, depending on the user, after a few seconds to half a minute. Berthoz et al. [144] tested the perception of forward vection induced by peripheral vision concluding that vision dominates in conflicting situations.

For both, rotation and horizontal motion, it was shown that the direction of an additional physical movement can differ from the visual stimulus [145, 146], which was the basis my own project *VRSpinning* [R6].

9.2.2 *Cybersickness*

Cybersickness or simulator sickness is a well known problem of VR applications and commonly considered as a subset of motion sickness (MS), since the symptoms and most probably the origin is related. Symptoms include eye strain, headache, sweating, vertigo and nausea [147]. It is still not clear what causes MS in general [148].

However, there is agreement that the two sensory systems, the visual and the vestibular, have an influence. There are three main theories (sensory conflict theory [149], postural instability theory [150] and poison theory [151]) that aim at explaining the origin of MS. The oldest one is also the most accepted one and is the sensory conflict theory [147]. This theory states that the mismatch of visual and vestibular information plays the leading role, as the brain is not able to cope with this conflict. The theory of postural instability states that the root cause of MS is the loss of stability that leads to unstable standing [150, 152]. The poison theory, in contrast, aims at answering why nausea or even vomiting is one of the symptoms, and states that the inconsistent information of the sensory signals are interpreted as have been poisoned. Nausea and vomiting are, according to this theory, a protective mechanism of the body. There is also a strong assumption that vection influences simulator sickness [153].

MS in general can be considered as part of the AT for interaction techniques and usually increases with greater similarity of feedback to the real one. Vertical oscillation increases motion sickness when presented with horizontal movement [154]. Accordingly, when navigation is realized by a controller and the camera is moved up and down to simulate the steps of the avatar, MS may become stronger and the technique less acceptable.

9.2.3 *Motion Feedback*

As described, motion feedback on one hand should increase the feeling of vection, but on the other hand it aims at reducing the visual-vestibular conflict to reduce or even to avoid motion sickness. Since motion feedback in the context of certain input (whether using a controller or using feet or arms) was already discussed, this part focuses on motion feedback for vehicular motion or on sensory stimulation that is only considered as feedback without regarding the input side.

Real motion feedback is hard to realize since the virtual motion would have to be exactly the same as in reality. One approach is, for example, the use of vehicular motion on which the virtual world adopts [155, 156]. Since the authors describe that the virtual motion can be slightly abstracted from the real motion, the actual project is more a subjective real one.

Subjective real motion feedback is often provided by motion platforms, which aim at creating a matching feedback for the virtual motion. Most motion platforms propose a six degrees of freedom feedback [157, 158]. Though, it has been shown that even smaller setups may suffice to create a sense of realistic motion. *HapSeat* [159], for example, applies three actuators for both arms and the head to simulate movement by applying force feedback to the seated body of the user. It was also proposed to use a wheelchair, controlled by a joystick [160]. The authors concluded that such a platform can produce similar results in terms of accuracy and pathfinding ability as in real walking. They also argue that full physical feedback on a simple search task could lead to higher search accuracy.

An alternative solution to raise vection is to induce false sensations. Galvanic vestibular stimulation (GVS), for example, stimulates the vestibular system by sending electrical signals to the inner ear. In combination with visual information, such feedback from the brain can be interpreted as realistic information. It was shown that such GVS may, combined with visual motion feedback, enhance the feeling of self-motion [161], or to decrease symptoms of simulator sickness [162].

Abstracted real: The current state of the art of only providing visual cues could be interpreted as abstracted real feedback, since the user obviously is able to tell real motion from virtual motion. To the best of my knowledge, there is no motion feedback project that aims to be perceived as an illusion.

Abstracted virtual: Ouarti et al. [163] propose to include haptic force feedback in the hands to enhance the feeling of vection. The force feedback was provided according to the virtual camera motion which created a higher feeling of vection compared to visual feedback only.

It was also proposed to use haptic feedback to increase the feeling of self-motion. Lécuyer et al. [164], for example, showed that haptic feedback consisting of rotating the participants' fist according to a visual presented rotation influences the feeling of motion.

Virtual: Motion platforms can also be used as virtual motion feedback, as it was for example done for storytelling. The SwiVR chair [165] controls the movement of the user and draws his attention to regions defined by the system.

Another fully virtual motion feedback is the already discussed missing feedback of teleportation, where users instantly change their location.

Part IV

RESEARCH QUESTIONS AND PAPER CONTRIBUTIONS

10

RESEARCH QUESTIONS

10.1 TOWARDS UNREALISTIC FEEDBACK

RQ 1: Is unrealistic feedback capable to increase the perceived realism of a virtual world?

The design of interaction in VR differs from the way it is designed using common interfaces like external displays or mouse and keyboard. VR allows to implement interaction in a more direct way. Most often controllers are still the main devices utilized to manipulate and interact with the virtual world. In contrast to controllers like gamepads, they are tracked in 3D space and represent the hands of the user. This allows for a more realistic interaction. But, as already discussed, what is *realistic* in the context of an artificial world and how far can the concept be stretched?

This research question also refers to the presented interaction continuum. On the one hand, the area of virtual interaction was proposed, which is either completely or very different from the interaction in reality. Here the question arises whether such forms of interaction can also lead to an increased sense of presence and thus, like their realistic counterparts, contribute to the positive overall experience of a virtual world. On the other hand, the category of abstract virtual interaction was proposed. It is characterized above all by an interaction that largely follows real rules, but deviates noticeably from reality. Here, too, the question arises as to whether noticeably unrealistic behavior can increase the presence and realism of a virtual world. Accordingly, the first research question aims at providing basic insights into the perceived realism of a virtual world.

10.2 FEEDBACK PREFERENCES

RQ 2: Can abstracted or unrealistic feedback be preferred over no feedback?

As already described, the feedback of current VR applications and hardware is limited. One of the major examples for this is the missing kinesthetic feedback. Virtual objects loose their physical properties such as weight which could be felt when lifted. If objects cannot be moved, the virtual hands typically clip through the virtual object as if it was permeable. The reason to this is that there is no physical restriction of an object that would prevent the hand from penetrating it.

There are other similar cases of interaction in virtual realities where the difference between the real and virtual world leads to the loss of feedback. This can also lead to user actions being performed differently than one would expect in reality. For example, lifting virtual objects without some form of weight representation means that any object, no matter how large or heavy, can always be lifted with one hand.

A basic prerequisite for the proposed interaction categories *abstracted real* or *abstracted virtual* and *virtual* is that the abstraction from reality made possible by these categories can create feedback which is preferred over the missing feedback of current state-of-the-art VR hard- and software.

10.3 PERCEPTIBLE MANIPULATIONS

RQ 3: Can manipulations be utilized in a perceptible way to increase their expressiveness while maintaining or even increasing the feeling of presence?

Manipulations are one way of increasing reality decoupling. Approaches such as RDW, aim at hiding manipulations from the user. While this allows for the most realistic experience, it also limits the expressiveness and efficiency of an approach. To infinitely walk a straight line in VR the proposed strength of manipulations still requires a physical space of more than 40m x 40m [45].

Such manipulations were summarized in the category *subjective real*. Although they allow a higher reality decoupling than the exclusive use of real rules, they are still strongly bound to the physical limits. As soon as virtual rules have more influence on the interaction, they can be recognized by the user and the interaction technique would exceed the DT. Interaction techniques whose manipulations can be detected by the user were summarized under the category *abstracted virtual*. It spans a large field on the continuum, ranging from detection of manipulation to rejection by users.

RQ 3 is mainly aimed at this category. Conceptually, a greater decoupling from reality can be achieved with stronger virtual rules. The question now is what effects a stronger virtual influence has on the perception of reality as well as on the feeling of presence. In addition, the question arises what influence the stronger rules can have on the decoupling of reality. RQ 3 further aims to create a comparison of DT and AT. This should enable a comparison of the strength of reality decoupling as well as the subjective experience.

10.4 TOWARDS A MAXIMUM OF MANIPULATIONS

RQ4: Is there a maximum of manipulations acceptable for the user and if so, how can it be determined?

Manipulations can be interpreted as an abstraction from the way we interact with the real world that may allow a greater decoupling of real and virtual world. As the example of redirected walking shows, the required physical space decreases with the strength of the applied manipulation. Therefore, it would be conceptually worth applying such manipulations as strong as possible.

Though, it is hard to provide a clear definition of the maximum of manipulations. It could be defined as the maximum a user can handle or the maximum a user perceives as realistic. We decided to regard the maximum under consideration of usability and acceptance. How far can a manipulation abstract from the known behaviour until user's would no longer like to use such a system. The detection of manipulation can be assessed via a two-alternative forced-choice test – a psychometric test that aims at measuring the perception of participants and which was described in section 3. One of the results of such a test is the so-called detection threshold (DT), which describes the intensity of a stimulus to be detected with a probability of more than 75%. To get insights on the maximum of manipulations we used subjective user ratings to kind of measure the acceptance of an interaction technique. The limit at which users will no longer accept a manipulation was defined as acceptance threshold (AT).

10.5 PAPER OVERVIEW

The contributions of each publication to the described research questions R1 to R4 are summarized in table 10.1. The papers will be discussed more precisely under regard of the proposed research questions in the following chapters.

	Slow-Motion	Haptics			Navigation		
	[R1]	[R3]	[R4]	[R8]	[R5]	[R7]	[R6]
RQ 1	●	(●)	(●)	(●)			(●)
RQ 2		(●)	●	(●)			●
RQ 3		●	●	(●)	●	●	●
RQ 4		●			●		

Table 10.1: The contributions of each publication to the described research questions R1 to R4 (● = major contribution; (●) = minor contribution).

11

PAPER CONTRIBUTIONS

The following sections describe the papers from the perspective of the proposed continuum for VR interaction. Further, they are regarded under consideration of the proposed research questions. For details about the implementation or study, please refer to the respective papers which can be found in the appendix of this thesis.

An overview of the works on the interaction continuum is illustrated in figure 11.1.

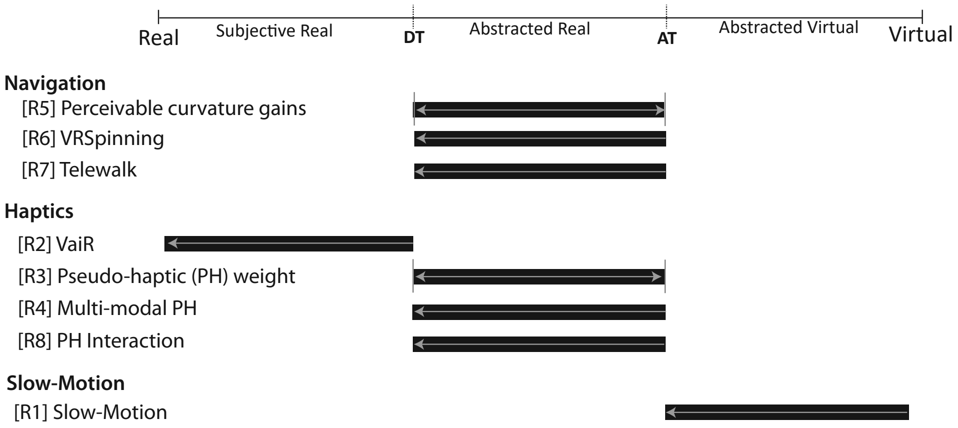

Figure 11.1: An overview of the underlying contributions of this thesis. The black bars indicate the focus of the project on the interaction continuum. The orange arrows indicate whether the project aimed at increasing realism or virtualism and the vertical lines indicate whether the DT or AT were measured.

11.1 REALISTIC VS. VIRTUALISTIC

There are several haptic cues that can be felt on other parts but the hands of the human body, with wind or airflow in general being one of them. To include such features into VR applications, we designed the VaiR head-mount [R2], a system that is capable of applying haptic stimuli in form of airflow with high accuracy and low latency. VaiR aims at providing wind feedback as close as possible to the real world.

The idea of VaiR was to design a feedback device which is capable of providing a highly realistic feedback of airflow. We identified two main aspects that contribute to realism, but were missing from the head-mounted airflow devices previously presented: the first being the resolution and the second being the reaction time. While prior works on airflow simulation in VR most of all used stationary or a minor amount of head mounted fans, we found fans to have a too high reaction time, since they need to accelerate until they provide the desired strength of airflow. Further, only a 2D plane was regarded in prior works on head mounted wind sources. We therefore decided to base our prototype on two main features. The first one was to use pressured air instead of fans to be able to provide feedback with less latency and the second was to attach the nozzles on motorized rotating bows to be able to animate airflow sources in 3D space. The prototype is shown in figure 11.2.

Figure 11.2: The VaiR headmount: Two motorized bows, each equipped with 5 nozzles are capable of animating multiple airflow sources in 3D space with very low latency (Image taken from [R2])

Besides the results of our study where we showed that such feedback is capable of increasing the feeling of presence, the design of the system showed an additional effect: Aiming towards the perfection of realism is highly demanding. Depending on the kind of feedback, there are many aspects to be considered. Even seemingly simple feedback, such as wind or other air flows, is still so complex that it is almost impossible to achieve the desired perfection of indistinguishability from real world stimuli.

However, VR allows to experience a world unrelated to what we know from reality. Such a situation was used as a starting point for answering the first research question. The perceived time is constant and any variation such as fast forward or slow-motion is only known from media like movies or games. In contrast to such linear media where the content is only passively consumed or to traditional games (played with indirect controls), VR allows direct interaction and may include a virtual body reference that behaves and moves according to the user. If the time is slowed down in a VR application first of all the passive parts of the system (e.g. audio and visual feedback) are influenced by the time manipulation. The user and their actions are in contrast not affected by the time manipulation since they still follow the physical constraints of the reality.

In the paper *The Matrix has you: Realizing Slow-Motion in Virtual Reality* [R1] we published a user study in which the participants were presented such a unrealistic experience of slow-motion. We compared the additional feedback of visually slowing down the user movements to just slowing down the environment and asked the participants to rate the realism of the experience. Interestingly, slow-motion in general was rated to be somehow realistic and the inclusion of unrealistic feedback in form of the visual manipulations of the avatar did even increase this feeling.

The results suggest that even feedback deviating from reality or, as in the case of slow motion, even experiencing a situation deviating from reality, can still be perceived as realistic. The fact that the unrealistic feedback of limiting the virtual avatars movement velocity even had a positive effect on the perceived realism even suggests a further assumption. As already described, I assume that there is a virtual counterpart to the term realistic. I defined this as virtualistic. While realistic can be described as *everything that happens follows the rules of the real world*, virtualistic describes the circumstance that *everything that happens in VR follows the corresponding logical rules of the virtual world*. The results described could therefore also support this definition. In the case of slow motion, virtual rules were built in, which did not relate to reality, but which were logically embedded in the virtual world.

Our works on haptic feedback ([R3, R4, R8]) as well as on navigation ([R6]) further support these findings and indicate that even unrealistic feedback can be contributing to the perceived realism. These works will be discussed in more detail in the following sections.

11.2 FORCES WITHOUT PHYSICAL COUNTERPART

Haptic feedback can be felt on the whole human body, while the hands are the prior source to investigate the world around us haptically. Several features, like texture, hardness, temperature and weight of objects can be explored via haptic feedback [33].

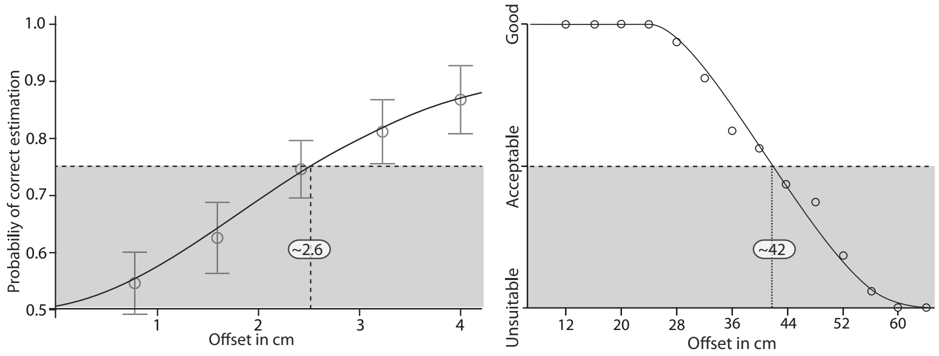

Figure 11.3: Detection and acceptance of pseudo-haptics. On the left: The result of a 2AFC task measuring the probability of detecting offsets; on the right: The result of subjective ratings whether the respective offset was applicable [R3].

The state of the art hardware, consisting of two handheld controllers, is only capable of presenting passive haptic feedback (that depends on the form factor of the controller) or abstract vibration feedback. Many object properties are not communicated nor do they affect the way a user interacts with an object. One of these properties is kinesthetic feedback – directional forces that are perceived as weight when an object is lifted or resistance when an object is moved. While such forces can be displayed using hardware (e.g. exo-skeletons), such forces would need hardware that is anchored in the physical world (and not on the user) to be displayed accurately. As already described, there are projects on displaying forces without such an anchor, like the EMG approach of Lopez et al. [112].

11.2.1 *Towards Visually Displayed Forces*

This section is based on the paper *Breaking the Tracking: Enabling Weight Perception Using Perceivable Tracking Offsets* [R3]. I, however, concentrated on the field of pseudo-haptic feedback, where the focus is on displaying haptic properties on the visual channel. Making use of the human visual dominance, it is possible to let the visual channel influence what is haptically felt. Prior works, though, focused on letting the user only perceive the pseudo-haptic effect while hiding the manipulation (*subjective real*). This way an object can be perceived as slightly heavier, but it is not possible to display higher variances of properties like e.g. weight.

I therefore designed a software-only approach that uses only visual information to display even higher deviations of weight. The idea was to introduce a new virtual rule in form of pseudo-physics. As long as a virtual object has no physical counterpart, the only physics that influences the respective object is the one of the virtual world. When a virtual object is grabbed the user still feels no difference, since the virtual properties of weight do not influence the interaction. It makes no difference whether a virtual object weights 100 g or 100 kg. The reason for this is that as long as the virtual object is gripped, it always follows the position measured by the controller – if possible without any deviation. This causes the object to lose its physical properties as long as it is held.

The pseudo-physics I implemented as virtual rule allows an object to keep its weight. It maps the weight (which is a directional force pointing towards the ground) to a visual offset between the virtual displayed position and the tracked position of the controller. To realize this offset, the object first of all remains its physical properties such as its weight. If implemented so, the object would instead of sticking to the tracked position of the controller be falling down. To counter the virtual weight force, I implemented a force that increases with the euclidean distance between virtual object and tracked position of an object: the heavier a virtual object, the stronger the resulting offset. The offset leads to two effects that should lead to interpreting or even perceive it as weight. First of all there is the pseudo-haptic effect that prior works have been shown. But second, there is an additional effect arising by applying perceivable offsets that are much higher compared to their not perceivable counterparts. To lift heavier virtual objects, the arms have to be lifted higher to reach the desired height. This also leads to an additional physical effort that increases with the weight of an object.

This work mainly targets two of the presented research questions (RQ 3 and 4). However, RQ 2, which asked whether unrealistic feedback cannot be preferred to feedback, is also affected by the project. The fact that the feeling of presence was increased by the inclusion of noticeable manipulations supports the assumption.

RQ 3 dealt with whether perceptible manipulations can be used to increase their expressiveness. The results of the present study also support this assumption. The subjective evaluations whether one could feel weights or not were clearly higher with the condition with abstract real pseudo-haptic feedback. The expressiveness, in this case for the representation of weight, was thus increased.

We further measured and compared the DT as well as the AT for such manipulations which can be assigned to RQ 4 (see figure 11.3). As a result,

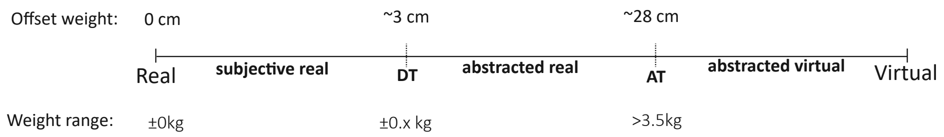

Figure 11.4: While using the DT only slight deviations of weight is possible, the AT allows to display a much higher deviation of weights.

we found that users recognize to be manipulated when objects result in an offset of around 3 cm, while they rated them as good until 28 cm and even accepted them until around 40 cm. In a second experiment, we asked participants to state which weight they associate to some tested offsets. We found that, though having a great variance in the associations, there was a clear tendency of increasing weight with increasing offsets. The median of the associated weight with a 28 cm offsets was at around 3.5 kg. This is shown in figure 11.4.

11.2.2 *Multimodal Pseudo-Haptics*

This section is based on the paper *Conveying the Perception of Kinesthetic Feedback using State-of-the-Art Hardware* [R4].

The described approach of using perceivable offsets to enable weight perception was further investigated on kinesthetic feedback in general. The common state-of-the-art is to use clipping effects (the virtual hands move through virtual barriers that cannot be moved) for unmovable objects and are moved without any resistance independent of their virtual weight. Using offsets to communicate directional forces such as resistance allows to include the mass of objects while interacting with them. A similar approach to the already described one was applied and further investigated. Since common questionnaires on presence or immersion do not fully cover aspects of kinesthetic feedback, a workshop was conducted to asses which quality metrics could be applied to rate such haptic feedback. Further, a multi-modal pseudo-haptic feedback approach was presented that combines visio-haptic effects (offsets) with vibration as metaphor for the pressure that is felt when pushing an object.

We could show, that this multi-modality further increases the feeling of presence and contributes to the perceived quality of the haptic feedback. Further, we found that offsets were preferred over clipping until a certain threshold which assumably is around the AT. For the study, we used the DT and AT that were determined in the previous work [R3].

This project was mainly targeted towards RQ 2. The question whether feedback which is perceived as unrealistic is preferred over no feedback. The lack of kinesthetic feedback leads to the virtual avatar's hands clipping through objects – as if they had no mass. Without a physical counterpart (either a passive haptic prop or additional hardware) the only way of avoid clipping effects is to decouple the virtual hands from the tracked position of the controllers, which was implemented in this project. The findings suggest that the manipulation and therefore unrealistic feedback is preferred over the missing haptic feedback (and clipping in this case).

11.2.3 *Pseudo-Haptic Interaction*

This section is based on the paper *Pseudo-Haptic Interaction: Adapting Input and Output to Haptic Properties of Virtual Objects* [R8].

By now we have only regarded the output side of communicating directional forces without any physical counterpart. The next step was to investigate if and how the input side could be affected by such virtual forces. I call the combination of pseudo-haptic feedback with input that also comes without any physical reference pseudo-haptic interaction. In the described paper, we used the tension of muscles as additional input device. While prior works already measured muscle tension they did not have a way of communicating the effects of this exertion. The typical way of implementing the respective input was using a hard threshold. A user therefore had to tense the muscles until this threshold was reached until when the object could be moved [166, 167]. As soon as the the user relaxed, the object could no longer be held or moved. Combining pseudo-haptic feedback with such input allows a whole new way of interaction. The already described offset force can be combined with another virtual force (that we call muscle force) that increases with the tension. Objects can therefore be moved without additional exertion but with a larger offset, or with exertion which leads to less offsets. The concept is illustrated in figure 11.5.

Our user study proved this concept to perform better regarding the feeling of presence and the perceived quality of haptics compared to pseudo-haptic feedback only as well as the ground truth being no pseudo-haptic feedback at all.

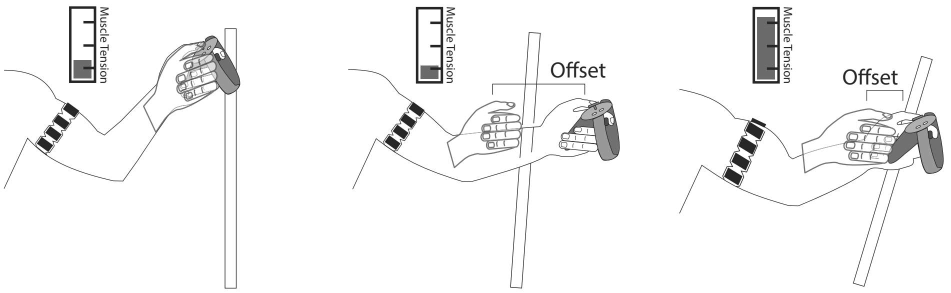

Figure 11.5: The concept of pseudo-haptic interaction using muscles as additional input: The stronger the measured muscle tension, the lower the resulting offset that is required to move an object. (Image taken from [R8])

11.3 NAVIGATION IN VR

As described in the prior part of this work, navigation techniques were categorized into four categories (motion-based, roomscale-based, controller-based, teleportation-based) [119]. While for controller-based navigation one of the biggest challenge is to avoid symptoms of motion sickness, it is on the other hand aimed to induce a feeling of vection (the feeling of physically moving while only visual movement is displayed). Motion-based navigation approaches have the problem of placing high space requirements on the physical world, at least if they are based on real walking. Often walking is only used as secondary mechanism. While for example teleportation is used to cover larger distances, the user actually walks only a few meters. The projects that are described in the following can be split in two parts. The *VRSpinning* system [R6] aimed at reducing motion sickness and enhancing the feeling of vection in a seated controller-based setup. The second part includes two works that aim at letting walking become a room-scale navigation approach without needing other strategies (such as teleportation).

11.3.1 *Controler Based Navigation*

This section is based on the paper *VRSpinning: Exploring the Design Space of a 1D Rotation Platform to Increase the Perception of Self-Motion in VR* [R6].

Motion feedback, if designed in a natural way, is very complex to be realized. It has to include 3D rotation as well as 3D translations to be able to cover the full range of possible virtual motions. With the VRSpinning system, we aimed at displaying every virtual motion by only using a 1D rotation platform. A motorized swivel chair was used as feedback device. While rotations around the up-axis are easy to implement using such a device, it was our main goal to display forward and backward motions as well. While first attempts on substituting linear motion with a certain velocity by constant rotation failed, we decided to substitute accelerations by rotation. Since the human vestibular system is only capable of measuring changes of velocity, we hoped that a synchronous vestibular stimulus would support the visual induced motion even if the directions of the stimuli differ.

In a user study we could show that such synchronous and short term rotations are indeed capable of reducing motion sickness but most of all of increasing the feeling of vection. VRSpinning is therefore an an example of abstracted real motion feedback. While the users were aware of being rotated and also stated to feel this rotation, they still accepted the substitution of forward acceleration by rotation.

Similar to the results of the pseudo-haptic studies, we found the unrealistic motion feedback to be preferred over missing feedback (RQ 2). The feedback also proved to enhance the desired feelings (such as vection or the feeling of accelerating). Interestingly, the many participants stated that they could actually tell that they were rotated, but still had a stronger feeling of accelerating forwards or backwards. These findings support RQ 3 and provide a further case in which feedback that is perceived as abstracted from reality still increases the expressiveness.

11.3.2 *Motion-based and room-scale navigation*

The second part of my works on navigation was on redirected walking. While the DT of gains was measured and presented several times, it was not investigated on how higher gains affect the general applicability of redirected walking. My focus was on the use of curvature and translational gains. Prior works stated a DT of 2.7 [45] or $4.9°/m$ [46] for curvature gains. Applying such gains would lead to a physical required space of 44m x 44m or 24 x 24m for walking a straight virtual line while walking on a circle in reality without noticing to be manipulated. Since such requirements are far beyond what can be considered as room-scale, we conducted a user study in which we let the participants rate several gains based on subjective scores that targeted towards measuring the AT.

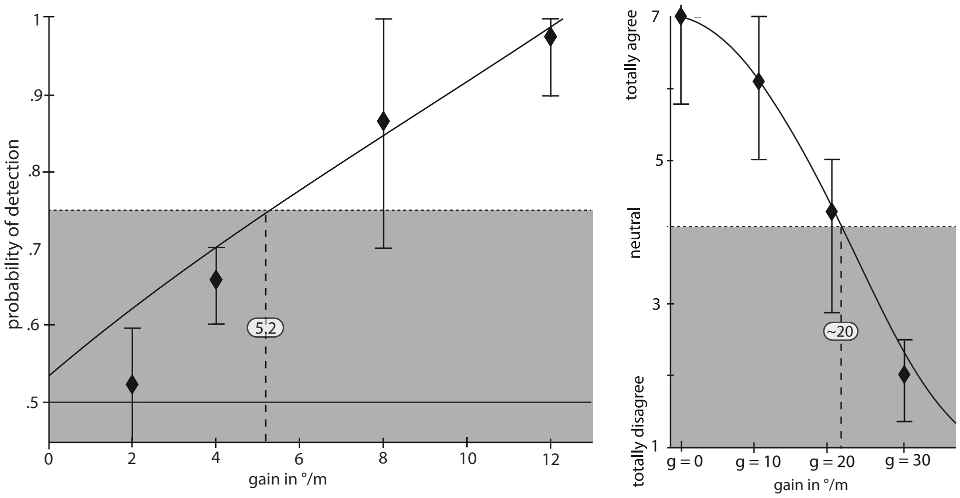

Figure 11.6: Detection and acceptance of curvature gains. On the left: The result of a 2AFC task measuring the probability of detecting curvature gains; on the right: The result of subjective ratings whether the respective gain was applicable [R5].

11.3.2.1 *Towards DT and AT of Redirected Walking gains*

This section is based on the paper *Rethinking Redirected Walking: On the Use of Curvature Gains Beyond Perceptual Limitations and Revisiting Bending Gains* [R5]. I would like to thank Martin Deubzer, who helped with this work in the context of a master project.

In a user study we asked the participants to rate several scores that contribute to the acceptance and applicability of a walking approach. These questions were as follows: (1) *Walking like this through a virtual world is natural.*, (2) *Walking this way through a virtual world is pleasant.*, (3) *I could imagine using this walking technique to move inside virtual worlds.* The participants should answer on a scale from *1: totally disagree* to *7: totally agree.* In addition, we used a single item to measure potential symptoms of motion sickness by asking (4) *How strong was the feeling of nausea or disorientation during walking?* on a scale from *1: non-existing* to *7: I wanted to abort the test.*

The results of the 2AFC task to measure the detection of curvature gains as well as the subjective ratings on how participants agreed to accept a certain offset is shown in figure 11.6. We found that curvature gains of around twice the DT ($10°/m$) did not lower the respective scores significantly, while four times the DT ($20°/m$), tough being rated worse than walking without gains, was still accepted by most of the participants. We therefore argue that the AT of curvature gains is around $20°/m$, which results in a required

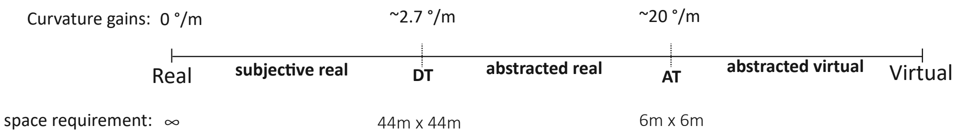

Figure 11.7: While using using curvature gains below the DT requires 44m x 44m (based on [45]), the AT allows to display a much higher gains and the room can be compressed to 6m x 6 m.

physical space of around 6m x 6m. The concept of curvature gains on the interaction continuum is illustrated in figure 11.7.

This project mainly targeted the research questions 3 and 4. On the one hand, the results of the comparison between DT and AT were in line with the results of my other projects. Again, much higher gains or manipulations than the DT could be applied. A doubling of the gain even showed no significant differences compared to no manipulation. The comparison of the subjective real implementation with the abstracted real implementation as shown in figure 11.7 also shows how much the expressiveness increased. But here again a maximum could be determined (RQ 4). However, the questions used turned out to be less target-oriented. The direct question about the acceptance correlated with every further question asked. A single question could therefore have been sufficient.

11.3.2.2 *An Abstracted Real Implementation of Redirected Walking for Room-scale Setups*

This section is based on the paper *Telewalk: Towards Free and Endless Walking in Room-Scale Virtual Reality* [R7]. Additionally, the proposed system is a further development of Martin Deubzer's Master thesis with the title *Telewalk: Towards a More Natural Locomotion in Virtual Reality.*

Since we found that redirected walking is not applicable in a room-scale setup only using curvature gains, I decided to combine them with two additional features. To apply redirected walking within a room-scale setup of 3m x 3m, a curvature gain of $38°/m$ is required, which is close to two times the AT we found in the prior experiment. The first additional feature was the use of perceivable translation gains. They let the user walk faster in the virtual world compared to the real world. Our goal was to reduce the stride length of a user, since a lower pace allows the use of higher

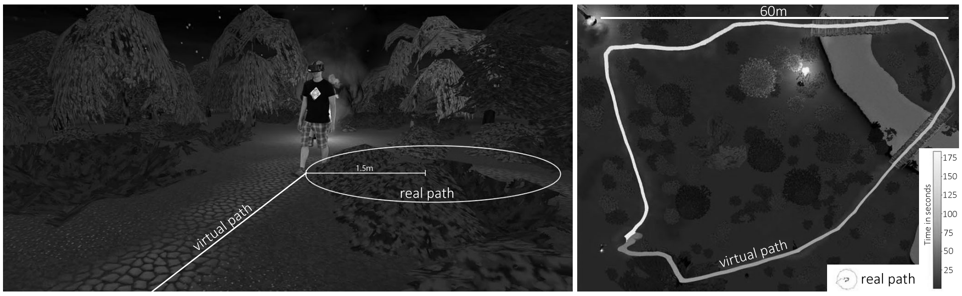

Figure 11.8: The concept of Telewalk: By applying perceptible curvature and translation gains, and by using the head rotation like a controller, the user is guided on a perfect circular path while freely walking through the virtual world. (Image taken from [R7])

curvature gains. The second feature aimed at solving the problem of directional changes. Prior implementations of redirected walking suggested to either use a steer-to-orbit or a steer-to-center approach, where the gains are dynamically adjusted to keep the user within a certain space even if they changes the direction of walking. To implement such an approach within a very limited physical spaces requires to dynamically adjust the gain within very short periods of time and with very high deviations. We found inconstant high gains to be confusing and inapplicable, since the user has to adjust to the new gains and their huge variances all of the time. We therefore implemented a novel virtual rule that should solve the problem of directional changes. In our implementation physical turns are substituted by rotating the head over a certain threshold. This way it is possible to change the direction of walking without actually physically turning. The concept of telewalk is illustrated in figure 11.8.

The combination of the described mechanism was a locomotion approach that is capable of predicting the exact walking path, which is always a perfect circle with a diameter that is depending on the applied curvature gains. In a user study we found that telewalk was a suitable navigation approach even on a physical space of 3m x 3m. Some participants though reported symptoms of motion sickness.

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DISCUSSION

As discussed, most works on interaction in VR strive to align the interaction as closely as possible with reality. Such an approach to reality has both advantages and disadvantages. On the one hand, there is a short familiarization period, as the interaction is already known and in many cases even commonplace which could be referred to as an inherent naturalness of interaction. What is already known from reality is most likely also considered natural. On the other hand, there are also potential disadvantages. In order to convey realistic feedback, a high technological effort is usually required (as shown in the example of the VaiR system for conveying feedback that is as realistic as possible). In addition, a closeness to reality often goes hand in hand with a higher reality coupling. The example of real walking in virtual worlds or the discreet abstraction through imperceptible gains in RDW leads, as discussed, to a high reality coupling and therefore to a potentially enormous space requirement.

Another possibility to realize interaction is the rarely used but in some areas widespread kind of virtual interaction (e.g. teleportation). This can give the user superpowers, can make the interaction more efficient and additionally lead to a strong reality decoupling. Nevertheless, such an interaction is often seen as a makeshift (e.g.: we cannot walk endlessly, so we teleport). This can also be seen in the lack of research on one of the most widespread navigation techniques in VR: teleportation. It is often used as a baseline for comparisons with alternative approaches. More often, statements are made such as that teleportation reduces spacial awareness or the feeling of being present. So far, however, to the best of my knowledge, it has never been considered how such interaction can be optimized to eliminate these problems. Therefore I argue, that this is a promising field of research.

The works presented in this thesis aim to strike a balance between virtual and real interactions. The four research questions presented in section 10 build on each other. Beginning with the fundamental question of whether feedback consciously deviating from reality is capable of increasing perceived realism, through the effect on the user, to the limits of such interaction approaches. Furthermore, the presented research questions aim at establishing the continuum for VR interaction presented in section 7. The abstracted real category is the middle ground of real and virtual interaction which is in focus for my work. In contrast to previous work, such an interaction is not intended to hide any manipulations from the user or to make the interaction as indistinguishable from reality as possible. In these approaches, conscious and noticeable deviations from reality can be integrated. Thereby the potential disadvantages of real interaction should be eliminated. The example of pseudo-haptic feedback shows that a potentially high technological effort for displaying kinesthetic feedback can be reduced. A higher reality decoupling on the other hand was achieved above all for the area of locomotion by looking at RDW beyond the detection threshold.

The research questions aim to establish the existence of such an interaction group.The first question aims to determine the general applicability of perceptible virtual rules. It shall be determined whether feedback deviating from reality or, as in the case of the presented project on slow motion in VR, unrealistic feedback in its basic features can nevertheless contribute to perceived realism. It was formulated as follows: **Is unrealistic feedback capable to increase the perceived realism of a virtual world.**

With the slow-motion application, indications were found that even unrealistic feedback can contribute to subjective realism. The findings of subsequent works in the fields of haptics and navigation, where unrealistic feedback was also used (such as the substitution of forward movements by rotations in the VRSpinning project, or the introduction of an offset force, which provides feedback on weight or resistance) support these insights. Therefore I claim that virtual rules can not only be used to enable interaction that would not be possible without them (like the just discussed example of teleportation), but can even contribute positively to the experience in the virtual world.

So far only the question has been considered whether unrealistic feedback can generally contribute to subjective perception of reality. The third hypothesis aimed at whether such abstract or unrealistic feedback is preferred to missing feedback. If one looks at today's VR applications which are bound to the current hardware, one notices above all in the area of haptics that corresponding feedback is usually not available: Hands that can glide through virtual objects because there is no resistance, or apparently heavy objects that can be lifted with ease are the result. The second research question, **is abstracted or unrealistic feedback preferred over no feedback?**, was mainly targeted in the project *Conveying the Perception of Kinesthetic Feedback using state-of-the-art hardware* [R4]. Here the presented offset forces were compared with exactly this missing feedback. As the results of the study suggest, the actually unrealistic forces lead to an increase in subjective realism. Further, the unrealistic feedback was preferred over missing feedback. In the case of the mentioned project on kinesthetic feedback such abstracted feedback was implemented without any additional hardware, but still lead to an increased feeling of presence and allowed the communication of directional forces. This circumstance also shows the potential power of such forms of interaction.

Corresponding results were also achieved for the navigation area. In the study of the VRSpinning project, preference was not asked, but the subjective assessment of increased feeling of vection as well as slightly reduced simulator sickness symptoms indicates that feedback deviating markedly from reality was preferred to no feedback (or in this case only visual motion feedback).

On the basis of these findings, the third research question could be formulated: **Can manipulations be utilized in a perceptible way to increase their expressiveness while maintaining or increasing the feeling of presence?** While for RQ1 mainly unrealistic feedback for an unrealistic situation was considered, for this hypothesis a more general assertion should be taken. The question is whether manipulations or illusions can be implemented perceptible and still be accepted by users.To answer this question, two studies were conducted in which detection and acceptance were directly compared. In the paper *Breaking the Tracking: Enabling Weight Perception Using Perceivable Tracking Offsets* [R3], the detection was measured using a 2AFC task and the acceptance was measured by directly asking participants whether they would accept such an offset in a VR application. The results strongly suggest that offsets far beyond detection can be applied. While offsets of around 3 cm were detected, offsets of up to 42cm were accepted and rated as *good* until around 28cm. In a second test, we compared the pseudo-haptic effect using perceptible offsets to the state-of-the-art of having no weight feedback. The results show that the feeling of presence not only remained the same but even increased when offsets were included into the interaction.

The second work where detection and acceptance were directly compared was presented in the paper *Rethinking Redirected Walking: On the Use of Curvature Gains Beyond Perceptual Limitations and Revisiting Bending Gains* [R5]. Again a 2AFC task was used to determine the DT and subjective ratings to determine the acceptance. While the calculated DT for curvature gains was found to be at around $5.2°/m$, participants accepted gains of more than $20°/m$. In the case of RDW, though only around $10°/m$ could be applied without lowering the remaining subjective ratings (e.g. naturalness or nausea) significantly. In summary, twice the DT still did not significantly decrease the experience and even around four times the DT was still accepted.

The last and fourth research question aims to define the area of the abstracted real area of the continuum more precisely and was stated as follows: **Is there a maximum regarding the strength of manipulations and if so, how can it be determined?** The starting point can be clearly defined as the detection of a deviation from reality or manipulation. The corresponding measurement methodology can be taken from the field of psychometric research and determined as DT of a corresponding function by 2AFC tests. The threshold for acceptance was already mentioned in the previous paragraph.

The measurement of acceptance is much more subjective than that of detection. This was also reflected in the measured results. In the tests in which the acceptance or applicability of an illusion was asked directly, there were huge variances between the test persons. In addition to this direct question, the work on RDW also asked for other subjective opinions, such as the feeling for nausea, disorientation, or how pleasant such a gain was perceived. It turned out that the answers to each of these questions correlated very strongly with the values of acceptance and also showed strong variances. Nevertheless, at least for most of the test persons there was a maximum at which they were no longer willing to use an interaction technique. There were however exceptions amongst the participants, such as one who participated in the study on pseudo-haptic weight. He testified that if he were to accept such offsets as a force to a small extent, he would also have to accept offsets of any magnitude. In his opinion, an object that was too heavy that he himself could not lift should also lead to offsets of any magnitude. However, I would argue that there is generally a maximum of deviation from reality as long as this interaction is based on real interaction. However, this maximum is very subjective and therefore very difficult to define universally for the whole population.

In terms of measuring this maximum, attempts have been made to identify it either through direct questions on acceptance or through related issues (as in the RDW example). In the future work part of the next chapter, suggestions are discussed on how a maximum could be calculated more precisely in the future.

Part V

CONCLUSION

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SUMMARY

There are many ways of realizing interaction in virtual reality. I have shown that different forms of interaction can be categorized and summarized on a continuum. I proposed to use the term of virtual and real rules to define how interaction is realized, while the relation of the influence of real to virtual rules on the interaction determines where an interaction technique is situated on the continuum. I further proposed the introduction of a second threshold (beside the level of detection: DT) being an acceptance threshold (AT). Given these two thresholds, an interaction technique can be objectively assigned to one of five categories on the interaction continuum. The introduction of the AT further proposes that interaction that is based on the way we interact with the real world may though differ strongly from the known way. This allows known interaction techniques to be viewed from a different angle. I showed that applying this novel metric to VR interaction offers new possibilities and that the expressiveness or effectiveness of input and output techniques can be enlarged.

The four research questions discussed in the previous part aim at this abstracted real interaction category. It was shown that even unrealistic feedback can contribute to subjectively perceived realism, that illusions can also be realized in a way which is noticeable by the user and that this can also have a positive influence on the feeling of presence. In addition, the existence of a maximum of this abstraction was discussed and found in the exemplary thematic fields, being kinesthetic feedback (using pseudo-haptics) and locomotion (with focus on redirected walking). I have shown that the expressiveness of pseudo-haptic feedback of e.g. displaying weight can be increased from a few grams to multiple kilo grams when taking the AT and not the DT as a reference. For redirected walking, I showed that even unlimited free walking within 3m x 3m is possible to realize under consideration of acceptance, while the level of detection requires more than 40m x 40m.

While these are examples for abstract real interactions, I also showed that it is possible to realize natural and realistic feedback without any reference to the real world. As an example, I chose the manipulation of time, since this included such unknown feedback. Interestingly, participants rated visually slowing down the own body movements as being more realistic than without. I therefore argue that there is a virtual counterpart of realistic that I call virtualistic. While we refer to realism in terms of behaviour that follows the known real world rules, I define virtualism as following understandable novel rules that a virtual reality defines. In case of the slow motion application, the virtual rule was that the body can only move until a defined maximum that is determined by the time flow. Since the participants perceived this rule as logic (the environment is slowed down and therefore the own body), the perceived realism was increased. Such interaction techniques that are fully decoupled from the real world are categorized under one of the two extrema of the continuum and are called virtual.

The *real* extremum on the other side of the proposed interaction continuum, was also aimed to be achieved. Since kinesthetic feedback also was implemented for this extrema by passive haptic feedback where real world objects equal to the virtually displayed ones are presented, I designed a feedback device to display airflow on the head region. The complex structure of the device including air stream based on pneumatic air pressure (which realized a very low latency compared to priorly used ventilators) as well as motorized rotating bows on which the nozzles were attached (to realize a higher resolution) aimed at providing respective feedback as realistic as possible. Although no DT was measured in this project, I suspect that the resulting feedback would still be distinguishable from reality. Therefore, it is also worth looking at other categories on the proposed interaction continuum.

The proposed interaction continuum consists of the already mentioned two extrema of real and virtual interaction and further defines two thresholds, one for detecting the difference between real and virtual and one for the maximum degree of abstraction a user will accept. This splits the continuum in three further parts (subjective real, abstracted real and abstracted virtual). Where an interaction technique is situated arises by the relation of real and virtual rules and their influence on the interaction. I defined real rules as behaviour that follows the real world way. In this case, redirected walking can be described by moving inside the virtual world by walking (which is the real rule) that further introduces one or more virtual rules, like curvature gains (when walking 1m, the world is rotated by x degrees). When x is kept very low, the virtual rule can be hidden from the user. The RDW approach can be categorized as subjective real, since the user cannot distinguish between real walking and redirected walking. I showed that virtual rules, though, can be realized beyond the level of detection, but until the acceptance threshold (AT) [R5]. The application of a higher curvature gain, which is recognized by users, leads to an abstracted real interaction.

Since the approaches described depend primarily on the way we interact in the real world (in this case walking), they are categorized as *real*, *subjectively real*, or *abstracted real*, all of which are summarized as reality-based interaction. If the main mechanism of an interaction technique is not grounded in a real world reference, the technique is classified as virtuality-based, which includes the categories abstracted virtual and virtual. Locomotion techniques such as arm swinging, mainly follow the virtual rule in which swinging with the arms leads to forward motion. Though, there are still references to the real world (each swing stands for a step and that the virtual character therefore moves forward with every step). Arm swinging is therefore considered to be a abstracted virtual locomotion approach.

But there are also approaches that have no references to the real world, like teleportation. Teleportation uses only virtual rules. To get from one place to another, a spot inside the virtual 3D space is selected and the teleportation is triggered (by e.g. pressing a button). The feedback, in this case, is also unrelated to the one we know from reality, since the target is reached without perceiving any visual or vestibular motion.

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DISCUSSION

I argue that there is no inherent rating of an interaction technique associated to the categorization on the continuum. Though, there are implications that have to be considered. Further, not every way interaction can be designed is suitable for every kind of application. The main contribution of the presented own works is the proposal of the AT which spans the category of abstracted real interaction. This implicates that abstracted real interactions can be designed more abstracted from the real interaction but have a certain maximum until when interaction should no longer be implemented following the respective real world rule.

14.1 ADVANTAGES AND DISADVANTAGES OF ABSTRACTING FROM REALITY

Most of the presented own works are categorized as abstracted real. Redirected walking as well as pseudo-haptic feedback were investigated under the assumption that the respective virtual rules and therefore the manipulation may be detected. I showed that such a view may enlarge the expressiveness and effectiveness of input and output techniques. Further, it may offer novel ways of interaction that is, though being far away from the real world way, still suitable and for some applications preferable. We often find a trade-off between limiting the real world or the virtual world. This is the cause of highly coupled realities (see section 6.1). For example, real walking requires either high demands on the physically available space or a restriction of the dimensions of the virtual world according to the available space. Therefore, either the physical space needs to be expanded in relation to the virtual requirements or the application has to be limited to match the physical space. The same could be stated for haptic feedback. Either the virtual world needs to be designed consisting of the same objects as the real world or vice versa. An alternative to such limitations is the inclusion of novel hardware that is capable of detaching real from virtual world while preserving the desired abilities. This could be for example haptic gloves or exo-skeletons to provide haptic feedback or the use of omni-directional treadmills to realize walking within a limited space. I call this process reality decoupling. As shown in figure 5.1, output devices may have the ability to transfer a real world stimulus to a virtual one (e.g. by excluding the real one and including a virtual one) and input devices may transfer an action intended to be applied in the virtual world to a likeness that is applied to the real world. The process of reality decoupling does not only include the transfer of one stimulus or action to another, but also the process of including feedback or output that is only present or applied inside the virtual world.

I argue, that there is a further way of reality decoupling that does not require additional or complex hardware. Illusions, as defined in section 5.3.3, can be used as subtle or perceptible virtual rules to manipulate and play with the human perception to deliver feedback that is not physically present. While having the disadvantage of less expressiveness when being designed too subtle, perceptible manipulations may at some point become inapplicable or not accepted anymore. On the other side, such illusions offer a whole new way of designing VR interaction, since in- and output can be decoupled from reality without necessarily requiring additional hardware. As showed, tracking offsets, for example, can be used to display directional forces.

But illusions also provide a way to overcome hardware limitations. The VR-Spinning project [R6], for example, aimed at providing motion feedback in any direction by just using a physical rotation. Even though such illusions may be perceived and recognized, they are still capable of enhancing feedback or in some cases even enable feedback where it would be otherwise not possible.

But abstracting in- and output from the way we know from reality also comes with certain drawbacks. Virtual rules are less intuitive when first being presented. The user has to learn how to interact in such a novel way and has to accustom to new and unknown feedback. A further drawback of such virtual rules is the abstraction from reality, which may in some cases be inapplicable. If the aim of a virtual reality application is of a simulation character, where for example actions should be trained, stronger deviations from reality are most likely inapplicable. Additionally, in some cases, high abstractions may also lead to unintended side effects like the symptoms of motion sickness some participants reported in the telewalk project.

14.2 IMPLICATIONS FOR DESIGNING VIRTUAL RULES

When novel rules that are distinct from the ones we know from reality are applied, these rules have to be learned. In such a case, the behaviour of the user as well as of the virtual world does no longer match the one we know from reality. Which interaction technique may or should be used therefore depends on several factors that are described in the following.

14.2.1 *Dependence on Domain*

The first important factor that has to be considered is the application domain. A simulation, for example, has a focus on the realism and should therefore consist of real or subjective real interactions and therefore only make use of subtle perceivable virtual rules. Gaming on the other hand is mostly focused on the experience or enjoyment the player has during playing. Realism may be contributing to this, but is not necessarily required. I therefore argue that each application has a different focus and therefore may and should consist of other interaction forms.

14.2.2 *Dependence on Application*

The application as well has an influence on the applicability of the interaction categories. The focus of an application may rely on the efficiency a user may solve tasks or on the engagement of a user interacting within the VR application, or it may just be enjoying the virtual content. Virtuality-based interactions in general may make interaction much more efficient than their reality-based counterparts. Locomotion is a great example for this. While walking allows for intuitive and realistic navigation, teleportation is much faster and allows to get from one place to another without great effort. The same can be stated for haptic feedback. It may be more efficient if there is no kinesthetic feedback, since every object can be moved without any exertion. Though it may not truly engage the user if even heaviest objects can be lifted without any exertion.

14.2.3 *Dependence on Physical Restrictions*

It also depends on the physical capabilities how interaction can be realized. Depending on which physical characteristics are available, the interaction can and must be designed accordingly. Be it the available space, the hardware or objects which can be used as passive haptic feedback. For the example of in- and output devices, kinesthetic feedback provided by an exo-skeleton would be preferable in many cases, but the availability of such devices is limited. The same applies for VR navigation. While it would be preferred to walk within a virtual world without any manipulation (or at least without perceiving it), the available physical space is seldom sufficient to be implemented.

14.2.4 *Dependence on User*

As a last important factor I would like to discuss the importance of subjectivity on the design of VR interaction. The more abstract and differing from what is known from reality an interaction is designed, the more subjective is the rating on how pleasant or applicable the interaction technique is. As an example, the Telewalk locomotion approach which utilized very high RDW gains and introduced a camera controller that does not rely on physical turns, but on rotating the head, was rated very distinct. The best example of such ratings was which technique the participants preferred (Telewalk or Teleport). In the respective user study one half of the participants preferred Telewalk and the other half preferred Teleportation. This may also be interpreted as a subjectiveness of the AT. Given the textual feedback of the participants, the reasons are quite similar to those stated in the *dependence on application* section. While some participants wanted to be as efficient as possible or were just too lazy to walk, other enjoyed the limitless walking.

As long as it is possible, I therefore suggest to include different implementations of the same interaction and let the user chose which one to use.

15

FUTURE WORK

15.1 DEFINING AND DETERMINING THE ACCEPTANCE THRESHOLD

In my works, I used several questions to determine the AT. Until now, there is no evaluated and standardized approach on how to measure acceptance. I most of all used a single item question that directly asked whether such a manipulation is accepted or whether the participant could imagine using such a technique in a VR application.

Further research could be done on standardizing the AT and its measurement and provide a unified and validated approach or questionnaire to determine this subjective score. One suggestion to this is the use of a similar approach as for the DT. A two-alternative forced-choice task could be used with the direct question about the acceptance with the answer option yes or no. The result would be a probability of acceptance. The maximum of the resulting curve could be interpreted as optimum, while a certain probability (which could be chosen in line with the level of detection as 75%) could be defined as AT.

As an alternative, I suggest to apply usability questionnaires to determine the AT. The system usability scale (SUS) [168], for example, is a standardized and validated questionnaire to measure a system's subjective usability. It consists of ten Likert scale questions such as "*I think that I would like to use this system frequently*" or "*I felt very confident using the system.*" I argue that a usability metric is an enrichment of knowledge, especially for an abstract real or virtuality-based interaction. Even if metrics like presence can (and in many cases should) be used here, usability questions can also be used to determine whether an interaction technique is efficient, easy to use or easy to learn.

15.2 INFLUENCE OF TIME ON THE AT

As already discussed, virtual rules have to be learned because a user does not know them from interaction in the real world. I regarded the influence of time for curvature gains when comparing the first and the second iteration of presenting a gain. The results suggest that a user indeed gets accustomed to higher gains. But this was only a short period of time that was regarded. A long term study could investigate how the adoption to novel rules changes the way a user interacts with virtual rules and how this changes the ratings of a certain interaction technique. It could also be of interest to investigate whether virtual rules override the knowledge of real rules that were already learned. If a user gets accustomed to walking faster in the virtual world compared to the real one, does they for example rate a one to one match of the velocity as unnatural after a certain amount of time?

15.3 A STRONGER FOCUS ON VIRTUALITY-BASED INTERACTION

As a last point I would like to motivate the topic of virtuality-based interaction. As the example of teleportation shows, even reality unrelated interactions may become a natural and accepted part of VR. I would argue, that virtuality-based interactions are by now only used when there is no reality-based alternative. Though, I think that such interaction techniques could be of great use for many VR applications. VR is not only about simulating the real world and to mimic the real world as close as possible. VR is capable of creating a new world with novel rules to be experienced without the limitations of the real world. Furthermore, I claim that even in the real world there is an effort to expand the human senses as well as the motor system (augmented human). Such human augmentations can easily be implemented inside a virtual world by just redefining the way a user interacts in a virtual world or by the way the virtual world behaves. Prior works have already shown that virtuality-based interactions may outperform their reality-based counterparts regarding their efficiency [23, 36, 133].

A

APPENDIX

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DECLARATION

Ich versichere hiermit, dass ich die Arbeit selbständig angefertigt habe und keine anderen als die angegebenen Quellen und Hilfsmittel benutzt sowie die wörtlich oder inhaltlich übernommenen Stellen als solche kenntlich gemacht und die zur Zeit gültige Satzung der Universität Ulm zur Sicherung guter wissenschaftlicher Praxis beachtet habe (§ 8 Abs. 1 Nr. 5 Rahmenpromotionsordnung).

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Ulm, 04.02.2019

Michael Rietzler

VaiR: Simulating 3D Airflows in Virtual Reality

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VaiR: Simulating 3D Airflows in Virtual Reality

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ABSTRACT

The integration of multi-sensory stimuli, e.g. haptic airflow, in virtual reality (VR) has become an important topic of VR research and proved to enhance the feeling of presence. VaiR focuses on an accurate and realistic airflow simulation that goes far beyond wind. While previous works on the topic of airflow in VR are restricted to wind, while focusing on the feeling of presence, there is to the best of our knowledge no work considering the conceptual background or on the various application areas. Our pneumatic prototype emits short and long term flows with a minimum delay and is able to animate wind sources in 3D space around the user's head. To get insights on how airflow can be used in VR and how such a device should be designed, we arranged focus groups and discussed the topic. Based on the gathered knowledge, we developed a prototype which proved to increase presence, as well as enjoyment and realism, while not disturbing the VR experience.

ACM Classification Keywords

H.5.2. User Interfaces: Haptic I/O; H.5.2. User Interfaces: Prototyping

Author Keywords

Virtual reality; airflow; presence; evaluation.

INTRODUCTION

Enhancing presence and immersion is one of the major goals of Virtual Reality (VR) research. The sense of *being there* [7] both occurs and can be supported in three dimensions: the personal, the environmental and the social forms of presence. The main focus of this paper is to enhance the personal feeling of presence. This can be achieved by simulating sensory stimuli as close as possible to the capability of a sensor regarding range and intensity. Appealing multiple senses amplifies the feeling of presence and immersion in VR applications [3, 6]. Besides the inherent integration of visual and audio [9, 13] in most VR systems, a large body of work exists to include further channels in the VR experience. Those channels include haptics [1, 19], warmth [4, 5] and smell [21, 20]. Regarding haptics, integration can be applied in different ways. In this paper, we focus on enriching haptics by simulating airflow accompanying visual and audio content.

Figure 1. The VaiR Prototype worn in combination with a HTC Vive head mounted display. Fixed to frame mounted onto the Vive's straps are two bows. These bows are moved by two separate motors, allowing both bows to each rotate 135°. Fixes on each bow are five nozzles (each 36° apart), were the air streams come out. Several nozzles can be used at the same time. Due to the modular design, nozzles can be moved along the bows and changed as needed. That way, angle and dispersion of the air streams can be customized. VaiR is so designed that a container of pressurized air, valves, power source and an arduino controller can be worn as a backpack.

Though simulating airflow, most of all in the form of wind, in VR has been researched in the past, little work regarding the conceptual side has been done. To fill this gap in knowledge, we conducted a series of three focus groups with participants of various VR literacy. In those focus groups we explored how, where, and in which situations air streams could be leveraged to enrich VR experiences. The discussions showed that airflow simulation can go far beyond the simulation of wind, reaching from realistic effects to unrealistic superpowers for gaming. Many desired applications need to be applied with less delay

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as possible and have to be precise or even animated in the three dimensional space.

The results of the focus groups led to the design of a prototype wearable on ones head. The proposed prototype, as shown in Figure 1, can easily be combined with current head mounted displays. It also allows three dimensional airflow simulation with a reaction time of less then 20 milliseconds until stimulus. Air streams are pneumatically generated, allowing a maximum air speed of around 25km/h. The advantages of using pneumatics translate in the size and weight of the prototype as well as the reaction time and maximum air speed that can be applied to the user. Prior systems either used a static wearable or a completely stationary approach, which both restricts the accurate animation of wind sources and do not support temporary effects like gusts due to too much delay.

The short reaction time of VaiR also offers new possibilities of staging a VR experience, since the duration of applied air pressure and its intensity is variable and responds within milliseconds to changes. This allows to use VaiR as both, an effect channel to directly support visual or auditive stimuli (e.g. the blast of an explosion), as well as a tool to simulate more steady conditions (e.g. wind at a coast). The movable bows on which the nozzles are mounted can rotate in angles of 270 degree of freedom, which can be e.g. used to follow animations of objects, like a helicopter flying over the user's head.

In a user study we analyzed how presence and enjoyment were affected by incorporating the wind models in four scenarios involving wind resulting form users' movements, static wind sources, a combination of both and air streams underlining certain effects. Our results on one hand support the results of prior works showing an increase of presence using airflow in VR. On the other side we could show that enjoyment is influenced even more.

The contributions of this paper can be summarized as conceptual, technical and empirical. First, the results of the focus groups provide conceptual insights in how diverse user groups could benefit from airflow simulation in VR. Second, the proposed prototype is the first mobile pneumatic airflow simulator designed for VR. We also introduce new features, including rotatable bows and short reaction times. And third, our empirical study, which showed how wind can enhance presence and enjoyment, including four different scenarios using different airflow sources and features.

RELATED WORK

There are several ways of generating air streams. The related work follows two major approaches: static sources placed around users, and systems mounted on users' head.

Static Sources

Deligiannidis et al. [2] used a stationary fan in front of the user to simulate the airflow of driving a scooter while traveling through a large scale virtual environment. They observed an increase of immersion when using the wind simulation. Moon et al. [16] presented WindCube, a wind display for VR applications. They used multiple fans placed in the users' surrounding to provide a three-dimensional wind experience. In their evaluation, participants could not distinguish wind sources having less gap than 45°. They also report a significant increase of subjective presence using wind.

Verlinden et al. [18] built a virtual sailing environment using eight static fans. Their evaluation results show an improved immersion when using wind. Participants suggested several improvements to the system, including higher airflow disparity, higher wind resolution, and reduction of noise. Pluijms et al. [17] used the same simulator to measure how good humans can distinguish different directions and strengths. The participants were expert sailors as well as non-sailors. Their results indicate, that the direction can be recognized more precise for frontal wind directions than for wind from behind. Wind was also perceived faster when impinged frontally.

Kulkarni et al. [12] enhanced a VR-cave with a very accurate wind simulation using vortices of airflow and applied a similar approach to their TreadPort Active Wind Tunnel (TPAWT) [11]. The TPAWT integrated locomotion interfaces as well as other sensory outputs like visual, auditory or olfactory. The design of the TPAWT allows each fan to produce a distributed full-body experience, similar to real wind.

Hüllsmann et al. [8] enhanced a cave by adding fans and lamps to simulate wind and warmth. Both influenced the subjective presence of participants. They also state a reaction time of their setup with around 3.1 seconds when turned on and 1.3 seconds when turned off.

Our prototype differs from the above mentioned work in three ways: First, we use pneumatic wind generation, leading to far less delay (below 2 ms). Second, our prototype is designed for mobile use. And third, through the movable bows our prototype allows more variable wind positions and even animations of wind wind sources.

Head Mounted Sources

Kojima et al. [10] described a wearable helmet that consists of four audio speakers that produce wind that is forwarded by tubes towards the user's ears, the region they found to be most sensitive. This wearable approach reduces the reaction times. They also state, that the region around the ear has a high spatial resolution of perception which would lead to a large number of wind sources. They evaluated the precision of wind localization of four participants, which indicated higher precision close to the ear.

Lehmann et al. [14] proposed both a stationary and a wearable approach of producing wind. Both approaches were implemented using two fans. As stated in other related work, the wind had in both cases a positive impact on presence. Yet, participants preferred the mobile over the stationary set-up.

Related work has proved, that a mobile wearable device can be build and is preferred by participants. Though there are no results on the implications and effects on immersive VR.

FOCUS GROUPS: ON THE USE OF AIRFLOW IN VR

We were interested in the potential knowhow on how to design airflow in VR. Especially since using air streams was regarded more as a technical challenge in prior work, we aimed at getting insights on potential application and use cases but also on technical requirements. Thus, we conducted a series of three focus groups, each consisting of participants from the VR user groups VR consumers, VR developers and VR researchers. In each focus group, we asked participants what potential they saw in airstreams in VR, which scenarios they imagined, and how such a device should be designed and implemented. Afterwards, the prototype was presented to each focus group. In an open discussion, the aforementioned topics regarding design and implementation as well as usage scenarios were revisited.

Participants

Participants were recruited through flyers and personal contact. For the VR consumer group, we recruited 5 participants. The average age was 23.8 years (2.45 SD), participants were students of computer science. VR consumers are mostly users of VR, without having developed VR applications. VR developers were participants who developed VR applications for at least a year on a regular basis, for examples games, without researching VR as such. We recruited 4 developers, with an average age of 26.5 (3.1 SD). The respective group included developers with focus on serious games, driving simulation and storytelling. Researching VR as such was a criterion for participants in the VR researcher group. Here, we recruited 5 participants (four of them HCI and one psychologist), at average 29.6 (7.23 SD) years old. All participants gave consent and received 5 €compensation. Each focus group took about one hour.

Results

The recordings of the focus groups were transcribed verbatim. Subsequently, three researchers performed an open coding on the transcript of the first focus groups (VR consumers). The codes were compared, conflicts were resolved with discussions and revisiting of the transcript. Following, the other two focus groups were coded in the same way. If agreed upon, codes from the first focus group were used, if not, new codes were created. Conflicts were solved through discussion and revisitation of transcripts. This way, we gained a codebook applicable to all three focus groups. Based on the initial codes, axial coding was performed to find themes and concepts. Namely, we identified the three categories: requirements, applications and experiences.

Requirements

Modelling the wind concerns either how wind should be rendered, but also how practitioners wished to be able to include it in their applications. Regarding the rendering of wind, it should be as realistic as possible, including dynamic aspects like gusts, precision, direction changes and reaction time. Developers expressed the need for a simple interface, preferably integratable in existing developing environments, and design guidelines covering how to provide the best experience.

Applications

Participants saw wide ranges of applications for wind in VR. Those applications ranged from realistic ones to unrealistic ones. Application areas covered entertainment, simulation, and feedback. In case of applications falling in the entertainment area, participants liked both realistic and unrealistic air stream simulations. Realistic rendering of air streams could amplify events, examples mentioned by developers include pressure resulting from explosions as well as weather conditions. Unrealistic air streams could be leveraged as representations of super powers in games, or represent energy states of players. Air streams were further regarded useful when guiding users attentions, e.g. to make them aware of risks or points of interest, or to render elements were users could not see them, e.g. the breath of a monster behind a player. Generally, air streams were seen useful in games, to raise the experience.

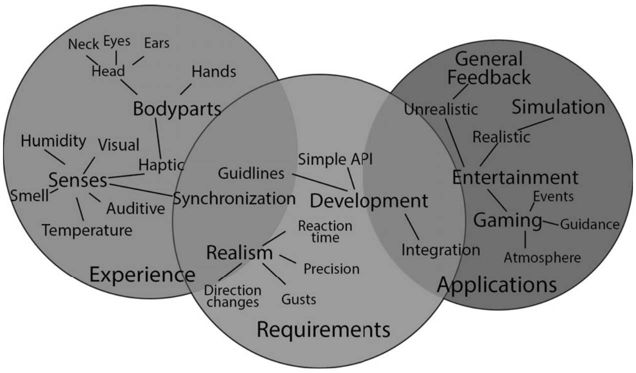

Figure 2. Overview of the focus group results.

Participants found air streams useful for enriching different simulations, covering simulations of environments like cliffs, seas, and deserts. Air streams could also be useful in sales simulations. Other types of simulations used air streams to underline the users movements, e.g. while riding a bicycle, driving in a convertible, riding a roller coaster or flying. Further, air streams were seen as useful for giving haptic feedback to users, e.g. for guiding users or simulating barriers as mentioned by one of the developers.

Experience of wind

Regarding the experience, focus group participants were concerned with the body part air streams are perceived most with as well as the synchronization with other channels. Regarding the body parts, most important were hands and head, were people usually do not wear cloths and thus feel real air streams more. Furthermore, head regions were of particular interest to participants. They explicitly mentioned several regions (neck, eye region, ears) of interest, since they were either important for certain use cases or seen as particularly sensitive for air streams. Additional to the region air streams were applied on, it was seen as important to synchronize them with other channels. Those channels covered especially audio, but also visual. During the discussion, other not yet implemented modalities like temperature, smell and humidity came up and were discussed by researchers and developers. Those were seen as closely linked with air streams, and could enrich and complete the experience even further. Examples for this included simulation of environments, like hot dry air in deserts, and humid and salty air at coasts. The researcher group also discussed

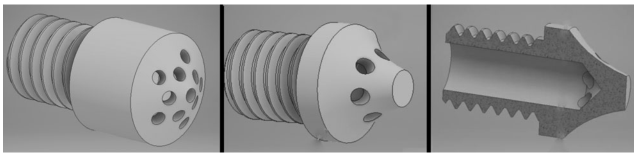

Figure 3. Examples of different nozzles to vary spray angle and intensity.

the potential problem of wearing VR glasses that mask large parts of the face. They suggested to use visual cues like a virtual character wearing glasses to enhance the experience. The same could also be done if the hands were not stimulated by airflow by having the character wearing gloves.

IMPLEMENTATION

The prototype consists of two main technical components, one being the head mount, and the second being a backpack including the logic board and valves to control the system. The software consists of two parts, a Unity plug-in that translates positions, angles and intensities into the the VaiR coordinate system and streams the respective data to the logic board (either via Bluetooth 4.0 Low Energy, or using the serial port). The prototype can therefore be used for sitting as well as mobile VR experiences.

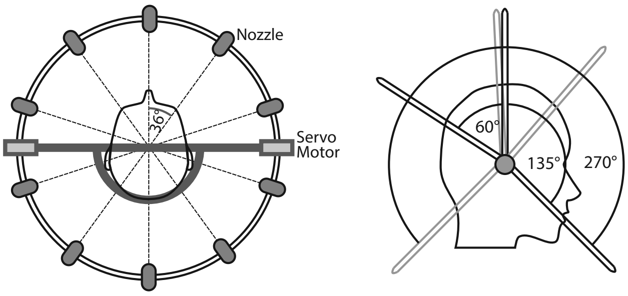

Figure 4. The VaiR setup: Two bows with nozzles having a angular distance of 36° and two servo motors to control the angle of each bow seperately (left). Each bow can be rotated 135°, overall 270° around the user's head and neck can be displayed (right).

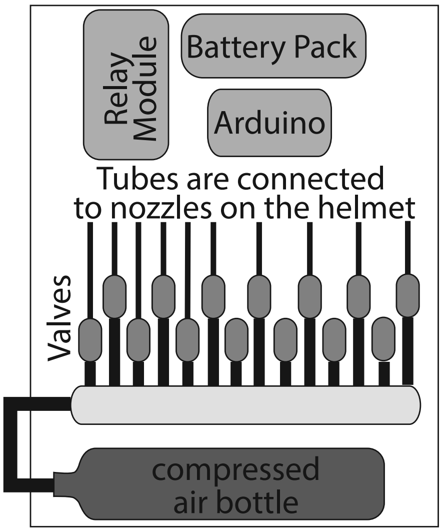

Figure 5. The Backpack consists of a compressed air bottle and 14 valves (ten for the nozzles, and four to vary the intensity) as well as the control unit.

Technical setup

Participants of the focus groups as well as related work suggest, that the region being most important for airflow application is the head region. Considering other found requirements like synchronization, fast reaction time and the possibility of simulating non constant airflow finally led to the desing of our pneumatic head mounted device. The use of fans, which have to be turned on and off takes too long would not meet the defined temporal requirements. To reduce the weight of the prototype, the setup mounted on the head was reduced to a minimum, consisting of two bows (each having 5 nozzles with an angular distance of 36°). We decided to use an angular distance of 36° instead of the proposed 45° since the latter would lead to a single nozzle pointing towards the ears. Since literature and related work emphasizes the importance of the ears for directional perception, the 36° arrangement enables to stimulate the ear region with nozzles per ear. We also designed a variety of nozzles with different spray angles as well as a different amount and diameter of holes. The different nozzles could be used to simulate different airflow sources. In our testing a triangular shape provided the best area to intensity ratio, which was important since hair blocked a fair amount of the wind intensity. The nozzles are mounted on the bows with a custom printed holder using threads to allow quick swapping for testing and to fit into the idea of a modular design. Some examples are shown in figure 3. The bows are rotated by two servo motors. To mount the setup on the user's head, a retainer which connects the components is located in the middle of the setup (see figure 4). The control unit is worn as a backpack for mobile scenarios, or can be placed anywhere within the user's reach. A Redbearlab Blend, a development board with BLE 4.0 support for mobile was chosen as central processing unit. The board controls the motors rotating the bows, as well as 14 valves, ten applied to the tubes attached to the nozzles on the bows and four as exhaust air valves to vary the pressure and therefore the air speed at the nozzles. The pressure of a maximum of 2 bar can be induced by e.g. compressed air bottles. The VaiR helmet is lightweight with around 766 g (compared to around 600 g of an HTC Vive), while the backpack currently weights about 4 kg. The current prototype consists of two heavy PVC sheets on which the electronics and valves are applied. The weights could though be reduced by using more lightweight components and by using valve blocks instead of single valves. The helmet's measures were kept as close as possible to a user's head wearing current VR glasses, which lead to a diameter of around 21 cm. The backpack currently measures 40 cm x 25 cm x 15 cm, but could be designed much smaller in a second iteration.

Unity3D Plug-In

The Unity3D plug-in consists of various airflow sources (static sources, effect sources and sources modeling the airflow of a moving user). A source can be configured by a set of attributes. These are e.g. the speed or the intensity of the modelled gusts, as well as the horizontal or vertical angles and a maximum distance.

Static sources can be used to model airflow of long term sources, which can be wind, a ventilator or a helicopter. Effect sources are triggered and the effect lasts for a defined time frame and are used as (repeated) short term sources, e.g. for firing a gun or support game effects like an explosion. All attributes can be staged by using scripts or animations.

For the calculation of the entry angle of airflow, the 3D coordinate system is split in two – a horizontal and a vertical angle. On hardware side, the horizontal angle is represented by the nozzles and the vertical one by the angle of the bows. The angular distance of the nozzles is 36°. Defining the origin of a nozzle as angle zero, each nozzle is used to simulate a source within an angular distance of $\pm 18°$. The horizontal entry angle is calculated by using the position of the source (P_S) and the position of the user (P_U) as well as the user's viewing direction as a quaternion (Q_U. The entry vector (V_E) and the horizontal and vertical angles (A_H, A_V) are calculated as follows:

$$V_E = Q_U^{-1} \cdot (P_U - P_S) \tag{1}$$

$$A_H = \arccos(\begin{bmatrix}0\\1\end{bmatrix} \cdot \begin{bmatrix}V_E.x\\V_E.z\end{bmatrix}) \cdot \frac{180}{\pi} \tag{2}$$

$$A_V = \arccos(\begin{bmatrix}0\\1\end{bmatrix} \cdot \begin{bmatrix}V_E.y\\V_E.z\end{bmatrix}) \cdot \frac{180}{\pi} \tag{3}$$

The horizontal angle is then mapped to the matching nozzle, and the vertical one is translated into the bow's coordinate system. If the speed is influenced by the distance, the loss of speed is interpreted as a linear mapping of distance to speed until reaching zero. Since the user will have to wear VR glasses, parts of the face are occluded and therefore no longer able to feel the stimulation of airflow. We therefore left out the respective angles. The bows keep resting on top of the glasses or below, depending on the calculated angle.

Design Space and applications

The short reaction time as well as the rotatable bows – allowing animated airflow sources as well as a 3D experience –, as well as the strong maximal wind speed of around 25 km/h makes the VaiR system suitable for a variety of applications and opens a large design space.

Static sources, like a global wind, that can be staged more realistic by simulating gusts, while even strong wind of over 25 km/h can be displayed. But also non static sources, like a rotatable ventilator can be simulated, by changing vertical angles by rotating the bows, or by changing horizontal angles by using different nozzles. A helicopter may fly over the user's head, where the gust property can be used to simulate turbulences of the rotor blades and the position of the helicopter is represented by the bow angles and the used nozzles.

Besides such sources which involve longer durations, it is also possible to apply short term effects. While playing a shooter for example, short blasts can support the feeling of shooting a gun, or simulate the shock wave of an explosion.

Since the VaiR system enables the simulation of two independent sources at a time, it is also possible to stage an experience with multiple effects, or a constant source with additional effects using short term blasts. When wearing the backpack, it is also possible to have a mobile experience using e.g. the HTC Vive.

EVALUATION

Since the main focus of the VaiR prototype is to enhance the feeling of presence and the enjoyment while consuming VR content, we focused our evaluation on these two factors. We developed four different Unity scenes, each of them having a focus on a different kind of airflow source. To exclude side effects which could arise by a user interacting in a different way, we decided to design the conditions passive only, with the user taking part as observer. This design ensured on one hand that the sequence of events was determined and equal for each participant and on the other hand excluded side effects on presence and enjoyment which could occur due to different behavior.

Participants

Overall 24 participants (20 male and four female, aged 20 to 36 – mean: 26) took part in our evaluation. Each of them was compensated with 10 €. We asked them to describe their previous experience with virtual reality on a five point Likert scale (from 0: no experience to 5: very experienced). The answers were evenly distributed with a mean of 2.7 and a standard deviation of around 1.5. There were as many novice VR users as experienced ones.

Scenes

We developed four different Unity3D scenes that allowed the participants to passively consume the VR content, without any distracting interactions. All scenes are shown in figure 6 and 7.

The first scene takes the participants to a cliff at the seaside. While standing right in front of the edge, the user can turn around facing the sea, where a static wind source is placed, which is simulating wind that blows from across the sea. The wind is modelled using weak gusts and an average wind speed of around 20 km/h. When turning one's back to the sea, a landscape with trees waving in the wind and small hills is presented.

In the second scene, the participants find themselves sitting in a fun ride in a fair scenario. The camera is placed in a cabin attached on the end of a rotating arm. The cabin, and therefore the participant's orientation was always horizontal to prevent sickness. The direction of the wind varied according to the cabin's movement, which was a circular one. The wind speed also varied according to the movement speed, with a maximum of around 25 km/h.

The third scene is staged in a windy and foggy area. The viewer sits in a golf cart, driving through the area. There are two different wind sources that can be felt at the same time. The first being the airstream of the moving cart blows in the inverse driving direction, while the second one is a static wind source located far behind the cart, on the right side. The far

Figure 6. The first and second scene used for the evaluation. a) The cliff scene looking towards the sea and b) view when turned around. c) The fair scene regarded from outside and d) the first person view. e) The golf cart scene from first person view.

Figure 7. The third and fourth scene used for the evaluation. a) The cart scene in first person view. b) The horror scene: bats flying over the head, c) a rotating saw runs through the viewer's neck and d) a Zombie appears.

distance allows the simulation of wind, with a constant global wind direction – independent of the actual position of the cart.

The last scene was the most complex one and most of all is based on the ideas gathered in the focus groups. The participants reported many use cases of airflow as an effect source and mentioned different examples in horror scenarios, like bats flying over the user's head, or non visual experiences including audio and airflow.
The scene starts at a foggy and gloomy place, with a wooden hut in the distance. There is a constant wind source blowing from behind, while a second wind source is used as an effect channel, supporting events. The first event is a group of bats flying from behind over the users head. The effect wind source starts behind the user and moves until coming from front. To simulate the strokes of the wings, this source has a high gust intensity. The wind therefore varies in speed and angle over time. The second event is a kind of zombie that comes closer in large steps, when he arrives directly in front of the user, a short and strong wind is applied to support the shocking moment. Then the virtual camera *runs* towards the hut. The movement is again supported by air stream, while the static wind source still blows from behind. When entering the hut, the visual image turns to black. Only the audio of a monster breathing from behind can be heard – and felt, since every breath is supported by airflow. The last event occurs, when the lights turn on again and a giant saw is rotating in front of the camera, which can be felt by a gusty airflow source. The saw starts moving directly under the camera, simulating to get the head cut off while the wind source of the saw moves towards the user's throat.

As discussed in the focus groups, potential application areas can be found in entertainment (realistic and unrealistic) or simulations. Two of the chosen scenes were discussed in the focus groups. First of all the cliff, as an example of an environmental simulation. The second discussed one was the horror scene, which is also an example of an unrealistic entertainment application. We furthermore wanted to cover different sources of airflow as discussed in the focus groups. External sources and ones induced by personal movements were both covered in the presented scenes. Since the fair covered the movements and the cliff scene the external one, the golf cart scene was chosen as combination of both, containing external wind as well as user's movements.

Method

We used a within subjects design, in which each participant was subjected to eight different treatments (four different scenes, either with the simulation of airflow or without). The sequence of the eight treatments was determined by a Latin Square to balance effects of adaption. To measure presence and engagement we used the E^2I questionnaire [15] without the items concerning the memory task, since they are not relevant for the presented conditions. The E^2I questionnaire has a separate presence and enjoyment score. While the presence score is determined by eight items, the enjoyment is the mean of four sub-scores.

Procedure

Each participant was welcomed and introduced to the subject of the evaluation and the procedure. Then the prototype was shown and the basic functionality described. After this, the participants signed a declaration of consent regarding the usage of the gathered information for scientific purposes and were then asked to complete a demographic questionnaire, including the items *age, gender* and *VR experience*. Afterwards, the participants were helped putting on the VaiR helmet, earphones and a Oculus Rift DK 2 as VR headset and started with the first treatment. Each sequence lasted for about 1.5 minutes. The participants completed the E^2I questionnaire after each condition until the end of the procedure. Finally, each participant filled out a final questionnaire, consisting of information regarding general interest in airflow simulation in VR, and how much each scene was influenced by the use of airflow. Each session lasted for about 40 minutes and the participants were thanked and compensated with 10 €.

Results

The results presented in the next sections are based on the questionnaire results raised as described.

Presence and Enjoyment

The E^2I Questionnaire includes eight items regarding the presence. We excluded two of them, since one is focused on a memory task, and a second, that compares two different systems. The presence score is calculated by the mean of all related items, while the distraction factor is inverted. The treatment using the VaiR helmet proved to have a significant positive impact on the felt presence of the participants (Wilcoxon signed-rank test: Z=-2.362, p<.05).

To calculate the enjoyment score, the mean of four different items is used. It consists of questions like how sad the participant felt when the experience was over, how much he enjoyed it, if he wanted to repeat it and how interesting it was. There was a significant increase of enjoyment using the wind treatment (Wilcoxon signed-rank test: Z=-5.518, p<.05). Interestingly, the mean improvements regarding enjoyment were much larger then the improvements of the presence score. When comparing each scenes separately to the respective control condition without VaiR the increase of enjoyment remained significant on the 5% level using the Wilcoxon signed-rank test (cart: Z= -2.858, cliff: Z = -3.698, fair:Z = -2.393, horror: Z= -1.770).

In a next step we regarded the difference between the scenes – by comparing all the control conditions and the VaiR conditions separately. Where the presence was not significantly different on the 5 % level (p = .075) without VaiR treatment, we observed significant differences when VaiR was used (p = .009) using the Friedman two way analysis of variance by ranks. We could find the difference between the horror scene compared to all others using a Bonferroni post-hoc test. We could find the increase of presence being highest in the horror scene, while the other scenes did not differ.

We could not observe any significant differences between the scenes regarding enjoyment. Since we assumed, that the increase of presence would also lead to an increase of enjoyment, we took a closer look on the horror scene and found a great variance regarding the perceived enjoyment between the users in the VaiR condition. While some rated the enjoyment as three times as high as without, there were participants stating only half the enjoyment. We assume that the high variance arised by the different affinity towards horror in general which will be considered in more detail in the *Discussion* section.

Distraction and Realism

We also regarded four items related to the subjective feeling of realism of the VR experience separately. Since the simulation of airflow is designed to increase the level of felt realism while consuming VR content, we compared the mean of the four sub-scores with and without VaiR. Again, the treatment with airflow simulation increased the perceived realism significantly (Wilcoxon signed-rank test: Z=-2.967, p<.05)

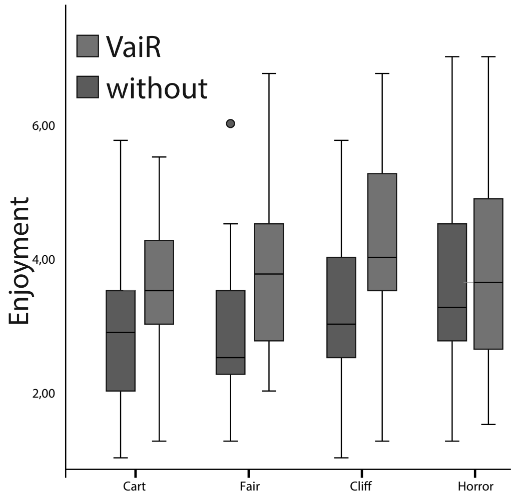

Figure 8. The results of the enjoyment scores per scene.

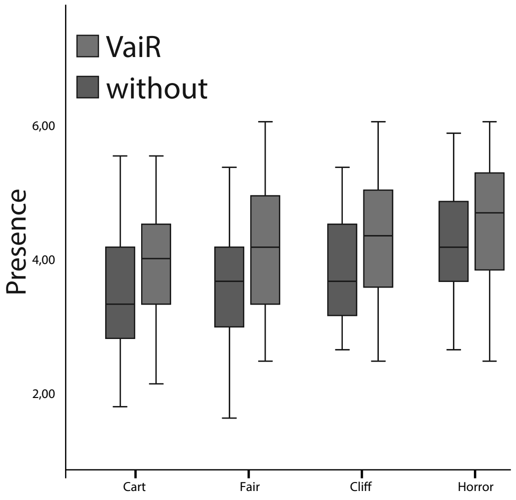

Figure 9. The results of the presence scores per scene.

The VaiR system is placed on the participant's head. This could lead to distractions when the bows move or the nozzles (being close to the ears) be heard. We therefore compared the distractions felt by the participants when using VaiR and when not. The E^2I questionnaire contains one item regarding the perceived distractions from outside VR. There could not be found any significant changes regarding the influence of VaiR on the perceived distractions (Wilcoxon signed-rank test: Z=-0.468, p>.05, mean (airflow) 2.89 vs 2.79 (no airflow)).

Participants preferences

At the end of the session, we asked the participants to complete one last questionnaire which contained more general questions regarding the consume of VR content with or without the proposed system. Only 2 of the 24 participants stated to prefer VR without VaiR, the same participants stated that they do not want to consume VR with any simulation of airflow at all. We also asked the participants if they had in general a stronger

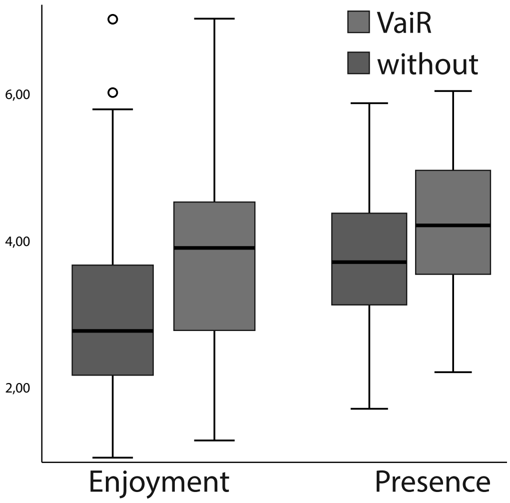

Figure 10. The results of the E^{2}I presence and enjoyment scores.

feeling of being there while using VaiR, which was confirmed by all participants, except the two mentioned ones.

Discussion

Our results on one side confirm the results of previous works on the simulation of airflow in virtual reality to increase the felt presence. In addition, we could show that there is an even higher impact on the enjoyment while consuming VR content. We assume that enjoyment as well as presence could even influenced more in interactive gaming situations, when airflow events are related to an action.

Each scene was significantly enjoyed more when consumed with the simulation of airflow. While we could not find any significant differences between the respective scenes, except for the horror scene, presence and enjoyment increased for each scene when using VaiR. The horror scene was rated very controversial – most of all in the VaiR condition. While there was a very strong effect regarding the presence when compared to the other scenes, we could not find a significant effect for enjoyment. Since some participants stated, that the horror scene was too exciting and that the airflow simulation involved them even more in the scene (which was not perceived as positive for these participants), we assume, that the overall experience was very high in the horror scene, which was perceived as either very positive, or as negative – depending on the personal affection to horror.

Since the increase of perceived presence and enjoyment was highest in the horror and the fair scene, we assume that the fast reaction time and the possibility of simulating airflow in 3D had an high impact, since the respective scenes most of all used the named features.

Though VaiR is head-mounted and having nozzles close to the user's head, there were no additional distractions from outside VR.

Overall, 22 of the 24 participants would like to use VaiR in the context of VR, while the remaining two participants stated to prefer no airflow simulation at all.

CONCLUSION

In this paper we presented VaiR, a pneumatic head-mounted, mobile prototype design for the enhancement of presence and enjoyment in virtual reality (VR) by allowing precise animations of airflow in real-time. The conceptual insights of three different focus groups (including developers, users and researchers in the field of VR) were used for the design of our prototype and provided deep insights about the potential applications of airflow simulation in VR.

The developed pneumatic prototype allows the simulation of various effects, ranging from static wind over fully animated, moving object like a helicopter, to short term effects (e.g. shock wave of an explosion) in real-time. The prototype can display two independent sources simultaneously, which allows the staging VR experiences using e.g. static sources and an additional effect channel.

The insights of the focus groups, as well as some findings of related work suggest a mobile set-up. Our head-mounted system is low weighted and has a fast reaction time of under 2 ms between the raised event and the felt actuation. The two independent rotating bows additionally support mobility by not only reacting on animated airflow sources, but on user's virtual orientation.

We could confirm results of previous experiments, which showed that the treatment with wind enhances presence and could further show, that also the felt realism and most of all enjoyment is strongly influenced by airflow. Our findings strongly underline the great potential of three dimensional real-time airflow application.

We plan to further enhance the experience by the simulation of warmth by preheating the airflow and by adding olfactory cues to the air. It is also planned to test the effects in a mobile gaming scenario.

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The Matrix Has You: Realizing Slow Motion in Full-Body Virtual Reality

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The Matrix Has You

Realizing Slow Motion in Full-Body Virtual Reality

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ABSTRACT

While we perceive time as a constant factor in the real world, it can be manipulated in media. Being quite easy for linear media, this is used for various aspects of storytelling e.g., by applying slow motion in movies or TV. Interactive media like VR however poses additional challenges, because user interaction speed is independent from media speed. While it is still possible to change the speed of the environment, for interaction it is also necessary to deal with the emerging speed mismatch, e.g., by slowing down visual feedback of user movements. In this paper, we explore the possibility of such manipulations of visual cues, with the goal of enabling the use of slow motion also in immersive interactive media like VR. We conducted a user study to investigate the impact of limiting angular velocity of a virtual character in first person view in VR. Our findings show that it is possible to use slow motion in VR while maintaining the same levels of presence, enjoyment and susceptibility to motion sickness, while users adjust to the maximum speed quickly. Moreover, our results also show an impact of slowing down user movements on their time estimations.

CCS CONCEPTS

• **Human-centered computing → Virtual reality**;

KEYWORDS

virtual reality; slow motion; time perception; evaluation.

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1 INTRODUCTION

Nowadays, manipulation of time is commonly used as a stylistic device in traditional linear media like movies and television, and to a certain degree also in games, as for replay scenes. The purpose of such manipulations ranges from storytelling aspects (often by imitating common human temporal illusions), to more analytic functions like slow motion replay in sports coverage. Speeding up or slowing down time is easy to implement in such media, given the fact that the events are not subject to user interactions, but unfolding linearly in front of the user who is merely a spectator. In interactive media, however, using time manipulation is much more difficult, as such a manipulation needs to target not only the media time, but also perceived time of the user, as the user's interaction speed does not necessarily change with a speed change in media. This is less of a problem with weakly-immersive media like games played on a traditional PC screen, because interactions occur indirectly, with feedback occurring separated from user input. However, in fully immersive scenarios like VR, where real-world body movements are often represented in the virtual world normally in real-time, time manipulation (e.g., by slowing down auditory and visual events in the environment) inevitably leads to a conflict between the close-coupled feedback which represents users real movements, and the desirable effect of time manipulation, to the point where aspects like realism or the level of immersion might be influenced negatively.

In this paper, we focus on the question of how time in interactive virtual realities still can be manipulated (e.g., for storytelling purposes or as an element of game play), in a way which not only aims to alter the actual time perception of the user, but also preserves or improves the user's level of presence and enjoyment. To address this challenges, we focus on methods to cover the perceptional mismatch between the user's visual sense and the proprioceptive sense, which allows humans to know their posture and movement in space without relying on their visual sense. By using several visual redirection techniques, we build on previous work (e.g., [Azmandian et al. 2016]), which exploits limits of the visual human sense in the spatial domain to enable interactions with real-world objects. Based on this work, our goal is to expand this approach into the temporal domain.

For this, we built a system that is able to manipulate two cues which are important for time perception. The first ones are environmental cues. These can be the visual speed of objects, or auditory cues, like playback speed and pitch. These cues are independent of the user and interactions, and their manipulation is well-known from linear media and also easily recognizable for the user. On top of this, we developed different cues for manipulating the users body and limb movement speed in VR as second indicator for slow motion. Both concepts were systematically evaluatedn in a user study with 16 participants.

Our results show that the presented approach and algorithms for visual redirection is an appropriate method for applying slow motion to user movements. While increasing enjoyment, no decrease of presence could be observed. In addition, our results show that

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manipulating the perceived movements significantly influenced user's time estimation, while manipulating only environmental cues did not show any effect. Besides this, we provide insights regarding more general aspects like simulator sickness and the visual perception of a redirected body in VR.

2 RELATED WORK

Time perception is a complex process, having no physical representation, but taking place solely in the human brain. Humans have senses for visual or auditory information, but no dedicated sensory organ for time. Our perception of time is most of all influenced by an internal imaginary clock that creates a sense of time out of a variety of other senses. Therefore, the perceived time may vary, e.g., depending on a task, since we have to count the "ticks", which is harder when being more distracted. These features may influence our time perception retrospectively, but not in the present. There is no situation in the real world where we perceive slow motion. Instead, it can be assumed that popular representations of slow motion are learned e.g., from depictions in media. Following out of this, there also exists no baseline of realism for manipulating time.

2.1 Human Time Perception

The perception of time is based on intervals, while it is hard to define what the concept of *now* really is. The perceived reality is a sampled interpretation of our visual, auditory and other senses. While the single senses are processed using different temporal resolutions, our brain needs to sample this information to a unified perception [Brockman 2009].

Slow motion itself is an imaginary, mostly learned concept, something never experienced in the real world. The only baseline arises out of linear media like movies. There, slow motion usually leads to visual aspects like increased motion blur and slower movements.

There are, however, some well-known aspects of basic time perception – mostly out of the domain of psychology and physiology. Humans may retrospectively estimate time as being shorter or longer than it really was. These differences in time estimation can arise through emotional states [Angrilli et al. 1997] (e.g., like awe [Rudd et al. 2012] or fear [Fayolle et al. 2014]), or even by space (e.g the Kappa effect [Cohen et al. 1953]).

2.2 Time Perception related to Gaming and Virtual Reality

Wood et al. [Wood et al. 2007] collected quantitative as well as qualitative data of 280 gamers through an online survey. They found that the perception of time is often lost while playing. This circumstance is most of all influenced by the complexity, missions, multi-player interaction and plot of the game. The loss of time was perceived as both, positive (relax and escape from reality) and negative (e.g., feeling of wasted time).

Tobin et al. [Tobin et al. 2010] compared retrospective and prospective time estimates while playing. They could confirm that prospective time estimates are longer than retrospective ones. Comparing different durations, they observed, that 35 minute and 58 minute retrospective estimates were significantly lower than 12 minute estimates. They also provide information indicating that gamers might have problems with time estimations while playing, resulting in inaccuracies of estimations.

There is also work on time perception in the context of VR. Bruder et al. [Bruder and Steinicke 2014] compared time perception while walking in VR and in the real world. Participants were able to estimate the time very accurately in the real world. There were only slight changes compared to the VR condition.

Schatzschneider and Bruder [Schatzschneider et al. 2016] analyzed the impact of a natural and unnatural movement of the virtual sun on time estimations. They compared immersive VR using an Oculus Rift, to a non-immersive setup using monitors. In addition, the participants were either involved in a cognitive task, or not. While not involved, participants overestimated duration, while slightly underestimated duration in conditions, where cognitive tasks had to be solved. Participants estimated duration as a little longer if no movement of the sun was displayed. Changing the speed of the sun did not significantly influence time perception.

2.3 Redirecting Movements in Virtual Reality

Since the real-world visual sense is fully overridden due to the use of VR glasses, it has been proven possible to also override the real-world body pose, orientation or movement by divergent visual information to a certain degree, thus rendering the proprioceptive sense less important [Azmandian et al. 2016; Kohli 2010]. Though, such techniques have a maximum threshold of manipulation, before users are able to perceive the manipulation.

3 SLOW MOTION IN INTERACTIVE VR

To enable the use of slow motion, e.g., as an additional tool for storytelling, different aspects need to be considered. As there exist no known direct means of altering time perception for humans, a direct manipulation of time also in VR seems impossible at a first glance. Furthermore, on a more basic level, humans even lack the experience of a manipulated temporal flow in reality at all (as time is experienced as linear and constant), meaning there is also no real reference for quantifying the result of attempts to manipulate time perception.

However, it is possible to manipulate various aspects of stimuli which are presumably used by the human brain to determine how time is passing, e.g., the speed of certain environmental changes over time, like movement or sound frequency. For both of those stimuli, humans have learned over the course of their life which relative speed is to be considered natural or "real-time". Our basic assumption for this work is that with increasing immersion and presence, the manipulation of such aspects thus leads to an altered perception of time, which in turn can be exploited for enabling slow motion in VR.

The main challenge with this approach however lies in the (at the first sight) contradicting requirements to maintain high levels of presence and immersion, while also manipulating parameters which are contributing to presence and immersion themselves. This especially applies to the mapping of bodily movements in the real world onto a virtual body in VR. One might assume that the more precise this mapping occurs, the higher levels of presence and immersion can be reached and maintained. However, for enabling slow motion, this mapping needs to be modified, as the human movement speed outside of the VR cannot be altered or limited without applying mechanical limiting devices. In contrast, it is however fairly easy to modify the position or maximum velocity of virtual limbs, a fact which we exploit for implementing redirection strategies.

Since this work is to the best of our knowledge the first to address the topic of active time manipulation in VR, we established several hypotheses, touching basics as well as practical issues, which are described in the following sections.

3.1 Relative Perception of Time

As it is difficult to get a hold on the absolute time perception of a user, in this work we focus on determining differences in relative time perception as an indicator of slow motion perception. Specifically, we aim to influence the relation between the perceived absolute time that passed compared to the actual absolute time that passed for a given scenario. This dimensionless ratio is further on called the *time quotient*. We hypothesize that this relation is being influenced by manipulating the *playback speed* of the virtual scene (with a speed of 1.0 being real-time), both considering the environment as well as interactions and movements, with the latter being a stronger influence factor.

3.2 User Interaction Behaviour

As there is no reference in the real world for experiencing a change in time flow, it is hard to guess how users react when dealing with such an effect. Furthermore, the actual implementation of this effect may also influence the reaction. We hypothesize that when visually restricting the movement speed in the virtual space, the user will also adapt to this change rather quickly in the real world by slowing down his movements accordingly. By sensibly designing the actual redirection of movements and choosing the right parameters for this mechanism, this should also be possible to achieve without a loss of control or realism.

3.3 Presence, Enjoyment and Simulator Sickness

Besides the actual effects listed above, which directly influence the feasibility of VR slow motion as a means of enhancing interactive storytelling, we also focus on more generic parameters of VR experiences like presence, enjoyment and simulator sickness. For slow motion to be a usable tool in VR, it is desirable that, by carefully designing the slow motion metaphors and redirection, those parameters at least stay at the same levels despite the obvious deviation between real world and virtual world. If slow motion is perceived as an appropriate additional means of storytelling, at least the values for enjoyment may even increase.

4 IMPLEMENTATION

To test our assumptions, we developed two different visual redirection techniques to enable slow motion in virtual reality, which are described in the following section. Both have in common that they slow down the movements of the user's virtual character and its limbs by a given amount, however using slightly different approaches when doing so. The approaches can be compared to a low pass filter applied on the angular velocity of the user's joints connected by a kinematic chain, a graph like system connecting the human joints by bones.

All of those joints have a defined rotation in 3D space, which is represented as quaternions in our system. Due to the kinematic chain, rotation of a joint leads to changes in position of all descendant joints. The way how exactly the velocity of the real human body joints is transferred to the virtual characters' joints greatly affects the type of slow motion effect that can be achieved.

4.1 Developing Slow Motion Movements

The idea behind our implementation was to use an algorithm that does not only slow down the user by just delaying movements, since such an approach could be interpreted as some kind of malfunction or lag. We therefore decided to design the approach in a way which is always reacting to the user's movements without any delay. A first idea was to compute the current direction and velocity of movement and keep the direction while decreasing the velocity if it is reaching the maximum. The problem of such an approach is that the virtual pose keeps separating from the real one and the arising mismatch between real and virtual pose accumulates over time, without ever synchronizing again.

We therefore decided to design our low pass approach to adapt to the current pose while only decreasing the velocity if necessary. This way, there is still a smooth virtual experience without delay. If a user adapts to the maximal angular velocity there is even no difference between real and virtual movements.

In addition to the described simple low pass, we implemented a second low pass approach where the maximal angular velocity is no longer a constant factor, but depending on the current velocity. The faster a user moves, the lower the maximal velocity. This approach should force the user to move slower, since moving too fast would lead to very slow virtual movements. This approach is further on called *restricted low pass*. An additional feature of the restricted low pass is, that while not moving, the virtual character stops moving as well. In the simple low pass condition, the virtual character moves at maximum velocity as long as the virtual and real poses match.

The last factor we tested was the whether users would like to get visually informed about their real pose. Therefore, we included a third condition that slowed the movements down by the simple low pass, but additionally showed a transparent body that always followed the real-world pose instantly.

4.2 Simple Low Pass

The first approach is implemented by applying a low pass filter on the angular velocity between a joint's angle of the tracked user $Q(t)$ and the similar joint's angle of the virtual character $Q(c)$ (which still is the one of the last frame). Using this kind of representation, the virtual body moves as fast as possible, with the current pose of the user as a reference. The virtual pose is slowly adapting the real one if the user moves too fast. The used equations are as follows:

$$\Delta Q(t) = (Q(t)^{-1} \cdot Q(c)) \cdot \Delta t \tag{1}$$

$$Q_t(c) = (\Delta Q(t) \cdot Q_{t-1}(c)) \tag{2}$$

In equation 1, we calculate the angular velocity per second ($\Delta Q(t)$) which is interpolated according to the maximal allowed angular velocity (see section *Threshold Estimation*). Equation 2 then applies the interpolated rotation to the character joint's last orientation. The rotation of a bone is directly influenced by the prior bone defined by a kinematic chain, a graph which defines the connection (bones) of skeletal joints in a hierarchy. We start our low pass at the center of the body and process each branch of the kinematic chain's graph until the leafs considering the prior rotations. The index j stands for the current joint, while $j - 1$ is the previous joint in the kinematic chain.

$$Q_t(u_j) = (Q_{t-1}(u_{j-1})^{-1} \cdot Q_t(u_{j-1})) \cdot Q_t(u_j) \tag{3}$$

4.3 Restricted Low Pass

The second approach is similar to the previous approach and is called a *restricted low pass*. While all calculations are done according to the regular low pass, an additional restriction regarding the angular velocity is applied. The calculated $\Delta Q(u)$ is no longer depending only on the maximum allowed velocity, but also on the current velocity of the user. The current velocity of a bone is divided by the threshold and applied to a non-linear function, which maps the quotient to a scale factor, which is 1 for movements slower than the threshold and slowly decreases to 0 when moving faster. Using this approach, the user should be able to control the virtual angular velocity better by actually forcing slower motions. While it is possible to see the virtual character move while not moving in reality using the simple low pass condition, the user has to move the respective bone to change the visual representation of posture with this approach. As long as the user's angular velocity is below the defined maximum, the character moves in real-time. When the user moves faster, the virtual character actually moves slower.

4.4 Low Pass with Forecast

The last feature we tested was showing the participant the adapted pose based on the slowed down movements, but the real pose as well, illustrated by a semi-transparent second body (see figure 1). When visually slowing down movements, the virtual body no longer follows the real movements which could lead to confusions or a loss of the feeling of body ownership and therefore to a decrease of presence. We therefore decided to use a third slow motion condition to get insights about whether users want to get feedback of their real-world movements. Since the virtual pose always adapted to the real pose with the maximal angular velocity, the transparent body which followed the movements in real-time can also be interpreted as forecast of virtual movements.

4.5 Pilot Test and Threshold Estimation

We conducted pilot tests with two initial participants to estimate thresholds for the maximal angular velocities for slow motion in VR. They performed the same test as described in the *study* section under real-time conditions. The measured mean angular velocities were used to determine the velocity thresholds, which were calculated as the mean angular velocity multiplied by 0.4 (the same time scale as the visual and auditory environmental cues). The threshold was determined for upper-body parts (around 60°/s) and lower-body parts (around 45°/s) separately.

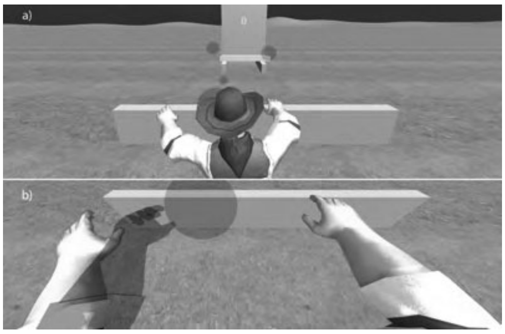

Figure 1: a) Overview of the scene. b) First person view of the transparent forecast metaphor.

5 STUDY DESIGN

Overall we used the three slow motion conditions: *simple low pass*, *restricted low pass* and *low pass with forecast* (each played with playback speed 0.4). Additionally, we tested a real-time condition without slowing down environmental cues nor the body movements. As a second ground truth, we also tested a condition where the virtual speed was in slow motion (playback speed 0.4) but without changing the character's movements. In this condition, the participants experienced slow motion only by environmental cues and were able to move as fast as they wanted.

In typical gaming scenarios, it is unlikely to experience slow motion at all times. Since one aim of the presented evaluation was on the playing experience, we tested each of the slow motion conditions two times, one with constant slow motion and one alternating real-time and slow motion multiple times during the tests.

We therefore tested eight conditions in total (the three slow motion conditions two times, plus the two ground truths). The sequence of conditions was determined by a latin square to compensate for learning effects in the analysis.

5.1 Method

We measured two experience related scores, presence and enjoyment, using the E^2I questionnaire [Lin et al. 2002] without memory task items after each condition. Since we slowed down movements, we also used the SSQ [Kennedy et al. 1993] questionnaire to test if simulator sickness is increased by our redirection approaches.

To analyze the movements of the participants, we also logged the angular velocity over time per joint. This data was used to get insights on how participants adapt their movements to the slow motion considering the different conditions.

To gain insights about the perceived control over the virtual body and realism, we asked participants to use a scale from *1 (not at all)* to *7 (absolutely)* to answer the following questions: *I was in control over my virtual body*, *I could predict the movements of the virtual character*, *The experience was realistic*, and *I would like to have such an experience in VR*. In addition, the participants should give an estimation of how long (in seconds) they had been playing. Both the questions and the estimation were asked for after each condition.

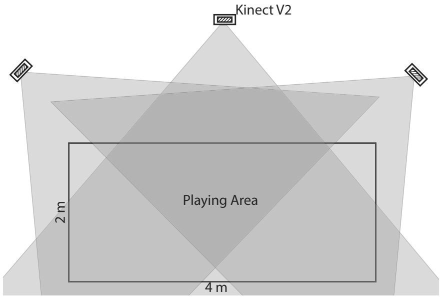

Figure 2: Top view of the playing area including Kinect positions.

After playing all conditions, an additional free text questionnaire was used to get qualitative insights on how the slow motion felt and what participants liked or disliked.

5.2 Participants

16 participants took part in our study (5 female; age 22 - 36 (mean 27)). Each participant was compensated with 5 Euro. We also asked each participant to describe their prior experience on VR on a five point Likert scale (from *1 none* to *5 very experienced*). Three participants had no prior VR experience, four stated the maximum of 5 (mean 3.7, standard deviation 1.4).

5.3 Setup

For tracking the movements, we used the FusionKit [Rietzler et al. 2016], a software designed for the fusion of multiple Kinect V2 sensors to enlarge the tracking space and optimize the accuracy compared to a single Kinect setup. The fused skeletal data was streamed via UDP to a mobile Unity3D application. A Unity3D application converted the skeletal data to its own coordinate system and transforms them to match a virtual character's bone angles. The virtual camera was applied to the head of the character, to allow a first person experience. We used a multi-Kinect setup with three Kinects placed in front of the user (see figure 2). Since the task did not involve turning around, the frontal tracking was sufficient. For the HMD hardware, we used a GearVR and a Samsung Galaxy S6, which was connected via WiFi to a master computer which handled the fusion of the Kinect data. We initially measured the delay between the FusionKit server and time of retrieval on the Smartphone, which was in mean below 3ms with a maximum of 10ms. The application was running at around 50 - 60 fps.

5.4 Task

We developed a game, where users had to hit bubbles that were flying towards the user within a limited area. The trajectories of the flying bubbles was chosen randomly within the area. Since the users could hit the bubbles with the whole body and the active playing area was large enough to force the user to walk within the tracking space, the task involved movements of all body parts as well as relocation of the user. We provided visual and auditory feedback about the playback speed. Visual feedback of the virtual playback speed was provided by the speed of the bubbles and the speed of falling raindrops. Auditory feedback included the sound of the rainfall, as well as the bursting sound when hitting a bubble, which were played slower and with less pitch during slow motion. The visual and auditory design of the scene was kept simple to leave the focus on the task and motions. We also wanted to include as less distracting factors as possible to reduce possible perceptual side effects. The scene (without effects) is shown in figure 1.

At the start of each condition, a training phase of 10 seconds was included, to let the participants get used to the current condition. The task started after the training phase.

While the participants were told to be able to influence the time of playing by hitting the targets, the duration was always limited to 70 seconds for all conditions. This time is given in real-time and not depending on the playback speed. This procedure was chosen to allow for a comparison between the perceived absolute time of playing and actual absolute one. Since the participants should not be influenced regarding their time estimation, they were not informed about any duration, including the duration of the training phase.

As stated above, a total of eight conditions was tested (listed here with the playback speed v and the type of movement redirection approach that was applied):

- *Control real-time*: Real-time (v = 1.0), no movement redirection
- *Control slow motion*: Permanent slow motion (v = 0.4), no movement redirection
- *Permanent low pass*: Permanent slow motion (v = 0.4), simple low pass movement redirection
- *Permanent forecast*: Permanent slow motion (v = 0.4), simple low pass movement redirection, w/ forecast
- *Permanent restricted low-pass*: slow motion (v = 0.4), restricted low-pass movement redirection
- *Alternating low pass*: Alternating slow motion (v = 0.4 ⊕ 1.0), simple low pass movement redirection
- *Alternating forecast*: Alternating slow motion (v = 0.4 ⊕ 1.0), simple low pass movement redirection, w/ forecast
- *Alternating restricted low-pass*: Alternating slow motion (v = 0.4 ⊕ 1.0), restricted low pass movement redirection

5.5 Procedure

Each participant was welcomed and informed about the topic of the study – the simulation of slow motion in VR. After this introduction, the participants signed a declaration of consent and a demographic questionnaire. The participants then played each condition in the order determined by a latin square. After each condition, the participants filled in the three questionnaires (E^2I, the SSQ and our own questionnaire). After the last condition, the participants filled in the final questionnaire, including free text questions. Each session lasted for about 45 minutes.

6 RESULTS

The presentation of the results is split in three categories. The first is about time perception, containing the results about time estimations. The second one contains the results of the recorded movements. The last category handles the results of the playing experience related items and questionnaires.

6.1 Impact on Time Perception

In the first part of our analysis we concentrate on how time perception and estimation was influenced by slow motion in general. These results were gained from the estimations given by the participants during the trials. All shown results are based on the *permanent* conditions, since the effect of alternating the playback speed is not predictable.

Comparing the Control Conditions: To be able to quantify the influence of environmental visual and auditory cues on the relation between estimated and real-time of playing, we first compared the two control conditions without any modifications of user movements, but only altered speed of environmental cues. We divided the estimated time by the real-time of playing (time quotient). Therefore, the estimate of 1.0 indicates a correct estimation, while e.g., 0.5 is an estimate of half the real-time of playing. Using the Wilcoxon signed-rank test for dependent variables we compared the medians of all of the participant's accuracy of time estimations. There was no significant difference between the two control conditions (p = .82).

Time Quotient in Redirected Slow Motion Conditions: We then ran the same comparison for the redirected, permanent slow motion conditions to both control conditions respectively, first using a Friedman *Two-Way Analysis of Variance by Ranks for dependent variables*. Here the difference was significant on the 5% level (see also figure 3). Since there was a significant difference, we also compared each slow motion condition with each control condition adjusting significance values by the Bonferroni correction. We could find significant ($p < .05$) differences between the low pass (*Median* 0.84) and the real-time control condition (*Median* 1.09) and between control condition 2 (*Median* 1.07) and all permanent redirected slow motion conditions.

In slow motion conditions including visual redirection, the participants judged the absolute time of playing about 25% less than in the real-time condition. This effect is likely caused by slowing down the movements since the comparison of the control groups showed that only slowing down visual and auditory cues did not have any significant effect. As shown in figure 3, there was a large standard deviation regarding the time estimations with *SD*=0.53 in the simple low pass condition, and *SD*=0.91 in the restricted low pass condition. Since even the real-time control condition had a large standard deviation of *SD*=0.67, we assume that it was difficult for participants to estimate the absolute duration in general at least during our tests.

Absolute Perceived Playback Speed: We also analyzed the relation of perceived playback speed to actual playback speed. When comparing perceived speed of the slow motion control condition to the redirected slow motion conditions, we found no significant differences ($p > .05$). This indicates that slowing down motions does not influence the perception of playback speed (see figure 3). When comparing slow motion conditions to the real-time conditions the results turned out as expected, since the slow motion effects could not be overlooked. Moreover, the participants were also able to estimate the absolute playback speed very well (real-time: 0.95 instead of 1.0, mean slow motion: ~0.47 instead of 0.4) – an extent of absolute precision we found to be interesting in itself.

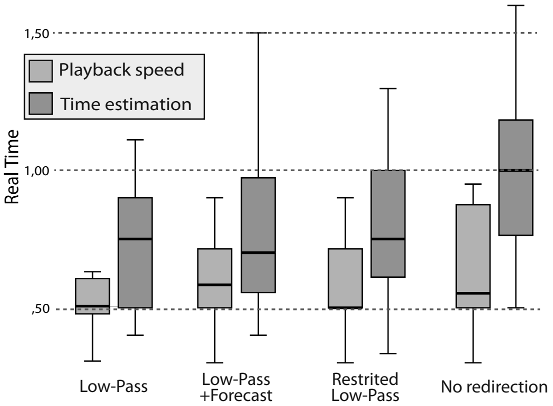

Figure 3: Box plots of the time quotient and perceived playback speed of the *permanent* conditions as well as the slow motion control condition (no redirection), each divided by the participants real-time control condition.

6.2 Movement

We also analyzed the movement data as logged during the trials, to gain insights on if and how users adjusted their body movements during the experiments.

Overall Adaptation of Movement Speed: We hypothesized that the participants would adapt their movement speed to the visually sensed maximum. We therefore analyzed the angular velocities over time of the fastest moving joint (which was in our tests the right elbow) since we assumed that this joint would mirror adaptions of speed in the best way. We compared the medians using an ANOVA and Tukey post-hoc tests. Interestingly, there was no significant difference between the simple and the restricted low pass condition (Means: 57°/s vs 62°/s, *SD*: 41 vs 42, $p > .05$). Considering the visual angular threshold of 60°/s for the wrist joints, users adapted their movement speed very precisely to the maximum.

In the real-time condition, the mean velocity was around 127°/s (*SD* = 175), while the slow motion control condition's mean was at around 125°/s (*SD* = 152). So there were no remarkable difference regarding the velocity of movements when only slowing down the playback speed without redirecting the movements.

Speed Group Distribution: To get further insights on how the participants moved in slow motion conditions, we normalized the angular velocities to five discrete groups. The categorization was done per participant considering the mean velocity and its standard deviation in the real-time condition. The first category was defined as *rest* which had the only constant threshold of 5°/s. *Slow movements* were defined as movements faster than rest and slower than *regular movements*, which started by the mean velocity minus half a standard deviation. *Fast movements* were defined as movements faster than the mean velocity plus half a standard deviation. Very fast movements, which we most of all considered to be *reactionary*

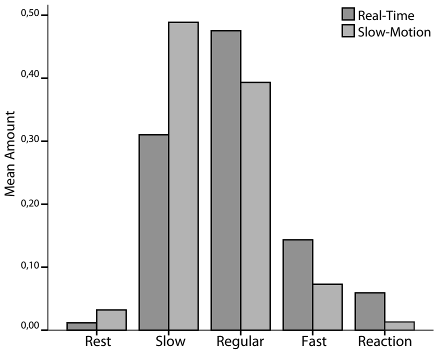

Figure 4: Distribution of the movement styles in real-time and slow motion.

actions, were defined as movements faster than the mean plus two times the standard deviation. The results (see figure 4) show, that the amount of slow movements in the slow motion conditions strongly increased, while most of all reactionary and fast actions were reduced. There was also little more resting in slow motion conditions, which could arise from the reduced speed of bubbles in the respective conditions. Since only little more resting periods could be measured, we assume that participants did not just move fast until the position they desired and rested, but truly adapted their velocity.

Adaptation rate: We also analyzed the times until a participant adapted to slow motion or real-time when alternated. Since there is no such definition of adaption, we defined a participant to have adapted to the condition at the time, when the mean velocity of the following 1.5 seconds was less or equal to the mean velocity of the same slow motion approach in the respective non-alternating conditions plus a tolerance of 5%. We excluded transitions, where a user was already moving slow before the time changed. The adaption time from real-time to slow motion was fastest using the restricted low pass (around 0.29s), followed by the restricted forecast condition (0.39ms). Using the simple low pass approach, the adaption took around 0.51ms. Though the reaction times differed using restrictions or the visual forecast, they did have a significant influence on the adaption time ($p < .05$ using Wilcoxon signed rank test). The adaption time from slow motion to real-time was equal for the restrictive and the simple low pass (around 0.5s), while it took significantly longer in the forecast condition (around 1s, $p < .05$ using Wilcoxon signed rank test). This leads to the conclusion that adaption of movement speed is a fast process, with the participants being faster when adapting to slow motion than to real-time velocities. An example of mean velocities sampled to 0.5 second steps is shown in figure 5.

6.3 Experience

After each condition, the participants filled the E^2I questionnaire and an own one containing items about the visually perceived movements (control, realism, predictability). The participants' answers were compared using the Friedman Two-Way Analysis of Variance by Ranks.

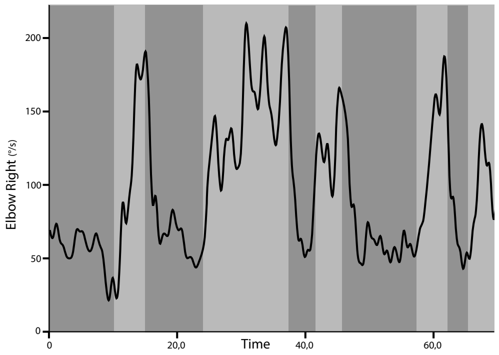

Figure 5: Average movement speed over time in the low pass alternating condition with time changes. (darker areas: slow motion)

Realism: There was a significant difference ($p < 0.05$) regarding the judged degree of realism between all conditions. We therefore compared the three slow motion conditions to the real-time control condition, where no difference could be found ($p = .863$). The restricted slow motion movements were perceived as realistic as the ones in real-time. The only significant change could be found for the *alternating simple low pass w/ forecast* condition, which proved to be perceived as significantly more realistic.

Control: Regarding the perceived control of movements, there was no significant change between control conditions and all slow motion conditions. The only significant change of perceived control could be observed in the restricted low pass condition, where the participants perceived a loss of control. Box plots of the results are shown in figure 6.

Predictability: Further, we analyzed the participants' answers to the question if the movements were predictable using the Friedman analysis. No difference could be observed between the conditions.

We observed that with the restricted low pass condition, which "forced" a user to move slowly, by decreasing the visual velocity when the real velocity increased over a threshold, answers turned out to be more controversial than within the other conditions. The standard deviation shows that there were participants which preferred this kind of redirection, while others rated it worst in all scores. We therefore took a closer look on correlations between how a user moved and how he rated realism and control of the virtual body in this condition. Though not significant, there were negative correlations regarding the strength of acceleration and the felt control ($p = .062$, $\rho = -.478$), predictability ($p = .118$, $\rho = -.406$) and realism ($p = .096$, $\rho = -.430$). Similar tendencies could be observed for the velocity. We thus assume that this condition only was enjoyable for participants fully accepting the slow motion by adapting their real-world movement speed.

Presence: Comparing all conditions using the Friedman Two-Way Analysis of Variance by Ranks, we could not find any effects regarding the felt presence (see also figure 7). The presence was slightly decreasing when slow motion was presented permanently

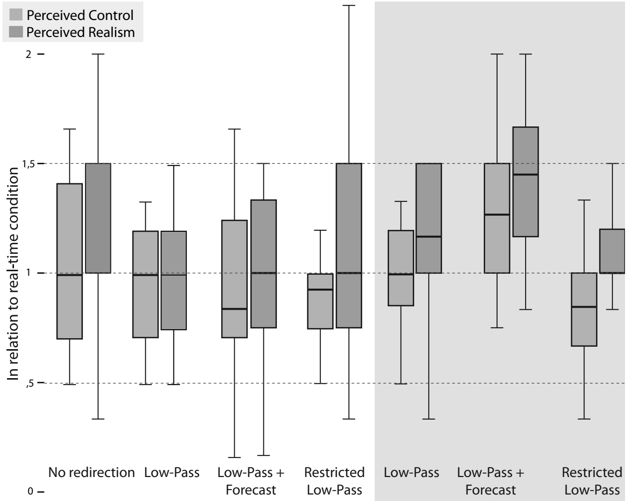

Figure 6: Boxplots of the perceived realism and control of movements relative to the control condition (the three conditions on the right are the alternating conditions).

during the whole test, while it even increased slightly for one condition when slow motion and real-time alternated.

Enjoyment: Regarding the enjoyment score, we found significant differences between the control group and the alternating conditions. Most of all, the difference between real-time and the alternating simple low pass with forecast (p = .013) and between real-time and alternating low pass (p = .028) showed that slow motion can have a positive effect on enjoyment in VR (see also figure 7). The same effect could also be observed when comparing the control conditions, whereas here the only significant increase of presence was found for the simple low-pass condition. Comparing the two control conditions, the resulting enjoyment scores did not show significant differences.

Simulator Sickness: We also analyzed the simulator sickness questionnaire (SSQ). None except one of the participant did suffer simulator sickness at all (scores below 5 – negligible). One had minimal symptoms for each condition. There was no difference between the conditions.

6.4 Overall analysis

We tried to gain further insights by combining data from the different questionnaires and the logged movements.

Relation of Presence, Control, Enjoyment and Realism: First, we searched for correlations using Spearman's rank correlation coefficient. Presence was strongly correlated to a feeling of control (p = .000, ρ = .646) and the perceived realism of movements (p = .000, ρ= .623). Enjoyment was most of all affected by the perceived realism of movements (p = .000, ρ = .740). This allows the assumption that perceived realism influences enjoyment in slow motion conditions.

Relation of Control, Predictability and User Adaptation: Combining the analyzed movement features with the questionnaires lead to more insights in how the user's adaption to the time conditions influenced the different scores. Though not significant, there was a remarkable negative correlation between acceleration in slow motion conditions and the felt control (p=.070, ρ=.-272) and predictability (p=.071, ρ=-.271) of movements. The amount of slow motions had a significant influence on enjoyment (p=.007, ρ=.398) – enjoyment was higher when participants adapted their movement speed. An equal effect could be observed for presence, though not significant on the 5% level (p=.076, ρ=.267).

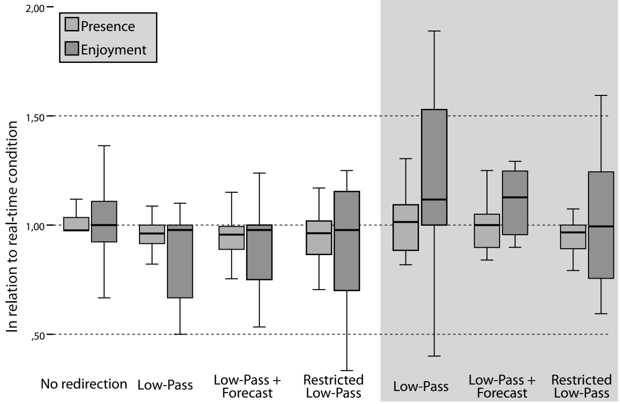

Figure 7: Box plots of presence and enjoyment scores relative to the control condition (the three conditions on the right are the alternating conditions).

User Acceptance: After each condition, the participants were asked if they would like to have such effects in VR applications on a 7 point Likert scale. Though there was no significant difference, a slight tendency towards the simple low pass with forecast could be observed (Mean: 5.4). The slow motion control condition (without affecting the movement) was less appreciated (Mean: 4.5). In a final questionnaire, we asked the participants if they liked slow motion in general. 87% of the participants affirmed this.

6.5 Participant's comments

In the final questionnaire, we also asked the participants to describe the different slow motion styles they could distinguish and how they perceived them. None of the participants could distinguish between the low pass and restricted low pass, though they rated both differently in the questionnaires. One participant requested a tutorial or a longer training phase. Many participants reported, that they liked the visual representation of a slowed down movement, but stated that it was too slow. One wished to have no restrictions of body movements at all. Some participants complained about the task which was either not demanding or not spectacular enough. The most frequent desire was the use of guns and to dodge bullets in a shooting scenario. One participant stated the desire for more visual feedback of slow motion like motion blur.

6.6 Interpretation and Discussion

In the first part of this paper, we stated several hypotheses regarding time perception, movements as well as on user experience. With the analysis of the gathered data, we are able to answer or at least partially answer the questions.

Regarding the influence of environmental slow motion effects on the time perception, the comparison of the two control condition showed no remarkable or significant difference. We therefore assume that such features do not influence time perception. Our results thus match Schatzschneider's and Bruder's results, who could also find no difference in time perception while changing the speed of a virtual sun.

We also analyzed the influence of slow motion movement redirection on time estimations. Due to our within subject design, we could only acquire prospective time estimates, since the participants would know to be asked for a time estimation after the first trial. Our results show, that there is a significant decrease of perceived duration in slow motion conditions – an effect that could only be observed when movements were visually slowed down. Changing the playback speed without affecting movements did not have any effect on time estimation. There were very high standard deviations regarding all estimates, however the perceived duration were significantly decreased by around 25% compared to the real-time (and 23% compared to the slow motion condition without influencing movements). This is a strong hint towards the potential of influencing time perception in VR by temporally scaling movements.

We also assumed that the perceived playback speed would be influenced by both, the environmental and the movement features. While both conditions significantly differed compared to the real-time condition (which is obvious), there was no difference between slow motion with and without redirection. The users could estimate the playback speed for each condition remarkably precisely (estimated: 0.46, applied: 0.4).

Regarding the user's motions, we could observe that the participants adapted their angular velocity very closely to the defined threshold of 60°/s (mean over all slow motion conditions: 59°/s). In addition, the measured time until the participants changed their angular velocity to the maximum, which was by around 0.3s. Those facts support the hypothesis that users adapt quickly to speed changes by restricting their movement speed. Participants on the other hand did not change their behavior when only playback speed was decreased.

The analysis of the questionnaire items about the perceived control and realism of movements showed that there is no difference between real-time and slow motion conditions. The comparison of realism even emphasized an increase when alternating times. We assume that this is caused by the desire of getting involved into the virtual world and that users are willing to accept unrealistic features as realistic, if they are reasonable (like the slowed down movements in slow motion).

We also compared the perceived presence between the different conditions and could not find any differences, independent of the applied redirection technique. For enjoyment, there was a significant increase when slow motion and real-time speed were alternating. In slow motion only conditions, the enjoyment was slightly but not significantly lower than during real-time only conditions. The results of the questionnaire items proved that participants liked the respective slow motion style, as well as 87% of participants stating they would like to have such slow motion effects in VR, which is also supporting the idea of using slow motion as a stylistic device in VR applications.

The negative correlations between the amount of slow movements and the felt presence and enjoyment (though not significant) led us to the assumption, that enjoyment and presence seem to be dependent on how the users adapt their speed. While the restricted low pass condition was designed to force the user to adopt angular velocities, it was perceived controversial. Some participants felt much more control and realism of the movements as well as an increased enjoyment and presence, while other users stated the opposite. Since we did not include any kind of tutorial on how to move in slow motion, we assume that this controversial was caused by the less intuitive phenomena of moving slower, when actually moving faster. While the participants who adapted their movements accordingly by decreasing velocity and acceleration felt significantly more enjoyment, there was also a non-significant tendency towards an increase of felt control, realism and predictability of movements when adapting. In addition, there was no participant who distinguished the simple low pass and the restrictive low pass conditions in the final questionnaire. We therefore assume that this approach – although performed worse than the others – could be promising when users get used to it.

The analysis of the SSQ did not show any changes between the conditions, while there was only one user at all suffering slight effects of simulator sickness during the participation.

6.7 Limitations

Though we gained a lot of insights in how users perceive slow motion in VR during different treatments, many more questions arise by the results, like the influence of the velocity thresholds. The chosen thresholds of scaling down the movements to 0.4 times the mean real-time velocity seemed to be too low for many participants. We assume that choosing higher thresholds could improve enjoyment as well as other presented results. On the other side, the extreme threshold shows, that the concept of visually slow down movements by redirecting can also be applied using extreme values.

The 16 participants were enough to get first insights on many of our hypotheses, but are not enough to finally validate or reject all of them. The list of different influence factors is much too long to be investigated probably in one study.

For the results regarding time estimation, we could only compare prospective data, due to the within subject design. In future work, this could also be done on retrospective estimations by reducing the tested conditions.

The design of the task was done without any disturbing or influencing visual or auditory cues, which on one side should make the experiments more controllable and the results more reliable, but on the other side, we assume that many effects (most of all the increase in enjoyment), would be much more impressive using a more appealing scenario and design of the virtual scene.

7 IMPLICATIONS

A large majority of the participants would like to have slow motion in virtual reality given a suitable use case. According to their preferences, slow motion should also be represented by manipulating the virtual character's movements. The results of our questionnaires support this finding. While enjoyment was increased, interestingly, the potential mismatch between the real and virtual pose did not decrease presence. Participants also did not report any loss of control over the virtual body when redirected, it was even increased in the *forecast* condition. Our item on the judgement of realism was an interesting one. Speaking of realism when actually manipulating time and even the own body movements is hard to define. Our participants rated realism as very high, and even higher when manipulating movements (in the *forecast* condition). We therefore argue, that movements should be affected by slow motion, but there should be a visual hint about the real pose.

In our *restricted low pass* condition, we forced the users to adapt to the maximal velocity. Here the results are ambiguous. Some participants rated this restriction most realistic, having the greatest experience of realism, while others rated it worst of all and reported a loss of control over the virtual body. As our results showed a negative correlation between velocity and enjoyment, we assume, that this kind of slow motion representation was the less intuitive one. Participants who adjusted their movements had a very good experience, while those who did not struggled with this condition. We therefore suggest providing some kind of tutorial that explains how the underlying mechanisms work to improve the experience.

Moreover, the applied maximal angular velocity of 60°/s was too low for some participants, we suggest testing other threshold values to improve the experience depending on the application.

8 CONCLUSION AND FUTURE WORK

In this paper we described the results of a study on simulating slow motion in virtual reality using full-body tracking. We compared three different conditions slowing down the movements of the virtual character to a defined maximum by visual redirections to two control conditions without redirection. Our results show, that it is possible to slow down body movements by redirection without decreasing presence or increasing simulator sickness. When slow motion and real-time alternates, which would be the case in common gaming scenarios, the participants even perceived the movements as more realistic and controllable compared to the two control conditions. Restricting body movements also proved to enhance the enjoyment and the participants stated to be fond of such effects in VR gaming. By measuring the angular velocities during the tests, we could show that the users adapt their real movement speed close to the visually perceived maximum within a short time, which helps in increasing presence and enjoyment.

In addition, we found that the restriction of body movements influences time estimations. Participants estimated the playing time to be 25% less in slow motion with redirection while it remained unchanged without.

We assume that our results can be applied to other virtual reality formats using three-dimensional tracking (like e.g., controllers or upper-body only situations), since the underlying principles are the same. The presented results therefore cover a wide area of scenarios and applications, since such an approach could also be applied to simulate other features, like e.g., the restriction of water or different gravitation.

We also were able to identify many possible influence factors that could be investigated in the future, like the influence of different thresholds on presence, enjoyment and time perception or the introduction of additional visual features, similar to the tested visual forecast, like stronger motion blur.

Overall, we conclude that VR seems to be suitable for including slow motion effects for storytelling purposes when done the right way. Our results strongly indicate that effects of slow motion should be applied to both environmental cues and the visual representation of character movements to get a persistent experience. Users adapt their own velocity to visually presented restrictions. When doing so presence not only remains untouched but may also even increase though the visual movements do no longer perfectly match the real ones. Our results further indicate that both movements – the real ones and the adapted ones – should be visualized to increase presence. Forcing a user to slow down movements negatively influenced presence and seems therefore not to be a suitable approach.

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Breaking the Tracking: Enabling Weight Perception using Perceivable Tracking Offsets

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Breaking the Tracking: Enabling Weight Perception using Perceivable Tracking Offsets

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Figure 1. We propose a solely software based approach of simulating weight in VR by deliberately using perceivable tracking offsets. These tracking offsets nudge users to lift their arm higher and result in a visual and haptic perception of weight.

ABSTRACT

Virtual reality (VR) technology strives to enable a highly immersive experience for the user by including a wide variety of modalities (e.g. visuals, haptics). Current VR hardware however lacks a sufficient way of communicating the perception of weight of an object, resulting in scenarios where users can not distinguish between lifting a bowling ball or a feather. We propose a solely software based approach of simulating weight in VR by deliberately using perceivable tracking offsets. These tracking offsets nudge users to lift their arm higher and result in a visual and haptic perception of weight. We conducted two user studies showing that participants intuitively associated them with the sensation of weight and accept them as part of the virtual world. We further show that compared to no weight simulation, our approach led to significantly higher levels of presence, immersion and enjoyment. Finally, we report perceptional thresholds and offset boundaries as design guidelines for practitioners.

ACM Classification Keywords

H.5.2. User Interfaces: Interaction styles; H.5.2. User Interfaces: Haptic I/O

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Author Keywords

Weight perception; virtual reality; pseudo haptics.

INTRODUCTION

Virtual reality (VR) Head-Mounted Displays (HMDs) are recently being released as consumer products (e.g. Playstation VR, Oculus VR, HTC VIVE) and are currently strongly promoted by the entertainment industry. One of the big advantages of VR HMDs is the level of presence and immersion they are capable of creating. While prior research on VR has traditionally focused on technical or visual aspects to increase the immersion, haptics has recently been identified as one of the missing aspects which has also a significant impact on immersion and presence. In this paper we focus on one specific aspect of haptics, namely *weight*.

Currently, there are two approaches to simulate weight in VR, either using a physical actuator [21, 2, 31] or through visual indicators [15, 16, 22, 23]. A drawback of physical actuators is that they require a modification of the used controllers, and that there is currently no technology or mechanism which is capable of fully and realistically simulating the sensation of weight. Software modifications share the advantage that they can be applied in most of the currently available VR devices, but are limited in their expressiveness in creating a perception of weight, since visual cues are used as subtle as possible to let users be unaware of any manipulation. In this paper, we present a software based approach capable of simulating a visual and a haptic perception of weight for tracking-based VR devices (e.g. Oculus Rift, HTC VIVE).

Our solution consists of intentional and controlled offsets in the positional tracking of the hands or controllers. This creates the visual sensation of weight by nudging the user to lift the arm higher to perceive some form of additional exertion. This exertion can further be associated with holding an object having a certain weight (fig. 1). We present a spring-like model and its implementation in Unity3D capable of generating the sensation of weight using a simple software modification. We further conducted an initial user study, showing the success of our approach in simulating weight and fathoming the acceptance threshold of users in terms of shifting offsets. In a second user study, we quantified the impact of our weight simulation on immersion, engagement and enjoyment, showing significant improvement over the current state of the art (no weight simulation). In a final step, we quantified the granularity of the detection thresholds of offsets using a *two-alternative forced choice* study and provide those as guidelines of how to deploy our approach in current applications.

The main contributions of this work are:

- A solely software based approach (perceivable tracking offsets) for simulating weight sensations (visual and haptic) for tracking based VR applications.
- A study showing the increase of enjoyment, engagement and presence using the proposed weight approach compared to no weight simulation.
- Quantifying the perceptional threshold and weight boundaries, as design guidelines for practitioners.

While prior research that used tracking offsets to simulate haptics mainly focused on concealing them from the user, our approach embraces them. To the best of our knowledge, we are the first to deliberately use perceived tracking offsets as a form of communicating haptics. This allows a far larger design space. We argue that our approach can easily be implemented inside all current tracking based VR interactions and results in a significant better (immersion, enjoyment and presence) experiences than the currently non-existent simulation of weight.

RELATED WORK

Multi-sensory feedback plays a significant role for presence in VR applications [6, 10], with haptics being one of the most important senses. There are different features of an object that can be explored based on haptics, like texture, hardness, temperature and weight [19]. All aspects are part of current VR research, while we focus on the latter one - the simulation of weight. For this, currently two main approaches are being researched. First, the simulation of real weight of a grabbed virtual object by exerting actual forces in the real world, and second, the use of visual features called pseudo-haptics.

Real Weight Simulation

Current controllers, like the ones of the Oculus Rift or HTC Vive, as well as tracking devices (e.g. Leap Motion), ignore kinesthetic feedback. It is difficult to physically represent different weights, since a controller has only one specific mass. Nevertheless, several research projects were published that try to overcome these limitations.

Ryuma Niiyama et al. [21] propose a weight-changing system using liquid metal that is pumped into the grabbed object. They were able to dynamically control the weight between 0.5 g/cm^3 to 3.2 g/cm^3. Another approach is the elastic arm [2, 1] which is based on an elastic armature mounted between the user's hand and shoulder. When extending the arm, users feel the resistance of the stretched bound.

Shifty [31] is a prototype which consists of a rod where a movable weight is mounted. The center of mass is shifted when this weight moves between the grip and top end of the rod. The user is then able to feel the change of rotational inertia. Yamamoto et al. propose shaking interaction [30], a system that simulates inertial forces while shaking. The forces are generated by accelerating a weight and apply in the axis of motion. The object's weight cannot be perceived while resting, though.

A work that is not about weight simulation, but about haptics regarding touch combines cognitive features of multi-sensory integration and visual dominance with real haptic feedback is presented by Kohli et al. [12]. They propose redirected haptics, warping the virtual space to match real geometries. Using their approach, a variety of virtual objects can be mapped onto a single real object to provide a feeling of touch. A similar approach was proposed by Azmandian et al. [3].

Physical weight representations allow the perception of weight over multiple senses and most likely provide the most realistic feedback in VR. Though such devices have their limitations regarding weight or comfort and most important require additional hardware which may not be available.

Integration of Haptic and Visual Sensations

Besides the attempt of generating real weights and forces, research suggests that our perception of weight – or haptic in general – is a multi-sensory process, which most of all depends on the integration of visual and haptic cues.

Our general perception is based on a variety of different senses that have to be merged [28, 9]. This is similar to the perception of object properties, which depends on different senses (particularly haptics, proprioceptive and visual ones). Rock and Victor [26] for example investigated the influence of visual information on the perceived size of an object. They found that vision had a larger effect on the size perception than haptics. Ernst and Banks [8] proposed a statistical model of visio-haptic integration, stating that the influence of each sense is dependent on the actual performance of the single sense. As visual stimulus, they used a dot stereogram as background plane, while displacing the dots to add noise to the visual sense. The influence of visual information on the perceived size depended on the applied noise.

Manipulating virtual objects requires a spatial mental model of the virtual environment, but in VR there is often only a single channel providing the necessary information. Biocca et al. [5] therefore hypothesized that participants would experience a form of visio-haptic cross modal transfers when interacting with virtual objects. They conducted an experiment in which participants manipulated objects in VR without haptic feedback and reported on haptic sensations. They could show that haptic sensations correlated with sensations of spatial and sensory presence.

The presented works show the importance of visual cues on haptic perception and are the fundamentals of pseudo-haptic feedback approaches. Since our approach is only based on visual features we build on the presented insights. While real weight perception should not include sensory mismatches (e.g. between the proprioceptive and visual one), we deliberately include such mismatches without the restriction that the manipulation of visual features should not be perceived. Redirecting motions in VR was e.g. done to enhance the perception of slow motion [25], where participants did not report on a loss of control. We found that participants liked obvious offsets as a weight representation and accepted them as part of the virtual world. We also implemented such an approach for general kinesthetic feedback and coupled the pseudo-haptic effect with vibration [24].

Pseudo-Haptics

Pseudo-haptic feedback is to provide haptic sensations without the actual matching haptic stimulus, but instead by inducing those sensations using vision [13]. Visual feedback is provided synchronized to motions or actions of users. Due to the sensory integration while generating haptic perceptions, it is possible to create such haptic illusions based on visual features.

Several experiments were conducted that show how pseudo-haptic feedback can be used to create several haptic illusions. For example, friction was implemented by manipulating speed and size of a mouse cursor [15, 16], stiffness was simulated by visually offsetting the hand position on a computer screen [27] or a multi-modal combination of force and displacement using a 3D mouse [17, 14]. Different object shapes were visualized by displacing the visual representation of the user's hand to match the object's surface [4]. Lécuyer et al. contributed that participants perceive friction, gravity or viscosity, when a virtual object was slowed down using a 2D and a 3D mouse [18]. Pusch et al. [22, 23] used visual hand displacements to create the illusion of resistance of wind in VR. In their results, 9 out of 13 participants stated that they could actually feel some kind of force that was pushing their hands.

J'auregui et al. [11] used different animations of lifting objects of different weights recorded by a motion capturing system. When applied on a virtual avatar they could show that these animations of a virtual avatar influence the perception of weight.

Dominjon et al. [7] used a pseudo-haptic approach to simulate weight. Participants compared the weight of virtual balls, seen on a computer screen, while lifting a real ball. When the visually sensed virtual motion of the object was amplified, they could observe, that the weight was perceived as less.

The approach of Dominjon et al. [7] to visually amplify motions in VR to simulate different weights shows promising results regarding weight perception simulation. As Biocca et al. [5] stated, haptic illusions even increase with the perceived spatial and sensory presence. We assume, that such effects even apply stronger in immersive VR scenarios, so that visual induced haptic perception increases with technical advancement. Though the presented results can not be applied directly to the context of VR, since they were exploring indirect manipulation (not 3D interaction) using a hidden static controller and a 2D representation on a screen. The sense of proprioception to locate the arm and hands in 3D space and the stronger sense of virtual body ownership are unique to VR and both potentially breaking with the use of offsets in tracking. In addition, there are no results beyond investigating the general idea of pseudo-haptics. Such effects were never applied to actual applications diminishing the value for practitioners, nor is there any guidance on how to apply such effects in VR applications. In addition, the current suggested pseudo-haptic implementation is not suitable for VR applications. When constantly amplifying motions, the offset will also constantly increase to the actual tracking, since lighter objects would constantly move faster than the actual hand. Though short interactions with lighter or heavier objects could be displayed, this approach is most probably not suitable beyond the short time of lifting an object.

We therefore developed an own model, based on prior works and not only tested perceptual thresholds, but also explored the design space as well as effects on weight perception in a VR gaming application.

WEIGHT MODELING APPROACH

The presented prior work showed the influence of visual feedback on haptic perception and that visual feedback can be modified to generate pseudo-haptic effects. Pseudo-haptics mainly focus on presenting subtle effects that are barely perceivable by the user and therefore only allow for small deviations of the perceived weight. Our idea is to take this approach one step further by including obvious offsets between the tracked and the visual position of the hands to generate a wider range of perceivable weights. Our approach uses two forms to convey the perception of weight: (a) obvious visual offsets for the visual sense (b) nudging the user to lift the arm higher for the haptic sensation.

Idea

We designed a weight metaphor based on a force model, without increasing the tracking offset, even during longer interactions. When considering the physics behind lifting an object in a simplified way, there are two forces that work against each other. The first one is the gravity, pulling the object towards the ground. The second one is the force which a person applies to lift the object. When lifting a heavier object, one has to increase the force and to strain one's muscles to a greater degree. This also makes up for the difference between lifting a virtual object, and a real one – the required force remains the same with virtual objects, as the controller weight never changes.

If different weights shall be presented, the forces that pull objects down also have to differ. The same amount of force needs to be applied in the opposite direction to keep it in the same height. Since there is no such force in VR, we define an offset vector between real tracking position and visually displayed position as a force vector. This offset force increases with the tracking offset until both, the weight and the offset force are equal. Therefore the lifting of heavier objects results in a larger offset. This indirectly results in a stronger perceived force a user has to apply to lift a heavier object compared to a lighter one.

Instead of a constant spatial offset between tracked and visual position the described mechanism acts like a spring between the tracked position and the actual visible one, while the visual hand is pulled down by the object's virtual weight. Furthermore, our approach considers inertial properties of the virtual object. We design heavier objects in a way they need more time to accelerate and to slow down. By applying these features we aim to create a visual perception of object's weights close to real physics behaviour.

However, we also had to implement a solution for the moment of grabbing. Using the previously described mechanisms a grabbed object (including the virtual hand) would fall down after the object was grabbed due to the applied weight force. We therefore decided, to increase the presented offset while lifting the object. As the virtual object falls down in the moment of grabbing, the visual position remains the same until the hand starts moving. The visual position then adjusts towards the virtual object's one while lifting. An object therefore moves slower during the first lifting. The heavier the object, the slower it starts moving.

Implementation

Basic Approach

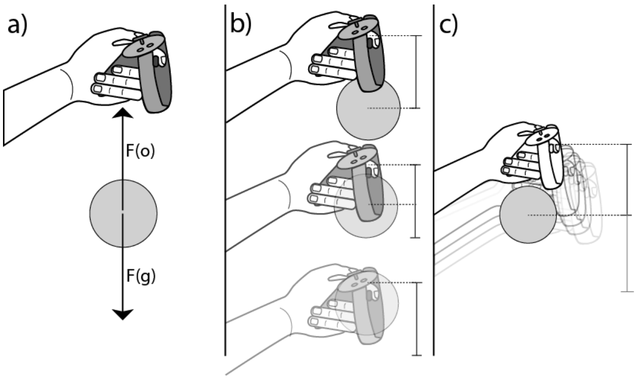

Figure 2. a) When an object is grabbed it is pulled down by the weight force (F(g)). The imaginary force (F(o)) is working against the weight force and increases with the offset between visual and tracked position. b) When an object is grabbed, the visual position first remains on the tracked position. While lifting, the visual position is shifted towards the object one's. c) The faster an object is moved, the more the visual position is shifted towards the tracked one.

To implement our approach, we divided the process of positioning the virtual hand and the object in two parts. The first one is the real hand's position as tracked by the sensor. The second one is an imaginary object (that is not necessarily displayed) which is described by its position, current velocity and a weight value. The movement of the object is influenced by two forces. The first one is the weight force, which is $F(g) = m \cdot g$, where g is the gravitational acceleration (around $9.81 m/s^2$ at sea level). The second one is an imaginary force that acts in the opposing direction which we further on call offset force ($F(o)$). The offset force is calculated by a function that multiplies a constant value (c in m/s^2) to the actual offset in meters. The offset force is a metaphor for the higher effort we have to expend when holding a heavier object. It can be compared to a spring applied between the tracked hand and the object with the constant c being the stiffness of the spring. Both forces are added to the object's velocity. The velocity is then applied to the current position of the object. The updated position of the object is therefore dependent on its last velocity (v_{t-1}), its last position (P_{t-1}) as well as the forces $F(g)$ and $F(o)$ and is calculated as follows.

$$P = P_{t-1} + v_{t-1} + \Delta t \cdot (F(g) + F(o)) \tag{1}$$

with

$$F(g) = m \cdot g \tag{2}$$

with m being the object's mass and g being the gravitational acceleration

and

$$F(o) = c \cdot o \tag{3}$$

with c being an imaginary constant and o being the offset between the object's position and the tracker's one

An equilibrium of both forces ($F(o) = F(g)$) defines the actual position where the object comes to rest (see figure 2). If the imaginary constant c is defined the same value as g, the final offset therefore would be equal to the object's mass.

Adding Inertia

Only applying these two forces would result in a maximum of inertia. When again considering the example of a spring, the object would take a longer time until being in rest, resulting in wobbly movements. We therefore apply a third force that slows down the object and is defined as a vector equal to the inverse direction of the object's current velocity. Depending on the object's weight, this force is scaled. Lighter objects follow the tracked movements very closely, while heavier objects accelerate and also slow down at a lower rate to enhance the feeling of the actual weight of the object. The heavier the object, the larger the magnitude of the inverse velocity vector during movements, while resulting in a smaller magnitude while resting.

The Grabbing Process

To prevent the object including the virtual hand from falling down directly after grabbing, we shift the actually displayed position according to the distance the hand was moved since grabbing started in relation to the offset. As soon as the hand moved as far as the magnitude of the tracking offset, the offset is continuously displayed. We illustrate this feature in figure 2. Until the offset is reached, the position of the virtual hand and object are calculated by:

$$P = P_H + \frac{\|(P_G - P_H)\|}{\|Offset\|} \cdot (P_O - P_H) \tag{4}$$

with P_H being the tracked hand's position, P_G the position where the object was grabbed, and P_O the object's position

The Influence of velocity

The last property we included for the simulation is another shifting between the tracked hand's and the object's position depending on the current velocity of the hand. While moving the hand, the visually displayed position of hand and object therefore get closer to the tracked position. We designed this feature to have only little influence. Though it is designed to support the metaphor of putting more effort into moving an object with a higher velocity of the hands, which in our case leads to less tracking offset. This feature is illustrated in figure 2 c).

FIRST STUDY

After implementing the system, we conducted a first study, with the goal of investigating how participants would perceive and interpret the described effects. Another goal was to find out how far we could go – how much offset between the actual and the visually sensed position could be applied until a user is no longer willing to accept the presented weight metaphor.

Procedure

The participants were welcomed and thanked for their interest. They were told that they could abort or pause at any time, signed a consent form and filled in a demographic questionnaire. In order to get answers that are not biased in any way, we first only introduced them to the used hardware (Oculus Rift CV1 with Touch controller), and instructed the participants to grab objects by pressing a trigger on the controller. None of the participants were informed about the topic of weight simulation. The presented scene was minimalist – only including a skybox and two equally sized spheres with the same neutral white texture on it. Then the participants were instructed to grab and lift the first sphere (which was the *lighter* one) with a resulting tracking offset of around 2 cm. When the object was released, it was reset to the initial position immediately without any animation. This was a measure to prevent communication of any other information regarding the object properties but the ones created by our algorithm. Afterwards, the participants grabbed the second and *heavier* object which resulted in a tracking offset of 8 cm. While doing so, the participants were allowed to lift both objects as often as they desired. We then asked the participants to think aloud about differences between both objects.

In the second task, the participants were instructed to lift several virtual objects onto a displayed box, while after each task, the virtual weight varied. We deactivated the initial lifting process, so that the sphere including the visual hand fell down as soon as the object was grabbed. This was done, because we wanted to know how much offset the participants would accept in VR, which would have been biased due to the slow offset increase during the lifting process. We asked the participants to state whether they would like to have the presented weight metaphor in a VR application, if they would accept it or if it would not be suitable. We presented 14 different weight offsets ranging from 10 cm to 64 cm. The weights were presented in a random order. After each weight was presented we repeated the procedure for another three times – again in a different random order.

Participants

We recruited ten participants (7 male, 3 female) with a mean age of 28 (standard deviation 1.5). We also asked them to state for how long they have been using VR systems in months before. The range was between 3 and 48 months and a mean of 19 months (standard deviation 14.6).

Results

When the participants were asked to think aloud about the two differences of both spheres, the first assumptions varied. Three stated that there would be no difference, while four instantly stated that the two spheres differed in weight. One participant first stated that lifting the *lighter* sphere felt like holding a Christmas ball while the other one felt more like a bowling ball. One participant stated to perceive the tracking offset. Other associations were about different inertia, or that one sphere would pull the hand downwards. Each participant except one came to the point of associating the different offsets with a different weight within 30 seconds of thinking aloud. One participant even stated to actually feel the weight while holding the heavier object.

In the next step, the participants had to lift spheres of different *weights* which resulted in an offset between 10 and 64 cm and were asked whether they would like to have such a weight representation, or would accept it or if it would not be suitable. There was one participant stating to fully accept the metaphor of weight resulting in offsets. If the offset was too high to lift the object, he compared it to an object that would be too heavy for him to lift in reality. Since this opinion was unique regarding the other participants, we excluded this participant from the following results. The participants repeated each weight four times and we compared the acceptance between the first and last iteration to see whether participants would get used to the metaphor. All participants rated the weight representation as *good* until an offset of 20 cm in the first iteration and accepted an offset of around 35 cm. These values increased in the last iteration to 24 cm (good) and 42 cm (accept).

SECOND STUDY

The first study provided the information that participants interpret the presented tracking offsets as weight and also about how far such an approach could go. The aim of the second study was to gather insights on how such a metaphor would influence presence, enjoyment and the perception of weight and consisted of three tasks. For the first one, we designed a bowling game, where the participants could either lift the balls with or without our metaphor. After the ball was thrown, the weight was equally treated by the physics engine in both conditions. The second task was designed to find out more about detection thresholds – how much offset is required to enable people to distinguish virtual weights. The third task was quite short and only had the goal of getting real, absolute weight associations using our virtual representation.

Procedure

The participants were first welcomed and thanked for their participation. They were then told that the study was about weight representation in virtual reality and that there were

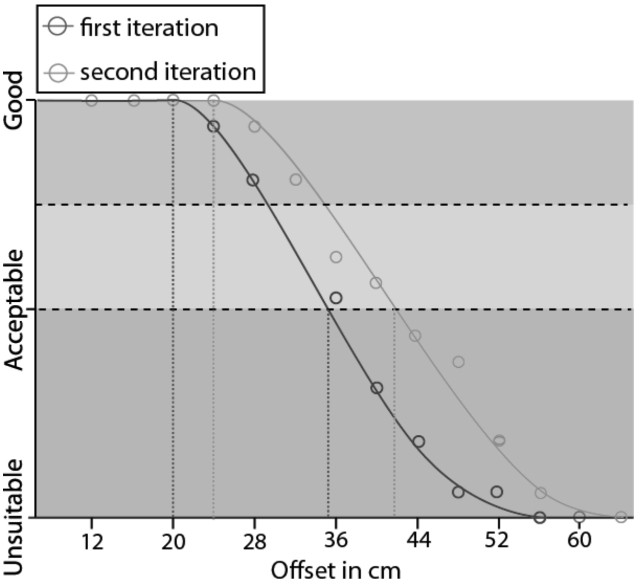

Figure 3. Plot of the participant ratings of different presented offsets as well as the trend line. The green area includes ratings where at least 50% of the participants rated the offsets as a *good* metaphor, the yellow area includes offsets which were accepted by all participants. The red area includes values which were not accepted by all participants.

three tasks, including two games of bowling. Each participant was also told that he or she could abort or pause at any time if they did not feel well. The mechanisms (e.g. offsets) that were used to represent weight were not explained to the participants. After this introduction, each participant signed a consent form and filled in a demographic questionnaire. In the next step, the participants were introduced to the VR glasses and the used controller, as well as its functionality. If there were no more questions, they started to play the first game of bowling, either with or without our weight metaphor. The order was counter balanced over the number of participants to overcome any biases that could arise by having each participant starting with the same condition. After the first game, which took about four minutes, the participants were instructed to fill out three questionnaires, including the Witmer-Singer presence questionnaire[29], the E^2I [20] questionnaire as well as our own questionnaire. The participants then played a second game of bowling, either with or without the presented weight metaphor (depending on the condition they started with). After the second game, the participants again filled out the mentioned questionnaires. Then a last questionnaire was presented including free textual feedback, as well as some comparative questions.

The next task was a two alternative forced choice (2AFC) task in which the participants should lift two equally looking, same sized spheres and should tell which one was the *heavier* one. Since such a method requires many iterations, the participants had to compare the two presented spheres for 120 times. This includes five weight steps applied on two different origin weights. Each comparison was repeated 12 times. The order was fully randomized. The study took on average one hour and participants received 10 Euro.

Figure 4. A screenshot of the bowling scene.

Part I: Bowling

During one game of bowling, each participants threw 10 balls in total. Every time a ball disappeared in the bowling gutter, its position was reset to the original position so that the participants did not have to, but could use different balls. Overall, six different balls were present, each having a different size (which was related to its actual weight) and were ordered with increasing weight from left to right. To give the participants an initial guess about the balls' weight in each condition, they were informed about this order. The pins were reset after two balls. After a strike, they were reset immediately. Therefore the participants could score up to 100 points (10 balls times 10 pins). The current score, as well as the remaining ball count was shown to the participants in a screen placed on the ceiling of the bowling alley (see figure 4).

The balls were set to be kinematic, which means they were not influenced by the physics engine as long as the objects were grabbed. As soon as they were released by the participant, the physics engine came into effect and controlled the balls physics. We also transferred an initial force to the engine, which was equal to the current velocity and strength of the virtual object to allow users to throw them despite the handover between our algorithm and the physics engine.

Part II: Detection Thresholds and Weight Estimation

Both the detection threshold and weight estimation task were kept quite simple. The scene was empty, only including a skybox of a sunset. Since the participants had to compare the *weights* of two spheres in the detection threshold task, two spheres were displayed, while only one was displayed during the weight estimation task. A screenshot of the detection threshold task is shown in figure 5.

In the threshold estimation task, the participants had to compare two identical looking spheres regarding their *weight*. One of the spheres had a weight resulting in a offset of either 8 cm or 20 cm, the other one had an additional offset ranging from 0.8 cm and 4 cm (in 0.8mm steps). The order as well as if the left or right sphere was heavier was randomized. The task was designed as a *two-alternative forced-choice* (2AFC) task. The idea behind such a task is to get the probability of correct estimates by repeating each comparison multiple times. If participants can not distinguish between both weights,

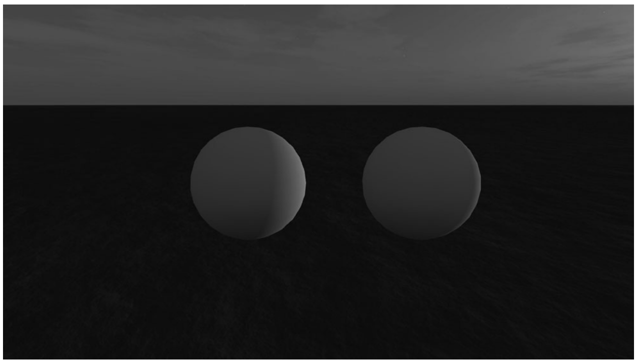

Figure 5. A screenshot of the detection threshold task scene.

they will answer randomly, resulting in a probability of 0.5. The more reliably they can distinguish them, the higher the number of correct estimates and therefore the probability of detection. In our case, each comparison was done 12 times. The participants had therefore 120 comparisons to do in total (5 additional offsets applied to 2 different weights times 12 repetitions).

The last task was used to gather an absolute weight estimation in kg being associated to the respective offset. We presented four different offsets (4 cm, 12 cm, 20 cm and 28 cm), each three times in a fully randomized order.

Participants

We recruited 18 participants (13 male and 5 female) aged between 21 and 30 (mean 26). In addition to the demographic questions, we asked the participants about their interest in VR technology on a seven point Likert scale (from 1 – no interest, to 7 – strong interest) resulting in a mean of 6 with a standard deviation of 0.8. We also asked for how many months they have already been consuming VR content, which was 12 in mean with a standard deviation of 15.

Results

Bowling Task We used the Wilcoxon signed rank test for non-parametric dependent variables to compare the two conditions regarding differences in the presence, immersion and enjoyment score. The results of the Witmer-Singer presence questionnaire showed a highly significant difference between the *with offset* and *without offset* condition, with a strong effect size ($p < .01$, $Z = -3{,}66$, $r{=}.61$). Both conditions resulted in a high median presence of 5.22 for the *without* and 5.58 in the *with offset* condition.

Regarding the immersion score of the E^2I, again a significant difference could be observed between both conditions ($p < .05$, $Z = -3.26$, $r = .54$). Again, the immersion in the *with offset* condition was slightly higher rated with a median of 5.4 compared to 5.3. The second score we got from he E^2I questionnaire was the enjoyment. Again, both conditions differed slightly but significantly ($p < 0.05$, $Z = -3.13$, $r = .52$) with a median of 5.8 in the *with offset* condition and 5.3 in the *without offset* condition. Boxplots of the results are given in figure 6.

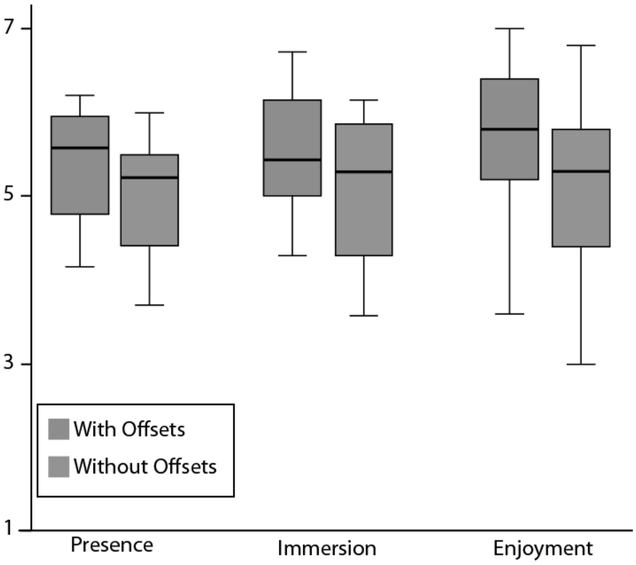

Figure 6. Boxplots of the Presence, immersion and enjoyment scores split by condition.

The results of our own questionnaire are illustrated in figure 7. Our questions all aimed at rating weight perception and estimation. The participants answered on a 5 point Likert scale how strong they would agree to the following questions (1: not agree, 5: strongly agree). On the question if they could actually feel the weight of the bowling balls, the median was at 4.0 in the *with offset* and 1.5 in the *without offset* condition. The difference was significant on the 1% level ($Z{=}-2.67$) using Wilcoxon signed rank test. A second question was whether they were able to estimate the weight of the bowling balls before releasing them. In the *with offset* condition the answers varied strongly between 1 and 5 with a median of 4, while the median in the *without offset* condition was 2 ($p < .01$, $Z = -3{,}12$). Regarding the question if they were able to estimate the ball's weight after the release the differences were no longer significant ($p > .05$, $Z = -1.53$). The median was 4 in the *with offset* and 3 in the *without offset* condition. Boxplots of the results are shown in figure 7.

After playing both conditions, the participants filled out a last questionnaire including questions targeted to learn about the participant's preferences. Most participants (67% or 12 out of 18) preferred playing with offsets, while 11% (2) preferred playing without. The remaining 22% (4) were undecided. We also asked the participants, which representation seemed to be more realistic. Overall 55% (10) of the participants stated that the *with offset* condition was more realistic, while only one (5.5%) stated the *without weight* condition was more realistic. 39% (7) stated that both conditions were equal regarding their realism as weight representation. The results are illustrated in figure 8.

Detection Threshold Task

The second task was the comparison of the weight of two virtual spheres while lifting them. We examined two different weights regarding the participant's ability to distinguish fine

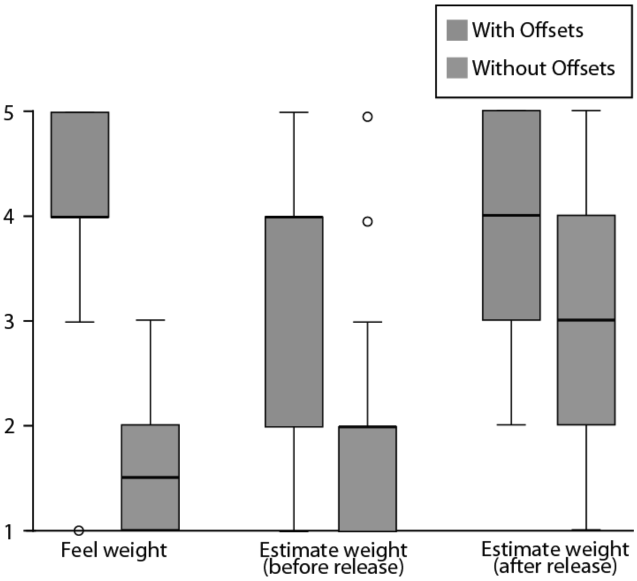

Figure 7. Boxplots of the results of our own questions regarding weight perception and estimation.

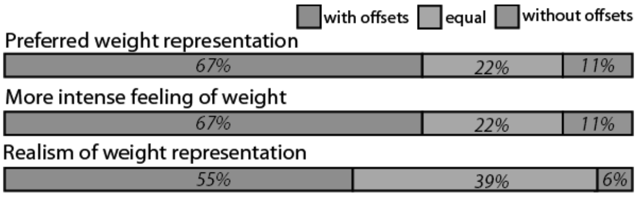

Figure 8. Illustration of the participants' rankings of the two conditions.

differences of offsets. The probability of detection reached 75% at a difference of 2.5 cm with an initial offset of 8 cm. This means that the participants could distinguish between objects with an offset of 8 cm and 10.5 cm. The detection thresholds for *heavier* objects with an initial offset of 20 cm was slightly higher, reaching the 75% at a difference of 3.6 cm. Participants could therefore distinguish between the offsets of 20 cm and 23.6 cm. The levels of detection therefore only varied by around 1 cm between *light* and *heavy* objects. We tested both reference weights for differences using a MANOVA (Wilks' Lambda). We found that the ability to distinguish different offsets is significantly (*p*=.00) influenced by the initial offset. The results of the detection thresholds are shown in figure 9.

Weight Association Task

The last task was to state a real, absolute weight, that the participants associate with a given offset. We presented four different offsets three times in a fully randomized order. The results show a strong tendency towards perceiving objects as heavier when presented with a larger offset, but also shows how strongly the associations vary. While the standard deviation for the 4 cm offset object was at around 0.8 kg, it increased to around 3 kg for the 28 cm objects. The median of the 4 cm offset was thereby at around 0.5 kg, which increased to around 3.5 kg for the 28 cm offsets. The results of the weight association task are illustrated in figure 10.

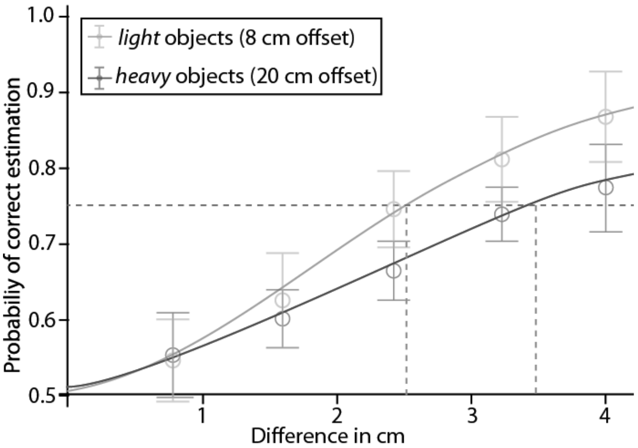

Figure 9. The probability and variances of correct estimations as well as a trend line when comparing two weights using different offsets.

Participant's Feedback

We asked the participants for general feedback about the bowling games and asked them to describe what they felt and perceived during both games. All participants except one stated that the balls' behavior differed while holding. Some wrote that they could perceive an offset between their real and virtual hand's position, but accepted this as part of the virtual world.

All participants except two commented that they could actually recognize a difference of the balls' weight in one condition, while they criticized the respective lack in the other condition. One participant stated to know that the offsets should be a metaphor for weight, but without actually perceiving a different weight. The same participant also stated that the offsets would destroy the immersion when grabbing heavier balls, though it also destroyed the immersion, when the weight was not visualized at all.

Some participants wrote that the weight representation led to a feeling of weight from hands to the shoulder in the offset condition and compared it to an elastic band which was sufficient to get the feeling of weight. Another wrote:"*The heavier balls felt more heavy, but I can not explain why. I had to put more effort into lifting heavier balls.*" Three participants stated that they were able to differentiate between the weights in the offset condition, but without being able to associate a real weight.

Three participants stated that the weight of the balls was surprising them when not having the offset representation. One of them additionally wrote that it would have felt wrong without any feedback of weight. Another described the lack of offsets as counter-intuitive since the balls weights only had an influence after releasing.

Discussion

The results of the two presented evaluations can be split in two main parts. First of all the perceptional part, with the focus

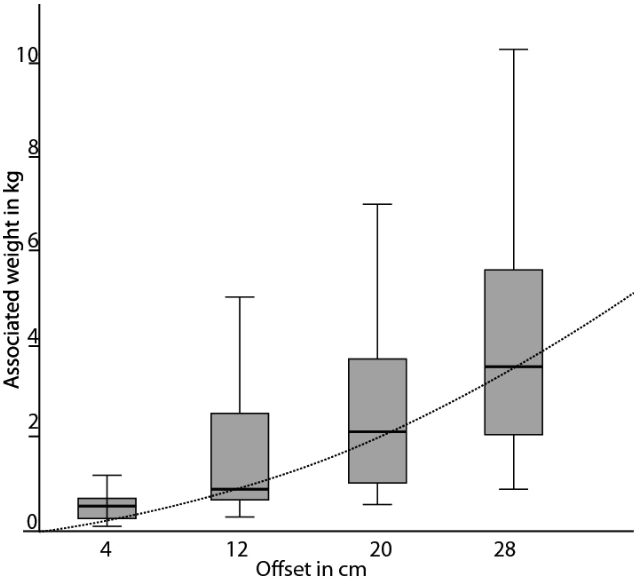

Figure 10. Participants' weight associations of different presented offsets.

on standardized questionnaires, as well as a set of individual questions regarding the weight perception and estimation. Other results more focus on the possible design space, including minimal differences regarding the presented offsets to be recognized, as well as the maximum of desired and accepted offsets.

Overall the metaphor of displaying weights by visually applying tracking offsets was well understood by most of the participants. While some only understood the metaphor others stated to actually feel the weights when presenting offsets. This was also emphasized by the stated preferences. Only two of the 18 participants preferred the condition without, while 12 preferred the condition with offsets. We could also show, that such a representation can positively influence the feeling of presence, immersion and enjoyment. Though all scores did not differ strongly regarding the median, the difference was significant. We assume, that the overall high presence, immersion and enjoyment scores made it hard to capture more pronounced differences. In addition, the questionnaires are not primed towards measuring the perception of weight in VR. We therefore included some own single items which should cover the missing items in the standardized scores. Here we could observe very obvious differences. While the median answer regarding if participants could feel the weight of the balls was at 1.5 (very close to 1: do not agree) without offsets, it was rated 4 (close to 5: completely agree) in the with offsets condition. A similar result was found for the question regarding weight estimation before the ball was released. We therefore argue, that applying tracking offsets to simulate weight in VR generates a feeling of weight and also allows the estimation of its magnitude. But though participants stated that they were able to estimate the weights, we observed very large variances between the participants' estimations which increased with the presented offset.

We also found that people are willing to accept very high offsets up to 42 cm as weight metaphor, while being able to detect differences of around 2.5 cm. This forms a large design space to represent a variety of different weights. Though all participants accepted large offsets, we suggest applying such extreme values only for short interactions while focusing on offsets below 24 cm for longer interactions. These are values all participants agreed to be a good and comfortable weight metaphor.

Since we only rendered the participants hands in our VR applications – as it is a common state of the art – we did not have to focus on aspects like inverse kinematics. If the whole human body should be displayed, such discrepancies between tracking and displaying need also to apply to other joints. However, this can be easily achieved by using existing inverse kinematics algorithms.

LIMITATIONS OF THE APPROACH

All pseudo-haptic effects require sight and are no longer present when the focus of attention shifts. In our study, we compensated for this by offering a variety of balls, nudging participants to compare differences between balls (as commonly done by beginners in real bowling). Regarding the bowling application, our results suggest that this was enough to get the feeling of weight. Still, the feeling of weight with perceivable tracking offsets has to be regarded as a metaphorical perception. While the participants stated to actually feel the weight, we believe that if first playing with a real physical weight would decrease the scores. We therefore argue that pseudo-haptic effects are very useful to communicate different weights, which increases the respective perception, but still will never be able to create a true and natural perception of weight. Another aspect of weight perception is tactile feedback like pressure which is felt when lifting an object. Our proposed approach does only consider tactile feedback in form of the controller held in the user's hands, which does not change during grabbing. Though, we could show the expressiveness and possibilities that are introduced by solely visual and software based weight representations.

Our results indicate, that participants accepted offsets of around 42 cm. This value has to be interpreted with care. This value was gathered in a short term interaction of lifting and translating an object. We believe that such huge offsets should thus normally be avoided or used with care. We suggest to stick to the 24 cm maximum which was what participants stated to like.

DESIGN CONSIDERATIONS/INSIGHTS

The following insights are derived from our user studies and experiences we collected while working and designing with our weight approach.

Embrace the Offset: Our results indicate that even obvious and perceivable tracking offsets can be used as a metaphor for weight and most probably for other VR features (e.g. resistance). While it is possible to design such visual offsets as subtle that they can not be recognized, our results strongly encourage designs where participants experience differences between tracking and visually displayed positions. Participants also preferred obvious offsets of around 24 cm and even accepted offsets up to 42 cm. In our case it did even raise the levels of presence, immersion and enjoyment. In prior evaluations, pseudo-haptic effects were designed as subtle as possible, without having the user perceive the actual offsets. This way, a given weight can be perceived as little heavier or lighter. Using our approach with the knowledge of having more degrees of freedom with perceivable offsets, even a very lightweight controller can be designed to convey a huge variety of different weights, ranging from light too heavy.

Use Relative not Absolute Weights: Our approach has to be seen more as a weight metaphor, which creates the perception of weight but cannot be mapped to a certain weight. As we let our participants guess the weights of different offsets, indeed larger offsets were associated with different weights, however there was a large variance in their guesses. Therefore, we suggest to work more on relative weight differences (e.g. sword vs stick) instead of having only one weighted object and focusing on this inside the experience.

Use Weight as a Natural Limit Inside Experiences: Instead of forbidding certain kinds of interactions to keep the user inside a certain limit (e.g. door does not open) we suggest using our weight metaphor as a natural form of limitation. Instead of making the door a non-interactive element one can make it to heavy to open. This creates the perception of a real and living virtual environment. Instead of forbidding to lift certain objects they can just be designed to be to heavy so the user can try to interact but naturally understands that it is currently not possible.

Accurate Tracking is Essential: The acceptance of tracking offsets as weight representation does however not mean that less accurate tracking would be sufficient. Accurate tracking is essential for applying our algorithm, as tracking errors would lead to unpredictable behaviours and thus most probably to a strong decrease of presence. Tracking has to be very accurate, but the visually displayed position of body parts may vary from the real one. This especially means that the relative precision of motions needs to remain untouched. We also assume, that equal approaches can be designed to display other effects in virtual reality which would need additional hardware or would be even impossible with another technique.

CONCLUSION

In this paper we presented a solely software based approach for tracking based VR interactions to generate a visual perception of weight. Our approach is based on introducing a controlled and perceivable tracking offset whereas heavier weights are represented as a higher offset. To gain a deeper understanding of the perception and effectiveness of our approach we conducted two user studies. We were able to show that people associate different tracking offset as different weights. Using a *two-alternative forced-choice* task we could quantify the detection threshold between two weights for *light* (approx. 2.5 cm) and *heavy* objects (approx. 3.6 cm). We also found, that users like even obvious and perceivable offsets of 24 cm as weight representation. By testing our approach not only for measuring perceptual thresholds, as it was done in related works, but also in a fully immersive VR game, we contribute to the positive effects on haptic perception as well as presence, immersion and enjoyment. We could show that our pseudo-haptic approach results in a significant better experiences than the currently non-existent simulation of weight.

Since our approach does not require any additional hardware, we argue that our approach can easily be implemented inside all current tracking based VR applications.

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Conveying the Perception of Kinesthetic Feedback in Virtual Reality using State-of-the-Art Hardware

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ABSTRACT

Including haptic feedback in current consumer VR applications is frequently challenging, since technical possibilities to create haptic feedback in consumer-grade VR are limited. While most systems include and make use of the possibility to create tactile feedback through vibration, kinesthetic feedback systems almost exclusively rely on external mechanical hardware to induce actual sensations so far. In this paper, we describe an approach to create a feeling of such sensations by using unmodified off-the-shelf hardware and a software solution for a multi-modal pseudo-haptics approach. We first explore this design space by applying user-elicited methods, and afterwards evaluate our refined solution in a user study. The results show that it is indeed possible to communicate kinesthetic feedback by visual and tactile cues only and even induce its perception. While visual clipping was generally unappreciated, our approach led to significant increases of enjoyment and presence.

ACM Classification Keywords

H.5.2. User Interfaces: Interaction styles; H.5.2. User Interfaces: Haptic I/O

Author Keywords

kinesthetic feedback; pseudo haptics; virtual reality.

INTRODUCTION

Virtual reality (VR) has made its way to the homes of end users. Current VR headsets are tracked by sensors and allow direct interaction using controllers which are as well tracked in the 3D space. This way, users can move freely in the tracking space and interact in a more natural way. However, along with this natural interaction, raised expectations of consumers are coming along – especially regarding feedback. In comparison to other interaction techniques such as mouse and keyboard or gamepads interaction with tracked controllers enables the illusion of virtual body ownership [44, 15]. If users interact with their real hands, users may tend much more to expect haptic feedback. The increasing advance in display technology and rendering lets the virtual world become some kind of true alternative reality. The real visual information is fully overridden by the virtual one. However, the same does not apply to other human senses. Due to the mismatch between virtual and real world, it is rather difficult to enable true haptic feedback. If a user pushes a virtual object, there is no restriction perceived or touch felt, because no real counterpart exists.

The feeling of touch is often represented using vibration, which is though not matching the real expectation, some kind of substituting tactile stimulus. The feeling of kinesthetic feedback (i.e. the resistance when physically pushing an object) is more difficult to display, since it depends on a physical directional force which is hard to realize without a matching real world counterpart. Though different solutions for providing *kinesthetic* haptic feedback in VR were presented by researchers, none of them is used in consumer hard- or software for facilitating kinesthetic feedback. These approaches require additional hardware, making it difficult to be included in consumer grade VR systems. In addition, most of the presented kinesthetic feedback devices are too big and expensive (e.g. exo-skeletons) to be integrated into consumer products.

The current state-of-the-art solution in today's VR games (e.g. [5, 21]) frequently is to let virtual hands clip through virtual objects. Since the real hand is not really colliding with the virtual object, there is no physical barrier to prevent the hands from penetrating a virtual object. In order to mitigate the effects thereof, i.e. breaks of immersion and presence, an approach to provide haptic feedback with current consumer-grade hardware is desirable. Further, such haptic feedback can provide benefits for developers of VR experiences, by offering new interaction possibilities currently limited by hardware. In general, two output channels can be used with the current consumer VR hardware: tactile haptics (in form of vibration) and visual (in form of pseudo-haptic feedback).

We hypothesize that it is possible to combine the tactile haptics and visual manipulations in a way to facilitate kinesthetic feedback for VR applications. By employing a user-elicited approach, we developed a first prototype using the available channels and let users interact with virtual objects. In a semi-structured interview we collected qualitative feedback on how to improve and design the respective channels. After updating the software prototype, we conducted a second study with the aim of getting insights on the effect of the different channels regarding immersion and enjoyment, but also on how realistic and sufficient the feedback was perceived. Finally,

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we contribute guidelines on how the feedback part of software should be designed to improve the VR experience.

We found that vibration can be combined with perceivable pseudo haptic effects to communicate kinesthetic feedback and even induce its perception to a certain degree. In addition, we found the current state-of-the-art using clipping is not appreciated by users. The presented solution, though, significantly increased immersion and enjoyment.

RELATED WORK

There are several object properties associated with haptics in general – such as pressure, temperature, size or weight. Considering kinesthetic feedback, the bone structure of the human body additionally forwards the resistance of a stationary object to be felt in larger parts of the body (e.g. pressing a hand against a wall can be felt in the shoulders). Researchers have presented a variety of solutions ranging from physical-only to software-only solutions to include such sensations inside VR. Since this paper is focused on tactile but most of all kinesthetic perception, the work presented in the following also is focused on these aspects.

Physical solutions

Tactile

The most common haptic feedback channel is vibration, as respective actuators are small and lightweight enough to fit in all kinds of wearables or controllers. It can also be found in the state of the art VR controllers (e.g. HTC Vive or Oculus Touch), was used in various kinds of wearables (e.g. [17, 28]) or was used in VR research projects (e.g. [34, 35]) to enhance tactile feedback.

Tactile feedback can also be applied by stretching the skin (e.g. [7, 2]), using physical shape displacement (e.g. [3]) or airflow (e.g. [43, 48]).

Weber et al. compared different ways of communicating collisions by visual, vibration and force feedback by a robotic arm [52]. They found that substituting force feedback with vibro-tactile cues increased the cognitive load, while visual feedback only was perceived as less ambiguous but increased the task completion time.

Kinesthetic

Those tactile interfaces do not allow displaying directional forces as needed to simulate kinesthetic feedback. Grabbing objects can for example be realized by using layer jamming (e.g. [47]). Another way of displaying directional forces is the use of tethers, which can be held (e.g. [33]) or stationary mounted around the user (e.g. [16]). Exoskeletons were also used to simulate forces or restrictions either on the hands [4, 6, 10, 13], an whole arm (e.g. [36]) or just attached between two body parts (e.g. [51]).The kinesthetic feedback of exoskeletons was also combined with tactile feedback (e.g. [20]).

Another way to provide directional kinesthetic feedback is the use of EMS (e.g. [11, 29, 30, 37, 50]) where single or groups of muscles are actuated. Lopes et al. used this approach to simulate even weight by actuating opposing muscles [31].

Using the real physical world

The physical mismatch between virtual and real world can be compensated by creating a physical world around the user. This was done using robots (e.g. [12, 32, 53]) or by other humans [8]. A similar idea is passive haptic feedback or the substitution of virtual objects with similarly shaped objects [14, 19, 46].

On the other hand, it was also suggested to visually redirect users' movements to match the virtual world with real world counterparts. This was done for touching static surfaces (e.g. [18, 45]) or objects [1].

Software solutions

Another way of communicating haptic feedback is by using pseudo-haptics, which can be applied using software-only solutions. The idea is to provide haptic feedback without the real stimulus, but by *faking* it via vision [22]. Visual stimuli are presented synchronized to interaction, like e.g. touching an object. Pseudo-haptics were most of all used for tactile feedback, such as friction [24, 25], stiffness [49]. Other works proposed to use pseudo-haptic effects to simulating forces [26, 23], the subtle resistance of airflow ([39, 40]) or weight [9]. On the other hand objects may react or deform as a reaction of touch (e.g. [38]).

These works show that it is possible to communicate directional forces by visual feedback only. Though, most of the presented works were not designed for the application in VR. The illusion of body ownership as well as the strong feeling of proprioception when directly interacting with a controller cannot be compared to on-screen-experiment using a mouse as input device (e.g. [23, 26]). Other approaches, which were tested and implemented for VR, use such effects in a very subtle way, without breaking with proprioception. It was shown, that virtual body motion can be manipulated to communicate special feedback (such as slow-motion) [42] and that perceivable tracking offsets are accepted as a metaphor for weight [41]. In contrast, we assumed that even obviously breaking with proprioception would still be more appreciated then the alternative of using clipping. We also expected that with increasing intensity of such effects the respective induced level of perception of kinesthetic feedback will increase.

PERCEIVABLE VISUAL MANIPULATIONS

Although different solutions to introduce haptic feedback in VR were presented, none of them was realized in consumer hardware. Even pseudo haptic effects which could be realized by a software-only solution are rarely found in applications. One problem of current pseudo haptic approaches is their expressiveness. This is due to limiting the design of visual manipulation in a way a user does not perceive breaking with proprioception. Though one could argue that this is of great importance to keep presence and immersion, we assume that perceivable manipulation can even enhance these feelings due to the additional feedback. Virtual reality does not have to be a one-to-one match of the real world. VR consumers already accept interaction metaphors as part of the virtual world (e.g. using teleportation for moving around). We therefore argue, that users may also accept perceivable visual manipulation as a metaphor of communicating kinesthetic feedback. On the other hand, the lack of perceivable manipulation has some drawbacks, too. When for example pushing against a virtual object that cannot be moved, the virtual hands have to penetrate it (clipping). We argue however, that such clipping effects are not less unrealistic than breaking the proprioception by applying stronger visual manipulations in form of tracking offsets.

With this paper, we aim at answering whether users prefer breaking with proprioception to enable the communication of kinesthetic feedback or dislike such a concept and prefer effects such as clipping. Further we strive to optimize such pseudo-haptic effects with the available haptic feedback channel (vibration).

We built our work on an approach based on user-elicitation and expert interviews. First, we conducted a workshop with VR researchers to discuss relevant aspects of haptic perception and the associated interaction, then we implemented a prototypical system that communicates kinesthetic feedback with perceivable tracking offsets as visual manipulation as well as vibration feedback. Based on the results of semi-structured interviews we improved the software prototype and conducted a second user study, in which we evaluated different combinations of channels for haptic feedback with respect to immersion, enjoyment and the perception of tactile and kinesthetic feedback. Finally, a second workshop with VR researchers was conducted to discuss the findings of the user study and their implications.

EXPERT WORKSHOP

The presence of natural haptic feedback in the real world is self-evident. A metric to describe the quality of haptic feedback is therefore not trivial. Since there is no questionnaire on measuring the quality of induced haptic perception, we invited five researchers working in the field of virtual reality to discuss the topic of haptic perception in VR. The experts were researchers with a focus on VR including three focused on interaction, one focused on perception and one working in the field of serious games.

Discussing the Quality of Haptic Perception

We motivated the discussion with the discordance of real and virtual space which prevents direct kinesthetic feedback.

It was first discussed that realism in terms of virtual reality might not be the same as in the real world. The consensus was that whether a certain feedback is actually realistic or not, it can be interpreted as realistic as long as it is perceived accordingly. Feedback should therefore conform to expectations. This should be represented by both, objects' behavior as well as the provided feedback. Expectations were divided into two main parts. The first was the presence of feedback or the respective stimulus. This implies, that e.g. a feeling of restriction, texture, touch or temperature, should be perceived at all. The second part of expectation conformity was seen as the realism of the respective feedback. The same two metrics could also be applied on objects' behavior, since objects should first of all react to user interaction, but also behave in a natural way.

Another important factor was seen in the ability of communicating objects properties in a way a user can compare two objects based on the respective feedback. This could be for example that one object is perceived as heavier, since it induces a stronger kinesthetic feedback.

The last topic was about direct manipulation. Haptic feedback should support the feeling of being in control of manipulating objects in the virtual world.

Though not relevant for our evaluation of kinesthetic feedback, two additional items were considered as relevant for special applications: (1) If there is kinesthetic feedback, it may be relevant how exhausting it was to interact with a virtual object. This effort could on one hand be interpreted as positive, if desired by the application e.g. in the simulation domain, or negative if too exhausting e.g. during casual gaming. (2) Some gaming scenarios could have an entirely different focus on haptic perception, since it may be more useful to communicate boundaries of interaction considering elements of game play, than to provide the most realistic feedback.

Deriving Questions

In the second part of the workshop the participants derived questions based on the discussion. This process was guided by the study conductor. The first two questions were based on the two discussed parts of expectation conformity. The first question, targeting towards measuring the presence of a stimulus was stated as *I could feel [a stimulus].* The second one, targeting to measure the perceived realism, was formulated as *The representation of [the stimulus] felt realistic.* The matching items for measuring the object behavior were *I could manipulate the behavior of objects with my actions* and *I had the feeling of manipulating real objects.* To measure the ability of communicating haptic properties to allow a discrimination on the basis of feedback was formulated as *I could perceive a different [object property] when interacting with the objects.*

USER STUDY I

We designed a simple VR application, in which participants had to interact directly with the virtual surrounding. By using state-of-the-art hardware we designed different feedback modalities using a common VR controller (Oculus Touch), as well as vibration and visual feedback in form of pseudo-haptics. We presented the different feedback modalities and measured immersion, enjoyment and our own items as discussed in the workshop. The focus of the first iteration was on collecting qualitative data regarding the perception of touch, how the stimuli should be presented and enhanced as well as how sufficient such haptic feedback would be for VR applications.

Participants

We recruited 12 participants (3 female) with an average age of 25.0 (*SD* = 2.3). They were mostly university students and employees. They had an average experience with VR of 9.4 months (*SD* = 11.6), ranging from none to 25 months. We aimed at recruiting very experienced but novice users (without any prior VR experience) as well to get as much variety of feedback as possible.

Design

This study was conducted as a 2x2 within-subjects design with the vibration of the controller and the visual redirection as variables. We did not use auditory feedback, except music to block out ambient noise and the sounds of the vibrating controller. We decided to exclude sound under the assumption, that the auditory channel does not play a major role when creating kinesthetic feedback. We consider auditory reactions of objects (e.g. objects falling to the floor) to be unrelated to the touch itself. We decided to exclude such sounds to prevent uncontrolled side effects, since such effect sounds assumedly only contribute to general presence and enjoyment.

Vibration

The vibration variable consisted of two states *vibration on* or *vibration off*. We implemented the controller to provide a short term vibration feedback of 200Hz for the duration of 50ms each time the virtual hand collided with an object. In the *vibration off* state there was no vibration at all.

Pseudo Haptics

The second variable was related to visual manipulation as pseudo-haptic feedback with two states (*pseudo-haptics on* and *pseudo-haptics off*). Both concepts are illustrated in Figure 1. In the common state-of-the art, the virtual representations of user's hands follow the tracked controller with the most possible accuracy. While the physics engine considers differences regarding weight and resistance between objects that are only virtually present, the controller (having also a real world representation) is treated differently, and is not influenced by virtual objects. While, for example, pushing a virtual object, there is no difference between heavy and light objects during the interaction. Objects, like walls, that are designed to be stationary in a scene and thus cannot be moved have to be clipped by the virtual representation of hands if they follow the tracked controller as close as possible. This state, which we consider as state-of-the-art, is further on referred to as *pseudo-haptics off*.

The second state (*pseudo-haptics on*) uses pseudo-haptic feedback without perceptual limitations and thus allowing a perceived conflict between proprioception and visual input. We designed the virtual hand to be detached from the tracked position of the controller and moved it by translating it each frame to match the real position. The virtual hands more or less modeled like any other physical object present in the virtual scene, but followed the tracking as close as possible as long as there was no barrier. When the hand collides with a virtual object, the kinesthetic force of the virtual hand presses against the virtual object. Depending on the virtual weight of the object, the required force to move it has to be greater or smaller. The euclidean distance between the tracked position and the virtual representation, which is applied as translation, is such a force. The applied force therefore depends on the offset between the virtual hand's representation and the tracked position of the controller. Depending on the object's resistance, the user perceives an increasing offset between visual and real position of the hands. Since a user has to stretch her hands farther for moving heavier objects, such a visual manipulation even leads to a higher effort. In the case of a static unmovable object, there is conceptually no offset limit and the unmovable object as well as the virtual hands keep their position.

Apparatus

As VR headset we used the Oculus Rift CV1 and the Oculus Touch controllers. Our application software was developed with Unity. The virtual environment contained four tasks that were implemented to be representative for different direct interactions with virtual objects (see Figure 2).

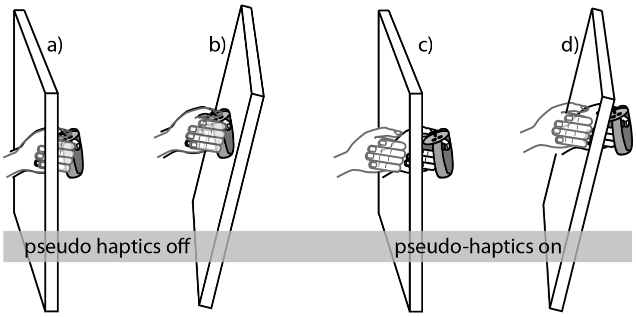

Figure 1. The visual effects present in both visual conditions (red hand represents the virtual one): a) Clipping: if an object cannot be moved, the virtual hand follows the tracked one and penetrates the object. b) when an object can be moved, there is no representation of physical resistance. c) using pseudo haptic feedback, the virtual hand does not penetrate the unmovable object, but the offset between tracker and virtual hand increases. d) An object communicates the resistance by no longer following the exact tracking position (the offset depends on the strength of physical resistance).

Heavy or static objects:

The first task consisted of three walls. The participants were instructed that they could overturn one of them, while the others would be solid. The walls were set to be unmovable until the first two were touched, to make sure that the participants have to try each wall. This condition was used to compare clipping with high pseudo haptic offsets. Depending on the condition, the hands clipped through the unmovable walls or suffered an increasing offset while pressing. The third wall did not resist when being pushed in the *pseudo-haptics off* state, though the visual appearance suggested a heavy weight. In the *pseudo-haptics on* state the wall *resisted*, which led to an offset between tracked controller and the visual position of the hands. This implies that the hands had to reach farther to overturn the wall.

Light objects:

The second task aimed at interacting with smaller and lighter objects. Three vases were placed on a base and the participants had to throw them down. Due to the low weight of the objects, there was only little difference between the *pseudo-haptics on* or *off* state. The pseudo-haptic manipulation only led to little offsets and therefore only little more effort to move the objects. The base was unmovable when touched which led to the already described effects.

Different weights:

As discussed in the workshop, a feedback modality should allow the comparison of object parameters. The third task was therefore to press three stone cubes into a slot in the wall. All cubes had a different weight and therefore resulted in a different strength of kinesthetic forces. In the *pseudo-haptics on* state the differences were represented offsets.

Heavy round object:

The first task involved short pushing of heavy objects, but with the focus on investigating effects of clipping. We therefore included a second task on interacting with heavy objects, though for a longer time. The last task was to roll a heavy stone sphere. Due to the heavy weight and strong friction of the sphere, both visual states differed strongly. In the *pseudo-haptics on* condition the resistance lead to large offsets which aggravated to get the stone rolling. There was no visual communication of resistance in the *pseudo-haptics off* state.

Procedure

The participants were welcomed and introduced to the topic of the study. The introduction included the problem definition of having no direct haptic feedback due to the mismatch between real and virtual world. They were also informed that they could pause or cease the test at any time. The participants were also instructed what to do in the respective tasks. Before starting with the first condition, each participant signed a consent form and completed a demographic questionnaire.

We tested four conditions based on the 2x2 study design (*vibration on, pseudo-haptics on*, *vibration on, pseudo-haptics off*, *vibration off, pseudo-haptics on* and *vibration off, pseudo-haptics off*). Participants played each condition in a different order balanced by a Latin square. After each condition the participants completed the E^{2}I questionnaire [27] to measure immersion and enjoyment. In addition, we used our own the questions as reported in the workshop.

The participants should state for each task separately how they agree to some statements on a scale from 1 (=strongly disagree) to 6 (=strongly agree). These statements were *“I had the feeling to touch the walls/vases/cubes/sphere”*, *“I could feel a resistance”*, *“The representation of physical constraints felt realistic"*, *I had the feeling of manipulating real objects* and *“I could manipulate the behavior of objects with my actions”*. For task 3, which involved different strength of kinesthetic feedback we also asked *I could feel a difference regarding the resistance of the cubes.* In addition to the items stated by the participants of the workshop, we included two more questions: *“The representation of physical constraints was sufficient for VR applications”* and *“I liked this representation of physical constraints”*.

After completing all tasks, we conducted a semi-structured interview. The topics of interest mostly considered how the participants perceived the different tasks and conditions and which conditions they preferred for each tasks. We also discussed how the respective feedback channels could be designed to increase the desired perception.

A session lasted around 40 minutes and each participant was compensated with 5 Euro.

Results

We first analyzed the difference between the tasks for each condition separately using Friedman’s variance analysis. If there was a significant difference, we compared the tasks pairwise adjusting the significance values with the Bonferroni correction. Here we tested only our individual items, since they were the only ones that were gathered for each task separately.

Though the Friedman test showed significant differences, there was no post-hoc difference between the tasks. We therefore calculated a mean of all tasks and used this mean for further comparisons.

	Vibration			Pseudo-haptics		
Score/Item	$\delta\varnothing$	*SD*	*p*	$\delta\varnothing$	*SD*	*p*
Immersion	0.52	0.80	.04*	0.40	0.62	.04*
Enjoyment	0.17	1.20	.53	0.70	0.97	.03*
Touch	0.57	1.45	.15	1.40	1.20	.003*
Resistance	1.00	1.80	.07	1.75	1.56	.003*
Sufficient	0.59	1.50	.01*	1.20	1.31	.007*
Realistic	0.67	1.50	.10	1.60	1.39	.004*
Like	0.90	1.60	.20	1.35	1.30	.001*

Table 1. Overview of the change of the scores compared to the ground truth without vibration and pseudo-haptics: $\delta\varnothing$ is the mean change of the scores when being treated with vibration or pseudo-haptics (positive implies an increase of the respective score).

In the next step, we examined the influence of visual and vibration feedback comparing the“*vibration on, visuals off*" and “*vibration off, visuals on*" conditions to the ground truth (*vibration off, visuals off*), using Wilcoxon’s signed rank test. Vibration significantly enhanced immersion and the approval about whether the representation was sufficient for VR applications. Giving visual feedback significantly improved all scores and items (see Table 1).

The recordings of the semi-structured interviews were transcribed in note form. Two researchers performed an open coding on the interviews. All codes were compared and conflicts resolved by discussion. By axial coding, based on the codes, themes and concepts were identified.

Vibration was seen as a supporting channel enhancing the visual feedback of touch (four mentions). If there was only vibration feedback, it was seen as disturbing (three mentions) or irrelevant (one mention). On the other hand, participants saw greater potential for vibration feedback to communicate kinesthetic and tactile feedback when combined with visual pseudo-haptics. Five participants emphasized the interaction between vibration and offsets. They saw vibration as a supportive channel, enhancing the feeling of kinesthetic forces when combined with pseudo-haptics, but not when presented alone. For one participant, vibration was enough tactile feedback.

Pseudo-haptic feedback was most of all described as realistic (eight mentions) while four participants stated a physical feeling of restrictions. Four participants commended the greater design space, since they could identify different levels of restrictions. One of them saw great potential for interactions. Besides this, the redirection metaphor was described as logical and playful. Participants also associated the offsets with pressure between hand and object. One participant criticized offsets of static objects when fully stretching the arms. Another participant stated **clipping** would be more realistic, since there is no matching real counterpart to touch. All other participants, however, were opposed to clipping. Some stated it felt like an error of the game while others just described it as unrealistic or that it would destroy the immersion.

Another topic of interest was **missing haptic feedback**. Two participants stated that it would destroy the immersion to get no real haptic feedback. The other participants did not miss haptics that much. Some stated that they just do not expect a true haptic feedback due to the nature of virtual reality. Eight participants stated that the representations were enough, while two emphasized the importance of vibration and five

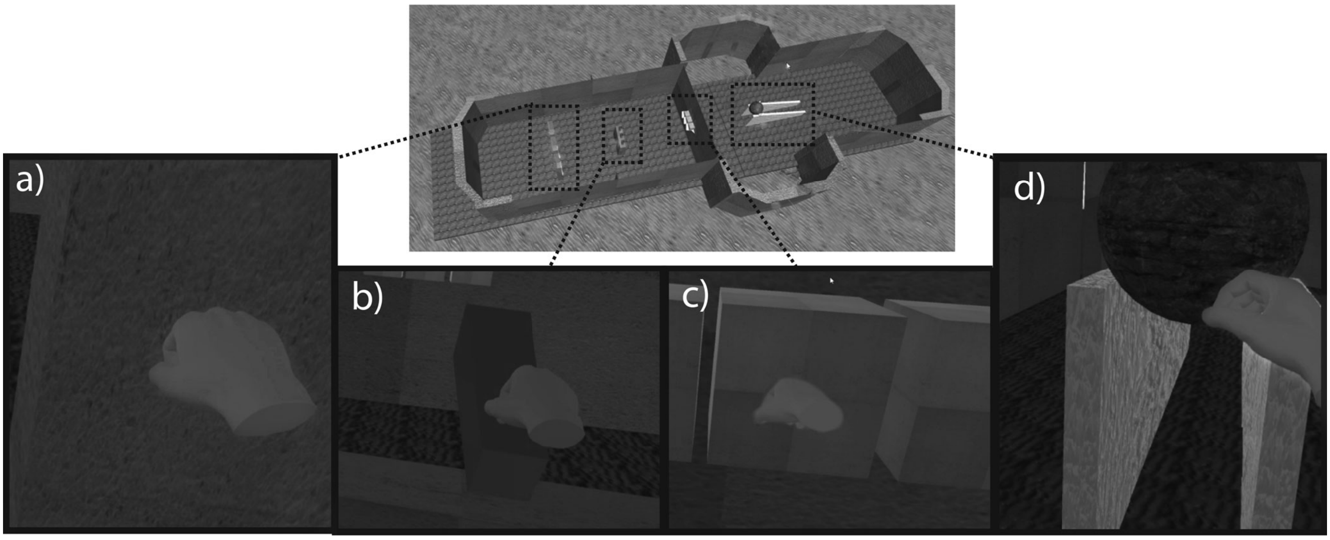

Figure 2. The different tasks as implemented for the study: a) one of the three stone walls which should be overturned, b) a vase on the base which should be thrown down, c) the cubes which should be pressed into the wall and d) the heavy stone sphere which should be rolled.

the pseudo-haptic. Another participant stated that visual and vibration is enough, but only compared to no feedback.

Finally, we identified potential **improvements** regarding the design of the available feedback channels. One half of the participants stated a desire for constant vibration while touching objects, while others wanted the vibration to be designed more subtle. Eight participants wished to couple the vibration with the visual feedback in a way that vibration increases with the pressure which was visualized by increasing offsets. Three participants desired the visual hands to react on the touch. This could for example be done by forming a fist, or if the hands are open prior to the touch, by stretching fingers. Two participants also talked about auditory feedback when manipulating objects. The participant who struggled with too high offsets when pressing against a static object with fully stretched hands suggested to use clipping as a fall back strategy in such cases.

USER STUDY II

We implemented the participants' suggestions for improving the feedback channels and conducted a second user study to further evaluate our research question. The same conditions were used as in the first study, i.e. vibration (on-off) and pseudo-haptics (on-off). Since some participants complained about missing auditory feedback we designed another condition (*full feedback*). This condition included all feedback channels with additional effect sounds. These effects were crashing sounds when the wall or vases drop to the ground, scratching when the cubes were pressed into the wall and a sound of a rolling ball while the sphere of the last task was moving. Besides the demand of the participants for heaving sound effects, we were also interested to test our solution in a condition which is more related to a common application, where sound effects are most likely part of.

Participants

We recruited another 20 participants (10 female) with an average age of 24.3 (*SD* = 2.3). They had 2.6 months of VR experience on average (*SD* = 6.4), ranging from none (10 participants) to 24 months. In this study, we aimed at recruiting most of all novice VR users, since we expected them to provide the most neutral feedback without being influenced by existing representations.

Apparatus

The same hardware setup was used as in the first user study and the virtual environment and tasks remained the same as well. However, we implemented a couple of software improvements we derived from the interviews.

Visual feedback: Since the participants hands were holding a controller, their hands already formed a fist (real and virtual). We therefore decided to visually close the hands more when an object was touched. This feature was implemented as an animation changing the finger angles as soon as the hand's collided with an object.

Vibration feedback: Most of the participants comments were about the vibration. They desired a constant feedback which should be coupled with the visual feedback. We therefore implemented vibration in two different ways. In the *vibration on, pseudo-haptics off* condition, vibration was changed to be lasting as long as an object was touched. We also decreased the frequency to 150Hz according to the wish of some participants.

In the *vibration on, pseudo-haptics on* condition, we increased the frequency of the vibration with the euclidean distance between the tracked position of the controller and the visually displayed hand. Since the increasing offsets were associated with pressure, the increasing frequency should also be used as the same metaphor as desired by some participants.

Procedure

The second study was designed equal to the first one, including the same introduction and questionnaires. The tested conditions remained the same in general except the described modifications. The order of conditions was again balanced by Latin square. After each task, participants completed the questionnaires known from the first study. After the last iteration, the participants were asked to fill in a final questionnaire containing more general questions. Participants stated their agreement on a scale from 1 (=strongly disagree) to 6 (=strongly agree) to several statements. The first statements regarded the different feedback channels and included the items *“The resistance of an object should be represented by vibration"*, *“The resistance of an object should be represented by visual offsets"* and *“My hands should penetrate objects that cannot be moved"*.

After this final questionnaire the participants were presented the last condition with additional effect sounds. This condition was always played last, since we refer effect audio not to be directly contributing to kinesthetic perceptions, but though most likely influencing some of the scores. We therefore did not compute any statistical test on this condition and only used it as hint towards how compelling a real application could be with the proposed combination of vibration and pseudo-haptic feedback. Here we also measured immersion, enjoyment as well as our own items.

A session lasted for about 45 minutes and each participant was compensated with 5 Euro.

Results

We split the description of results in four main parts. Starting with the difference between the tasks, we compare the influence of the different feedback channels as well as the differences between the first and second iteration. We conclude with the results of the final questionnaire.

Tasks

As a first step, we compared the tasks of each condition for differences regarding the scores with Friedman's variance analysis for dependent variables. There was no significant difference, so we calculated a mean score over all tasks as score for the whole condition.

Feedback Channels

The results of presence and enjoyment is illustrated in Figure 4, the individual items are shown in Figure 6 and Figure 5. The ratings for the rating whether the representation was sufficient are illustrated in Figure 3.

We compared the conditions having only one feedback channel being in the *on* state to the ground truth (all states *off*) using Wilcoxon's signed rank tests to get insights on the influence of the different feedback channels.

While immersion and enjoyment was not influenced significantly by vibration, we could find a significant increase of the feeling of touch (*p=.028; Z=2.0; r=.45*) and resistance (*p=.021; Z=2.4; r=.54*).

Comparing the *pseudo-haptics* with the ground truth, immersion (*p=.025; Z=2.50; r=.56*) and enjoyment (*p=.048; Z=1.95; r=.44*) were significantly increased. We also observed a significant increase of the feeling of touch (*p=.002; Z=3.03; r=.68*) and resistance (*p=.001; Z=3.23; r=.72*). There was also a significant difference regarding the rating whether the haptic feedback would be sufficient (*p=.001; Z=3.27; r=.73*). The participant also reported a significant higher feeling of touching real objects (*p=.002; Z=3.10; r=.70*) and the feeling of being more in control of the manipulations (*p=.033; Z=2.14; r=.48*).

The item whether participants could distinguish between different strengths of kinesthetic feedback was only asked for the third task and was therefore not averaged over all tasks. While vibration did not increase the ability to differentiate kinesthetic feedback (*p=.63; Z=.74; r=.17*). The pseudo-haptics though significantly increased this ability (*p=.007; Z=2.72; r=.06*).

The condition where vibration was coupled with pseudo-haptic feedback increased the immersion (*p=.012; Z=2.5; r=.56*) and enjoyment score (*p=.031; Z=2.16; r=.48*) as well as the single items regarding the feeling of touch (*p=.00; Z=3.70; r=.83*), restriction (*p=.00; Z=3.75; r=.84*), realism (*p=.001; Z=3.21; r=.72*) as well as the feeling of interacting with real objects (*p=.001; Z=3.19; r=.71*) and being on control (*p=.003; Z=3.02; r=.68*). Participants also liked the condition more (*p=.004; Z=2.90; r=.65*) and rated it to be more sufficient (*p=.00; Z=3.49; r=.78*). The ability to differentiate different strengths of kinesthetic feedback was also judged as significantly higher (*p=.00; Z=3.66; r=.82*).

We also compared the three feedback modalities (vibration, pseudo-haptic and the combination of pseudo-haptic feedback and vibration) using the Friedman's analysis of variance.

While immersion and enjoyment did not differ significantly, our individual items did all show significant differences. Pairwise comparisons with Bonferroni corrected significance values showed that the combined feedback provided a better feeling of touch (*p=.002; Z=3.41; r=.76*) and resistance (*p=.003; Z=3.32; r=.74*) than vibration only. It was also liked more (*p=.028; Z=2.60; r=.58*) and rated more sufficient (*p=.001; Z=3.72; r=.83*) and realistic (*p=.003; Z=3.33; r=.74*) than vibration only. The use of pseudo-haptic feedback only also provided a stronger feeling of resistance compared to vibration only (*p=.027*).

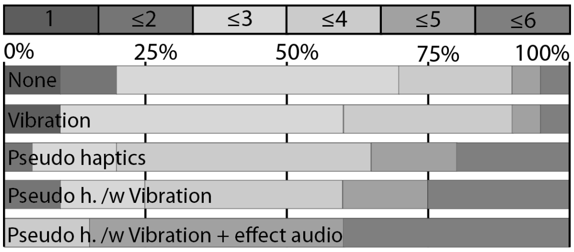

Figure 3. The ratings of the item whether the feedback modality was sufficient to communicate kinesthetic feedback.

Study I vs Study II

We also compared both iterations using the Mann-Whitney-U test. The only condition that was the same in both iterations was the ground truth with all states *off*. Here we found no significant difference between both iterations.

There was also no significant difference comparing the pseudo-haptics and vibration only conditions. The *“pseudo-haptics on, vibration on"* condition though was significantly different in the first and second iteration regarding immersion (*p=.048*) and enjoyment (*p=.043*) as well as the single items whether the

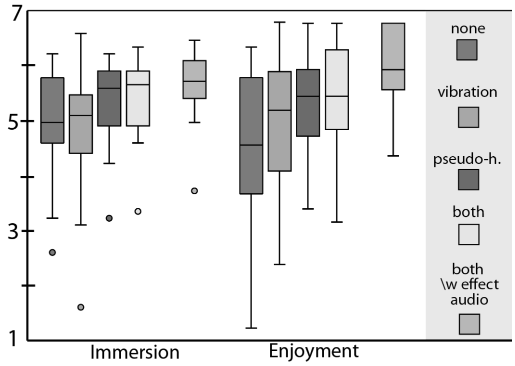

Figure 4. Box plots of the immersion and enjoyment scores.

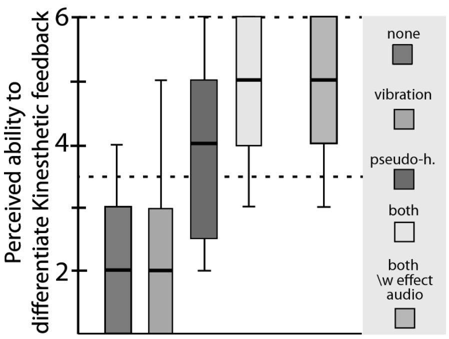

Figure 5. Box plots of the ratings whether the participants could distinguish different kinesthetic feedback. Note: Scores are only based on task 3.

feedback was sufficient (*p=.008*) and realistic (*p=.050*). We also found a significant increase on the perception of touching real objects (*p=.025*) and the perceived ability to manipulate them (*p=.025*). Participants also liked the second iteration significantly more then the first one (*p=.002*). An overview of the results is presented in Figure 7.

Final Questionnaire

After all conditions (except the separate condition including effect sounds) were played and all questionnaires were completed, the participants answered one last questionnaire containing items concerning their general preferences. The participants were asked to answer whether they agree to statements about the use of the respective feedback channels. Most participants agreed that vibration and pseudo-haptic feedback should be used to represent kinesthetic feedback, while clipping should be avoided. The results are shown in Figure 8.

EXPERT DISCUSSION

We presented the results to the same VR researchers, that were involved in the initial workshop. We discussed implications, as well as limitations in general. Before the discussion, all participants tested the different conditions.

The item whether the haptic representation was sufficient was discussed a lot. All agreed that sufficient has to be distinguished from more positive adjectives (e.g. good). On the other hand, they discussed that VR consumers have low expectations on haptic feedback which could also lead to higher scores. The item *sufficient* should as well be interpreted in the context of the application. A representation may be sufficient for gaming but not for simulations.

Another interesting part of the discussion was about the context. Pseudo-haptic feedback was described as a good way to communicate kinesthetic feedback, but in some gaming scenarios this may not be in focus. Sometimes it is of greater importance to communicate simple object states. In case of static or movable objects it may therefore be useful to use clipping, since it is faster in communicating whether the user can or cannot interact with an object. On the other hand, most of all the pseudo-haptic effects were largely appreciated since they do not only provide some kind of haptic information, but can also be used as part of the game play. Displaying different resistances by tracking offsets could lead to playful effects, such as needing both hands to push an object. According to the experts, the pseudo-haptic feedback also leads to a more natural behavior of objects (e.g. a heavier object moves slower). The experts emphasized the importance of the suggestion raised in the first iteration using an escape strategy, such as clipping, when offsets increase too high. The experts saw a great importance of including stronger effects like the used deformation of the hands to communicate touch or pressure. It was suggested to deform the fingers and change their color to simulate accumulation of blood while pressing.

DISCUSSION

Our questionnaire consisted of two standardized scores (immersion and enjoyment) and some individual items as discussed in the initial workshop. The following discussion will be divided in three main categories: *expectation conformity, game play* and *participants preferences*.

Expectation Conformity

As discussed in the initial workshop, four of the own items were related to expectation conformity and realism. We also associate the immersion score to be contributing towards realism.

Regarding the different feedback modalities, the pseudo-haptic feedback proved to have the greatest effect on the perception of kinesthetic feedback. While we expected that vibration would have a greater effect on the feeling of touch, and pseudo-haptics being more suitable to communicate kinesthetic feedback, pseudo-haptics proved to be as suitable as vibration to communicate the touch.

Interestingly, the combination of pseudo-haptics with vibration increased immersion, as well as the other scores the most. This matches the results of the semi-structured interview of the first study. Here participants rated vibration as a support channel for visual offsets.

In general, though there were significant differences the rather large variances have to be considered when interpreting the data. The single feedback modalities (vibration only or pseudo-haptics only), as well as the ground truth, all resulted in very diverse judgments, while the combination of vibration and pseudo-haptics seemed to be more consistent. We interpret these variances as result of different expectations. While some participants may be used to vibration as general feedback

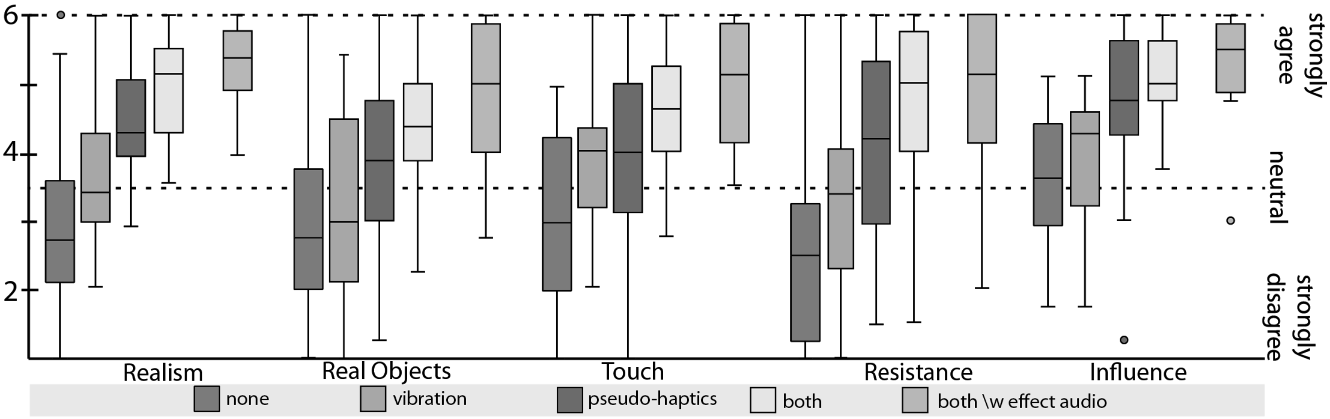

Figure 6. Box plots of the own items.

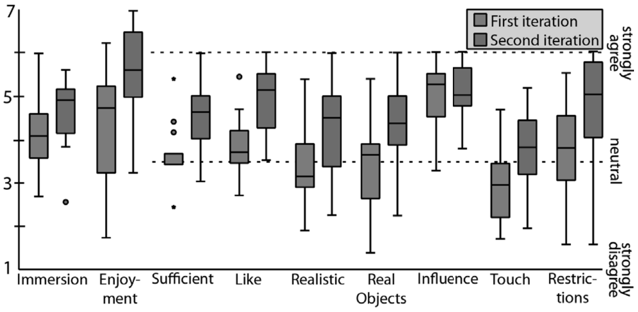

Figure 7. Results of the first and second iteration of the *vibration on, pseudo-haptics on* condition. Note: Immersion and enjoyment scores are on a scale from 1 (minimum) to 7 (maximum), while other items are on a scale from 1 (strongly disagree) to 6 (strongly agree)

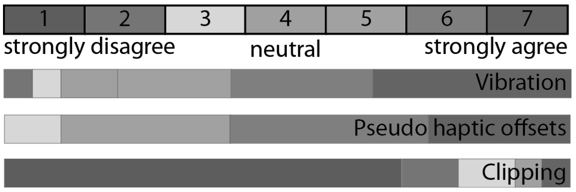

Figure 8. Participants desired the use of vibration and most of all pseudo-haptic effects, while they most of all disagreed with the use of clipping.

channel – which is common in many video games – others may be not.

The use of effect audio: The additional use of effect audio showed interesting effects. While some scores were influenced stronger than others, most of all the variances in the ratings decreased (see Figures 4 and 6). This is a hint towards the importance of auditory effects on the perceived realism. Objects should not only react visually but also via audio to user interactions.

Game Play

We associate the scores of influencing objects as well as the enjoyment score to be contributing to game play issues. The application was not designed as a game, since we did not want to distract the participants from the provided haptic feedback. We therefore want to emphasize that enjoyment scores could vary strongly depending on the context of the application. Since enjoyment was not the focus of the experiment, it was not unexpected that the scores did not vary strongly over the different conditions. Yet most of all, pseudo-haptics did positively influence the enjoyment score (besides effect audio). We assume, that introducing larger visual offsets also introduces new challenges such as judging the required strength to set objects in motion. Interestingly, the perceived ability to influence objects was strongest improved by pseudo-haptic effects. Though the presented offsets did aggravate the manipulation of objects (since they visually resisted) participants had the impression of being more in control.

Participant's Preferences

The participants agreed on simulating haptic feedback with both, vibration and pseudo-haptic offsets. In contrast, the participants did refuse the use of clipping. This emphasizes the importance of introducing even perceivable offsets in virtual reality. The avoidance of clipping requires the introduction of offsets, since unmovable objects cannot be displayed in another way.

Interestingly, the current feedback modalities were seen as sufficient for VR applications. In the condition combining vibration and pseudo-haptics with auditory effects there was no participant stating the feedback was insufficient. But as already discussed by the experts, this item has to be interpreted with care. Though haptic feedback can be displayed in a kind of sufficient way – if designed well – we argue, that this does not imply that there is no need for better haptic devices.

Limitations

Since we only used state-of-the-art hardware, we had no condition involving real and natural haptic feedback. We believe, that some judgments of the participants would differ when comparing the haptic metaphors like vibration and pseudo-haptics to the interaction with real objects. Most of all the item regarding whether the kinesthetic feedback as sufficient has to be distinguished from more positive adjectives, and could also be influenced by the low expectations of participants towards receiving kinesthetic feedback in VR (see Section *Expert Discussion*).

Measuring the quality of haptic feedback in VR is not trivial, as was discussed in the initial workshop. We believe that many of our items are strongly related to expectations and the application itself. While some participants accept haptic metaphors like vibration and pseudo-haptic feedback, others did not. This led to huge variances regarding the results, which aggravates the interpretation. Though, we found a significant trend that even obvious offsets were preferred over clipping or the complete absence of kinesthetic feedback, as it is the current state-of-the art.

Regarding the comparison of study I and II it should be considered that a different amount of users with a different distribution of experience was tested.

IMPLICATIONS

Our results indicate that it is possible to communicate kinesthetic feedback with the current state-of-the-art hardware. Most of all the stronger visual manipulation using offsets proved to be of great importance. However, such effects are currently either not used at all, or used too subtle in VR applications. We could show that offsets can be used far beyond the limits of not conflicting with proprioception.

While the perception of kinesthetic feedback as well as most of the scores about realism and even enjoyment was increased by introducing such pseudo-kinesthetic feedback (most of all when combining visual and vibration feedback), we argue that there is a huge potential – even beyond immersion and presence. We showed that by using stronger visual manipulation by offsets, objects can be compared regarding the strength of resistance. Further, users have to exert more intensely to compensate the offsets and move objects with higher friction or weight. Kinesthetic feedback can therefore also be used as part of the game play, where users can explore objects more closely and where kinesthetic forces even lead to higher exertion. We therefore suggest the following to improve the perception of kinesthetic feedback:

Avoid clipping: Our results show a huge impact of pseudo-haptic effects on the perception of kinesthetic feedback as well as immersion. Along with that finding, the common state of the art of using clipping for static objects was very much unpopular. Our results indicate that offsets are a desired feature, and not perceived as disturbing. Most of all, realism was increased by introducing tracking offsets, since objects behave differently depending on their properties, even during direct manipulations.

Synchronize vibration with visual pseudo-haptics: Vibration as a standalone feature was less expressive and suitable for communicating haptic features and was seen as a supportive channel for visual pseudo-haptic effects. In our tests, the coupling of vibration with pseudo-haptic offsets (and therefore the pressure a user exerts on an object) provided the best haptic (tactile and kinesthetic) perception using the state-of-the-art hardware. Combined with effect audio, there was no participant stating this kind of feedback was insufficient for VR applications.

Use pseudo-haptic effects – but with care: We argue, that perceivable pseudo-haptic feedback is a very promising approach for VR applications, since it is able to communicate kinesthetic feedback. We therefore suggest to pay greater attention to higher degrees of visual manipulation as it was done prior. Our results show that even larger offsets, breaking obviously with proprioception, were accepted and appreciated as metaphor for kinesthetic feedback. However, there is a limit of such effects that should be considered for static objects, where offsets conceptually can increase unlimited. Participants and experts suggested to use clipping as escape strategy, when offsets increase too much.

Kinesthetic Feedback as a Game Mechanic: Our approach is able to create the perception of kinesthetic feedback and allows its comparison. With regard to games, however, it even enables new types of play experiences. The possibility to create different types of object properties can be used in various types of exploratory game experiences. For example, players could have to find hidden switches in walls by searching for differences in resistance. Communicating these object properties would be difficult with regular button interaction.

CONCLUSION

VR got to a point, where most of all the visual consumer hardware has made huge steps. On the other hand, there is a tendency towards direct interaction using tracked controllers, where users stand or even walk in reality. This additional degree of freedom also leads to new challenges concerning the mismatch of real and virtual world. Compared to the use of indirect interaction, like playing with a gamepad, users expect haptic or kinesthetic feedback when touching virtual objects. The current hardware is very limited displaying haptic features while the controller in the user's hands as well as vibration is the only available haptic modality.

We used the state-of-the-art-hardware, implemented different haptic representations using vibration and pseudo-haptics. Our pseudo-haptic manipulation go much farther than prior reported ones, and can lead to obvious breaks with proprioception, but thereby increase their expressiveness. We measured the influence on immersion, enjoyment and perception related items, which were determined in a workshop with VR researchers. We also collected qualitative feedback on how the available channels should be designed and improved. Improving the software implementation based on the suggestions, we found a strong influence of pseudo-haptic effects, while vibration was most of all seen as a supportive channel for visual effects. In addition, we found a very promising interaction between visual and vibration feedback for the communication of kinesthetic feedback.

According to our participants, the combination of visual and vibration feedback is sufficient to communicate kinesthetic feedback. We therefore argue, that when being implemented well, kinesthetic feedback can not only be used to increase immersion, but also to increase enjoyment by becoming part of the game play.

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VRSpinning: Exploring the Desing Space of a 1D Rotation Platform to Increase the Perception of Self-Motion in VR

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VRSpinning: Exploring the Design Space of a 1D Rotation Platform to Increase the Perception of Self-Motion in VR

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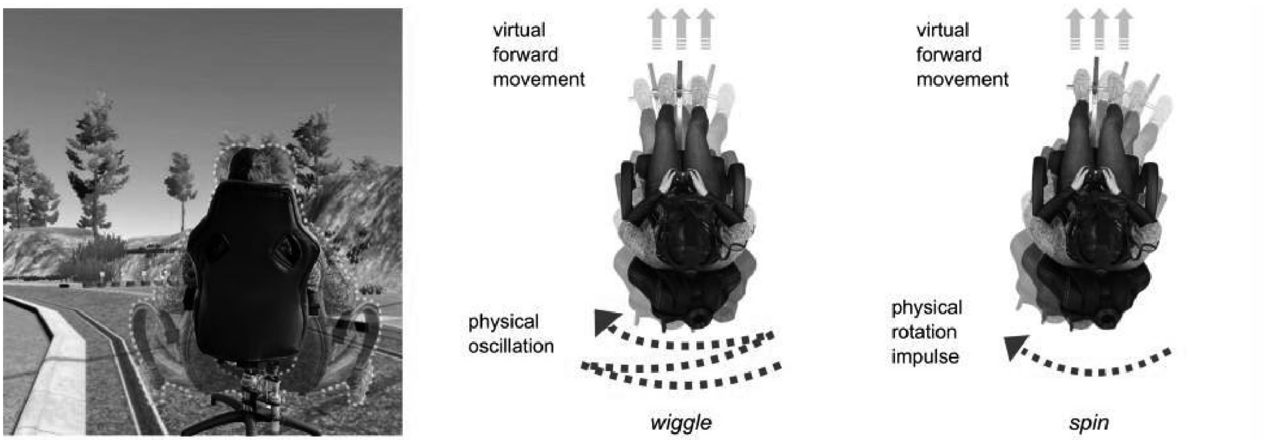

Figure 1. Forward motion approaches of *VRSpinning* to increase vection and reduce simulator sickness: *wiggle* movement to simulate steps or environmental events in VR (left middle), *spin* movement to simulate forward acceleration in VR by applying a short rotational impulse.

ABSTRACT

Current approaches for locomotion in virtual reality are either creating a visual-vestibular conflict, which is assumed to cause simulator sickness, or use metaphors such as teleportation to travel longer distances, lacking the perception of self motion. We propose *VRSpinning*, a seated locomotion approach based around stimulating the user's vestibular system using a rotational impulse to induce the perception of linear self-motion. In a first study we explored the approach of oscillating the chair in different frequencies during visual forward motion and collected user preferences on applying these feedback types. In a second user study we used short bursts of rotational acceleration to match the visual forward acceleration. We found that this rotational stimulus significantly reduced simulator sickness and increased the perception of self-motion in comparison to no physical motion.

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virtual reality; simulator sickness; vection; seated navigation.

INTRODUCTION

The majority of current locomotion techniques for virtual reality (VR) are focused around standing and short term walking experiences (e.g. HTC Vive or Oculus Rift) using teleportation as a metaphor for traveling longer distances. However, this excludes applications such as driving or flight simulators, where self-motion cannot be solved by teleportation. Additionally, virtual reality requires to be designed to immerse the user for a longer duration than most current short demonstrations (e.g. Fallout 4 VR, Skyrim VR, Doom VR, Gran Tourismo VR) to become a relevant medium for entertainment. All of these recent AAA titles and most likely the upcoming games depend on some kind of locomotion suitable for a longer exposure.

The two currently most dominant forms of locomotion are either physical movement through a tracked space (e.g. HTC Vive) or virtual metaphors such as teleportation (e.g. Fallout 4 VR, Doom VR) and virtual movement (e.g. Resident Evil VR). Since a tracked space is often smaller than the virtual world the user explores, physical movement is often combined with a form of virtual metaphors, when a user reaches the physical limits. Physical movement over time results in high levels of fatigue and will become uncomfortable for longer experiences. Virtual metaphors on the other hand can be used over a longer duration (also while seated) but lack the perception of vection (e.g. teleportation) and can result in higher levels of simulator sickness (e.g. virtual movement) [5]. Therefore, VR requires a (physical) locomotion feedback that creates the feeling of self-motion without causing simulator sickness.

We propose to use physical feedback generated through a motion platform on an actuated swivel chair, which we call *VRSpinning*. We implemented different actuation patterns (*wiggle*, *spin*) and introduce the concept of presenting a visual stimulus (forward acceleration) synchronously with a short and non-matching vestibular stimulus (rotational acceleration), tricking human perception into interpreting the rotational acceleration cue as a forward acceleration (see Figure 1). We found that this approach significantly reduces simulator sickness and increases the perception of self-motion.

To fine tune the stimuli we developed *VRSpinning* using a user centered design approach. We explored two different rotational stimuli to enhance the feeling of forward motion and ran two studies. In the first study we used oscillation for simulating three different movement approaches for forward motion (walking, driving, flying). We ran an exploratory study, exposing the user with the technique and having a think aloud feedback session, collecting calibration values and preferences. We found that users quickly mapped the oscillation to virtual steps but disliked the continuous stimulus when virtually driving or flying. Based on this feedback we redesigned the stimulus to be a short physical rotational acceleration only at the start of a visual forward motion. We countered the physical rotation inside of VR so that users are physically rotated but still keep looking in the same virtual direction. In the second study we measured vection, simulator sickness and presence compared to no physical rotation. We found that the rotational impulse of *VRSpinning* reduced simulator sickness and significantly increased vection as well as the feeling of acceleration compared to no physical motion.

The main contributions of our work are:

- The concept of presenting a visual stimulus (forward acceleration) synchronously with a short and non-matching vestibular stimulus (rotational acceleration), tricking human perception into interpreting the rotational acceleration cue as a forward acceleration.
- Findings from an exploratory user study on an oscillating stimulus for a walking metaphor and resulting user preferences.
- Findings from a second comparative study showing the decrease of simulator sickness and increase of vection using the *VRSpinning* concept for forward motion in virtual reality.

RELATED WORK

Vection

According to [1] and [19] vection can be defined as a *conscious subjective experience of self-motion*, which includes both perceptions and feelings of self-motion. Vection is thereby induced by optokinetic stimulation, but is also influenced by other sensory systems including the vestibular one.

It has been shown that during circular vection, i.e. illusory self-rotation, the perceived direction is opposite to the actual moving direction. This effect is caused by three semi-circular canals of the inner ear that act similar to leaky integrators. Therefore, a constant signal of velocity will decay after less than a minute, which causes that humans are not able to detect rotational movement without visual stimuli [7]. A similar effect can be observed in terms of forward motion. As the vestibular system only detects changes of velocity (accelerations), it will not respond to a constant velocity and also not detect any conflict (since the null signal is expected). This effect is referred to as onset latency, which can vary from a few seconds to half a minute [23]. We leverage this effect by applying a rotational acceleration in order to simulate forward movement in virtual reality. We assume that the direction of a short term acceleration cannot be recognized. However, it should be enough to support the feeling of self-motion induced by the visual stimulus.

Simulator Sickness

The phenomenon of simulator sickness is a well known problem of VR applications. It is commonly considered as a subset of motion sickness, therefore symptoms are related and include eye strain, headache, sweating, vertigo and nausea [15]. The cause of simulator sickness is of polygenic nature [12], however, scientific consent points towards vection as a possible cause of simulator sickness [10]. The two perceptual systems that are mainly involved in perception of self-motion are the vestibular and the visual sensory system. The vestibulo-ocular reflex, which ensures that the eyes are kept in place while the head is moving, elucidates the important relationship between these two senses [15]. Three main theories (sensory conflict theory [21], postural instability theory [22] and poison theory [27]) give an explanation for the phenomenon. The sensory conflict theory is the oldest and most accepted one [15]. It states that the body is not able to handle dissimilar information from different sensory systems. In VR a person usually perceives motion visually, while the vestibular system signals stasis. We counter this by giving a vestibular stimulus (rotational acceleration) synchronously with a visual stimulus. Though conflicting concerning the direction of acceleration, we assume that the short application of physical stimulation is long enough to be perceived as vestibular stimulus, but short enough to prevent the perception of the actual direction. Combined with the fact that the visual stimulus is considered more dominant lead to our assumption that using a rotational impulse combined with visual motion could increase vection and reduce simulator sickness.

Vection During Sensory Conflicts

The human central nervous system integrates visual and vestibular information to get a compelling perception of motion. According to the sensory conflict theory, conflicts arise when merging sensory information does not lead to a coherent and robust perception. One way to constitute a solution is the dominance of one sense over the others.

Although the visual sense is able to dominate the perception of motion, it is not clear how vestibular information integrates with visual information. Wright [28] tested horizontal and vertical visual motions on seated participants during forward motion. For both horizontal and vertical motion, participants' reported perception of self-motion coincided with the visual phase (not the inertial one). Even when the actual forward inertial motion was orthogonal to the visual one. Additionally, the perceived feeling of self-motion increased correspondingly to the amplitude of the inertial feedback. Berthoz et al. [3] tested the perception of forward self-motion induced by peripheral vision and also found that vision dominated in conflicting situations in which visual cues contradicted vestibular ones. According to these findings the feeling of vection increases with the amplitude of vestibular feedback, but does not primarily depend on its direction. We build up on these findings by using a physical, rotational acceleration to increase the feeling of self-motion during a visual forward motion scenario.

Motion Feedback

To solve conflicts arising from visual and vestibular perceptual information in terms of using real motion various approaches were made. One of them is to stimulate human sensory systems by inducing false sensory input, which, combined with visual information, is interpreted as realistic information by the brain. Galvanic vestibular stimulation (GVS) stimulates the vestibular system by sending electrical signals to the inner ear. Maeda et al. [17] indicate that a visually induced feeling of self-motion can be increased by combining visual stimuli with GVS. Further, Gálvez-García et al. [6] point out that galvanic cutaneous stimulation (GCS) mitigates simulator sickness symptoms. However, technical limitations and medical concerns are currently too immense for GVS and GCS to be used in consumer grade hardware.

Walking setups are another approach to bridge the gap between vestibular and visual information. Room scale tracking allows the user to freely roam around in the real world, free of any sensory conflict as real and virtual motion match. However, in most settings only limited space is available. Therefore, redirected walking [20] aims at redirecting the users steps in the real world to walk curved paths while walking straight in the virtual world. Another way to provide natural and immersive virtual locomotion is the walking-in-place (WIP) approach. VR-STEP [26] offers intuitive real-time pedometry to implement virtual locomotion. Users stand and provide continuous stepping input while walking through the virtual wold. In combination with head-tilt WIP can even be used for multidirectional navigation in the direction of the user's gaze [25]. However, redirected walking and WIP approaches may not be used for longer periods of time due to physical exhaustion.

Another way to create motion in the real world when moving in the virtual one are motion platforms that create real related motions to match virtual ones. While in the past motion platforms with six degrees of freedom were used to create motion [16, 11], it has been shown that smaller setups suffice to create a sense of realistic motion. The advantage of these smaller platforms and feedback devices is that they can be used in domestic settings. *HapSeat* [4] uses three actuators for both arms and head to simulate motion through applying force feedbacks on the user's seated body. Ouarti et al. [18] use a haptic force feedback in the hands of the user to enhance the sensation of self-motion. When coherent with the virtual camera motion, the force feedback stimulation creates a higher sensation of self-motion in contrast to visual feedback alone in moving a virtual environment. However, these systems only create a sensation of motion by simulating motion through an applied force feedback. But humans perceive motion by interpreting information from their visual, auditory, vestibular and kinesthetic sensory systems [2, 9]. Therefore, *VRSpinning* is based on a swivel chair [8] that creates real motion instead of simulating it.

ON THE DESIGN OF MOTION USING ROTATION

Our aim was to represent both, forward and rotational motion in VR based on a swivel chair as motion platform. Since the vestibular system measures acceleration, but does not detect constant motion, we concentrated on representing rotational and forward accelerations in VR. While rotation is rather easy to represent, forward motion is more problematic as it cannot be displayed as a one to one match by the chair. As indicated by related work, the vestibular system is not very accurate and human perception can be tricked into interpreting an acceleration stimulus as orthogonal or opposite to its actual direction. We take advantage of the inaccuracy of human perception and present visual stimuli synchronously with non-matching vestibular stimuli (rotational acceleration) that are interpreted as forward acceleration.

Besides the limits of human perception, usability should be considered. Motion platforms may increase the feeling of self-motion by adding physical motion to the virtual one. However, accelerations are known to cause simulator sickness. More aspects that have to be considered are peoples' preferences on what kind of motions should be enriched with motion feedback (e.g. walking, driving, flying). Therefore, we used an user-centered design approach to get further insights on how to design a motion approach on the basis of an actuated swivel chair as motion platform.

FIRST PROTOTYPE

We implemented a first prototype based on the SwiVRChair platform [8] (see Figure 2). The prototype consists of a motorized swivel chair with a VR ready laptop on its back.

In terms of feedback we used a one to one mapping of virtual to physical rotations (e.g. when the user rotated left inside the virtual world the chair would rotate left). Additionally, we added an oscillation of the chair when a forward motion was performed inside of the virtual environment (*wiggle*). The main idea of that oscillation was to stimulate the users' vestibular system and trick him into perceiving a forward motion. The concept is illustrated in Figure 3.

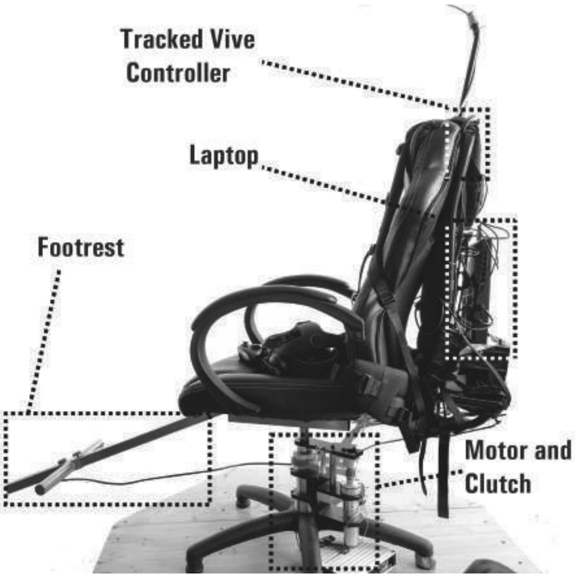

Figure 2. Technical setup of our prototype. A footrest is attached to the chair to have a more comfortable position and to not perceive rotational direction. A VR ready laptop is attached to the back of the chair, as well as an HTC Vive controller, the rotation values of which are used to remove the chair's physical rotation from the virtual view (participant keeps looking in the same direction although the chair is rotating).

While the driving and flying conditions included an avatar in form of a car or a cockpit, the player was represented only by a marker on the ground in the walking condition.

Setup

We equipped a swivel chair with a gearbox, a clutch and an electric motor to enable automatic rotation of the chair. To alleviate some performance issues, several design modification were made. The wireless connection was replaced with an USB connection to reduce latency and increase reliability, which are both crucial for the feedback mechanism we evaluated. Additionally, the motor driver board was replaced with an additional 20 V power supply to enable a gentler motion of the chair, while enhancing the grip of the clutch, which could then be powered with the full 24 V. Furthermore, the Samsung Gear VR headset used in the SwiVRChair project was replaced with the HTC Vive, which drastically increased processing power and overall performance. The chair's physics integration into the virtual world was one of the most challenging parts of the setup, as it's virtual representation had to match the real world object. Therefore, we attached a Vive controller to the back of the chair. We only regarded the Euler angle's Y component to describe the chair's rotation in 3D space, since the other parts are most of all results of tilting the chair. Finally, we added a footrest to the setup (see Figure 2) to avoid participants perceiving the direction of the rotation by having their feet drag over the floor.

Design

We chose a study method which is a mix between a quantitative and qualitative approach aimed towards better understanding user preferences and the overall experience of a 1D motion platform. The study was conducted using a within-subject design with the type of motion (*walking, driving, flying*) as independent variable. Additionally three options of motion feedback were applied (*chair rotation, chair oscillation, chair rotation & oscillation*). Participants were free to turn the options on/off according to their preferences using an Xbox 360 controller. The three scenarios were presented to the participants using a Latin square for counterbalancing. Users were encouraged to talk out loud and the whole session was video recorded, transcribed and analyzed. The motion feedback options worked as follows:

Chair rotation Using this option the chair was rotated synchronously with the virtual rotation at a fixed rotation speed. This feature could either be turned on or off.
Chair oscillation This option was applied during forward motion. Besides turning the feature on and off, participants could adjust frequency and motor strength during the oscillation.
Oscillation during rotation While either moving forward or rotating, either the rotation or the oscillation was presented. Rotating while being in motion is though a combination of both. We therefore decided to include another option that allowed participants to combine the chair rotation with the oscillation. This feature could either be turned on or off.

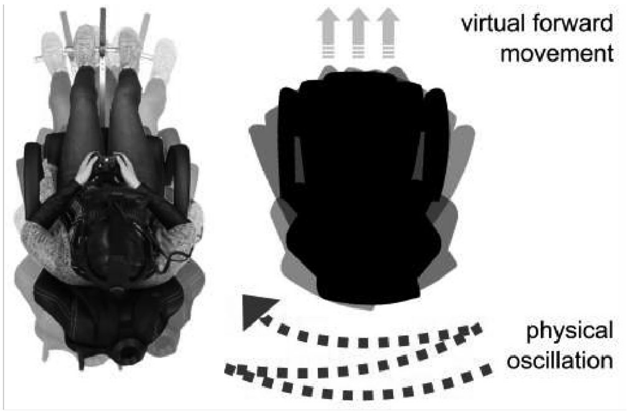

Figure 3. The *wiggle* concept is realized by letting the chair oscillate within a given rate during visual forward or backward motions. The movement is mapped e.g. steps during walking.

We designed three applications including the most common motion types: walking, driving and flying (see Figure 4).

Procedure

The study was conducted in an university lab. Participants were introduced to the topic of the study, stated their consent, and completed a demographics questionnaire. They also self-assessed their susceptibility to motion and cybersickness. After introducing the setup (chair, HMD, Xbox controller), participants were given some time to freely explore and get familiar with the setup. Then each of the three scenarios was presented in a counterbalanced order. Participants were asked to freely move in the virtual environment and test the different options for force feedback. Participants were encouraged to constantly talk about their decisions and explain why they

Figure 4. The different motion types used in the first study: a) walking scenario; b) car driving scenario; c) flying through asteroids.

did what. This was audio recorded and later transcribed and coded to deeper understand the needs for such a rotational locomotion platform.

Participants

The study was conducted with 24 participants (5 female) with an average age of 24.7 (*SD* = 3.03) years. All participants were university students or employees and participated voluntarily. Although participants showed great interest in VR technologies (mdn 6 on a 7-point Likert-scale), their experience levels varied greatly. However, the effect of this potential bias on the results could be neglected, as the target demographic of this study are all potential VR users. Participants reported low susceptibility towards motion sickness (mdn 2 on a 7-point Likert-scale), values for cybersickness were slightly higher (mdn 3 on a 7-point Likert-scale).

Measures

The study aimed to include users early in the design process of evaluating forward motion approaches for a rotational locomotion platform. We mainly wanted to find out what type of feedback can be used and how people react to the *wiggling* we designed for forward motion. We further aimed to elicit user preferences and leverage ideas about designing a locomotion platform solely on a rotational impulse. Additionally, we collected participants' preferences on oscillation and rotation values (frequency and motor strength).

Quantitative Results

The following results are based on the preferences we logged during the study and the user feedback we recorded.

Chair Rotation was a desired feature, which most participants turned on (see Fig. 5). Most of the participants that turned the rotation off reasoned their decision by the circumstance that the behavior of the character becomes too unrealistic when following the physical boundaries of acceleration. Other participants talked about an increase of the perception of actually turning and the reduction of simulator sickness.

Chair Oscillation was seen as controversial. While some participants turned it on in all conditions, others turned it off for each condition. The majority of participants desired to map chair oscillation to a virtual event (e.g. driving off-road or clashing with an asteroid), instead of using it for actual motion. As long as there was no mapping they stated to prefer some kind of vibration instead of oscillation, which they would map to the motor. In the case of walking however, 75% of the participants turned oscillation on as they mapped it on steps. Here, they chose a low frequency (2.2 Hz) for slow walking and a slightly higher frequency (3.4 Hz) for running. Participants who did not use the oscillation feature, argued again with the too intense feeling of motion, which would disturb them during longer experience.

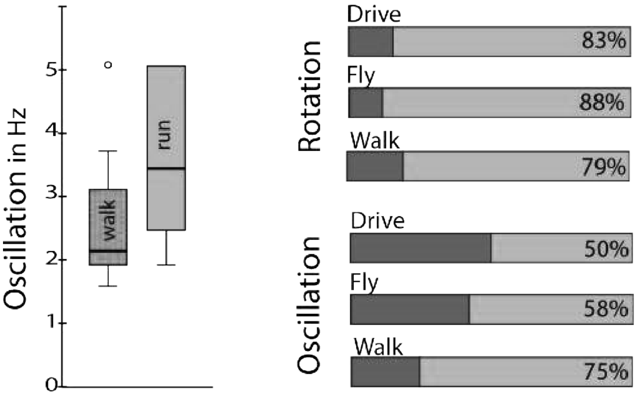

Figure 5. Participants set the oscillation to very low frequencies. As the results of the think aloud suggest, the oscillation was mapped to steps, with having a higher frequency for running (green) then for slow walking (blue). Most participants liked to be rotated with the virtual avatar, while the oscillation was only appreciated in the walking condition.

Discussion and Calibration Results

The following results are based on the thematic analysis of the transcript of each participant and the verbal feedback we collected about the rational behind each decision.

Wiggling as a good metaphor for walking: Participants mainly adapted the frequency of the *wiggle* to match a walking motion (slow for walking fast for running). Since we already are familiar with a slight nudge while walking this metaphor was positively perceived. Participants reported this could potentially increase the sense of presence but did not work perfectly with the rotation. When rotating on the spot the inertia of the chair lead to the perception one is sitting inside a robot. Overall, participants reported that it is a nice feedback mechanism but it could become annoying and cumbersome to use over a longer duration.

Stabilization of the head compensated the wiggle: During the study we observed an interesting effect when using the wiggling mechanism. When being inside the virtual scene and focusing on a certain point participants always managed to keep their head stable and thereby compensated the *wiggle*. Similar to the stabilization of the head of a chicken humans also tend to stabilize certain motion when focused on a target. Therefore, we could not use this *wiggle* motion to induce any form of signal to the vestibular system.

Wiggling as a force feedback of the environment: Participants reported that most types of feedback should rather come from the environment and would fit better to simulate the surrounding virtual world than a motion. When hit by some virtual object the chair could imitate the impact. When driving over a rough road the wiggling could mimic the underground. When flying through an asteroid field the wiggling could simulate the impact the asteroids do on the spaceship. We deducted that the wiggling motion is mainly usable to simulate environmental impact rather than using it as a metaphor for acceleration.

No big differences between the motion metaphors: Besides the incidental metaphor of walking and wiggling, participants reported no big differences between the three motion approaches (walking, flying, driving). Since the main preference was to map the feedback on the environment the actual simulation of the motion should be similar across all the modalities.

Based on the quantitative and qualitative findings we learned that our wiggling approach works best to simulate environmental properties or that it can be used as metaphor for steps during walking. Furthermore, we used the feedback to design an new motion approach. Since people reported that a constant *wiggle* is cumbersome we decided to only use one short impulse burst when a virtual acceleration occurs. To also avoid the stabilization of the head we decided to not have a one to one mapping between virtual and physical rotation of the chair but compensate for every physical rotation so the virtual direction is always fixed. This allowed us to have physical rotation while visually being stable and having a forward acceleration. This should potentially stimulate the vestibular system with an impulse and also trick the user in perceiving a forward motion. Since participants asked for the same form of motion along all three motion approaches we decided not to distinguish between them anymore and design one motion approach suitable for the general concept of forward acceleration.

SECOND PROTOTYPE

For the second prototype we implemented a general motion approach for virtual reality aiming to represent forward motion. To give vestibular cues during forward acceleration we stimulated the vestibular system with a short rotational impulse presented synchronously with visual acceleration. To make sure the rotational acceleration impulse would be mapped to forward movement we subtracted the chair's physical rotation from the visual one (see Video). By iterative testing, we adjusted the physical rotation to be short (50 ms of acceleration), but relatively strong (up to˜$20^\circ/m$). The idea was to create a vestibular stimulus that is strong enough to be recognized, but too short to be mapped to the actual direction. The concept is illustrated in Figure 6.

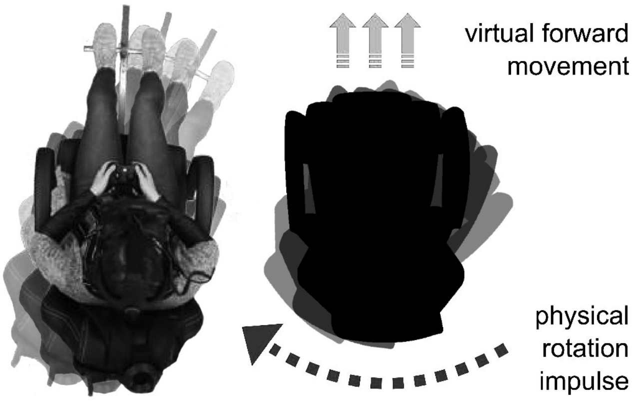

Figure 6. The *spin* concept is realized by a short rotational acceleration impulse synchronous to the visual forward or backward acceleration.

Setup

We used the same motorized swivel chair and HMD as in the first iteration. As physical and virtual rotation should be separated for this second study we used the HTC Vive controller attached to the back of the swivel chair. We added the controller's inverse rotation value to the virtual camera's one in order to remove the chair's rotation from the view. This way, the virtual camera remains in the same orientation even when the chair is rotating.

Design

The study was conducted in a within-subjects design with the form of rotational stimulus as independent variable. The participants experienced a strong but short ($20\ ^\circ/s^2$ over 0.3s) rotation to the right at the start of an acceleration and the inverse when braking (or accelerating backwards). The two tested conditions were (1) visual stimulus only (*visual*) and (2) visual and physical stimuli (*physical*). The order was counterbalanced using a Latin square.

Procedure

The study took place in an university lab. Participants were introduced to the topic of the study, stated their consent, and completed a demographic questionnaire. Then they were placed in a virtual environment using an HTC Vive while sitting on the motorized swivel chair. The virtual environment contained a virtual road (see Figure 7) and participants took part in an experience similar to car driving on the road. The experience comprised of several phases of acceleration and braking (as well as accelerating backwards). We designed the application in a way that acceleration, braking and constant motion alternated within small time frames. The longest phase of moving with a constant velocity was three seconds long. Overall the participants were exposed around one minute to virtual motion. For both conditions participants were passive observers of the virtual scene and did not have an active task.

After they finished all conditions, participants were compensated with 10€ . The respective experiment lasted for around 30 minutes.

Figure 7. In the second experiment the participants drove through a virtual canyon.

Participants

We recruited 20 participants (8 female) with an average age of 24.3 (*SD* = 2.7) years. They were mostly university students with a technological background. Their previous experience in virtual reality was comparably low. Seven participants stated that they had never experienced VR before, while two stated they consumed more than 50 hours of VR (mdn: 1-10 hours). 11 participants reported that they get motion sick, e.g. when reading in a moving car.

Measures

In this experiment we were interested in the participants' levels of simulator sickness, presence, and experience of vection. Simulator sickness was measured in two ways. The sickness during the experience was assesed by using the question "On a scale from 1 to 10, 1 being how you felt before the test, 10 is that you wanted to stop, how did you feel during your time in the virtual world?". To measure the symptoms after the experience we used the SSQ [13]. The participants' presence was assessed using Slater, Usoh, and Steed's (SUS) presence questionnaire [24]. To measure vection, we employed a question asking the participants to rate their feeling of self-motion similar to [10]. They propose to present an explanation of the illusion of self-motion and to rate to which degree they experienced such on a 4-point Likert scale from "no feelings of self-motion" to "very strong feelings of self-motion".

Since vection is based on the feeling of self-motion, which can also occur during longer phases of forward movement, we also asked for the more critical aspects of self-motion: acceleration and braking. These situations are also the ones considered to cause simulator sickness, which made them to be of special interest. This is also the reason why we did not include longer phases of forward motion, but included multiple, alternating accelerations and braking time frames. In addition to the prior named questions, the participants should state how much they agree to the following statements: "I felt a physical acceleration" and "I felt a physical braking". In addition, we asked the participants to state how realistic the perception of acceleration and braking was ("The feeling of physical acceleration(/braking) felt realistic". The used scale was from 1: "not at all" to 7: "absolutely".

Results

Vection: We count the vection item, as well as the own items concerning acceleration and breaking to be contributing to vection. We compared each item separately using the Wilcoxon signed rank test. Differences are considered to be significant on the 5% level, while being highly significant when being below the 1% level. Boxplots of the results are shown in Figure 8. We found a highly significant increase of vection in the *physical* condition ($p < .01$, $Z = -2.24$, $r = .50$). The feeling of acceleration ($p < .01$, $Z = -2.06$, $r = .46$) and braking ($p < .01$, $Z = -2.37$, $r = .53$) was also highly significantly increased. The perceived realism of acceleration ($p < .01$, $Z = -2.19$, $r = .49$) and braking ($p < .01$, $Z = -2.01$, $r = .45$) was also increased highly significantly.

Simulator Sickness: We asked the participants to rate the intensity of symptoms of simulator sickness during the experience on a scale from 1 to 10. Additionally, we included the SSQ questionnaire to measure the symptoms after the VR experience. Boxplots of the results are shown in Figure 8. Sickness symptoms during the experience (measured using the single question) were significantly stronger in the *visual* condition ($p < .05$, $Z = -1.57$, $r = -.35$) than in the *physical* one. Sickness symptoms after the experiences (measured with the SSQ) were rather low (visual: 19.2 (mdn), physical: 9.6 (mdn)) and did not vary significantly between both conditions ($p = .11$, $Z = -1.12$, $r = -.25$).

Presence: The SUS presence score was increased highly significant by introducing the short vestibular stimulus ($p < .01$, $Z = -1.83$, $r = .41$) and is illustrated in Figure 8.

DISCUSSION

Vection: We found that the short rotational acceleration we applied strongly increased vection compared to presenting visual stimuli only. Similar to Wright [28] we found an increased feeling of self-motion in the condition with vestibular stimulus compared to using only visual cues, though the vestibular stimulus was applied in another direction. We assume that the short duration of the vestibular stimulus was enough to increase the feeling of self-motion, while being too short to perceive its direction.

Simulator Sickness: Concerning the question how participants felt during their time in the virtual world, a significant decrease of simulator sickness in the physical condition compared to the visual one could be found. For the symptoms that occurred after the VR exposure no significant difference could be found, as for both conditions SSQ values were relatively low (visual: 19.2 (mdn), physical: 9.6 (mdn)). Although we did not find a significant difference, we observed an interesting trend towards decreased SSQ scores in the physical condition compared to the visual one. These findings were quite surprising as we applied various stimuli that are known to increase simulator sickness (multiple accelerations/brakes and short amounts of time driving with constant velocity).

Presence: Applying rotational stimuli did significantly increase the feeling of being present in the virtual world. Therefore, we assume our forward motion approach to be a natural way of simulating forward motion in virtual reality.

Countering the Conflict: Our results indicate that the approach of simulating forward (or backward) accelerations in virtual reality increases the feeling of self-motion while decreasing simulator sickness at the same time during the VR experience.

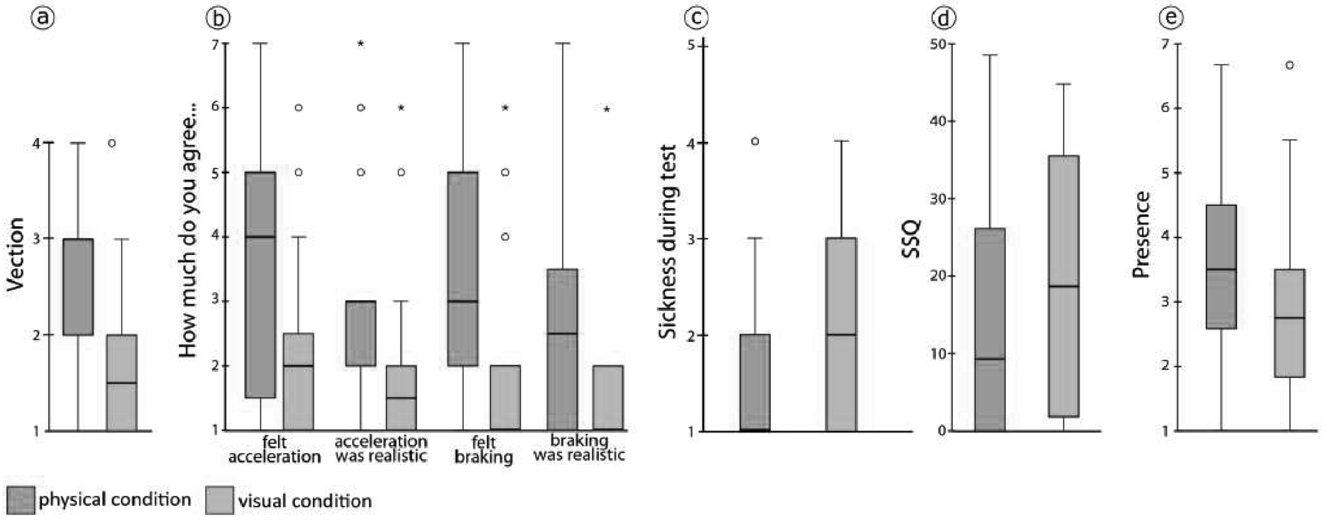

Figure 8. The results of the second study: (a) vection was significantly increased when a physical rotation was applied. (b) participants stated a higher feeling of acceleration and braking in the *physical* condition. In both conditions acceleration and braking were not considered as *realistic*, however, ratings for both were slightly increased by the physical rotation. (c) simulator sickness symptoms during the test were significantly reduced by the physical rotation. (d) there was no significant difference regarding simulator sickness symptoms after the test. (e) the SUS presence score was significantly higher during the *physical* condition.

Interestingly, these findings are in contrast to the results proposed by related work, where it is stated that an increased feeling of vection also leads to an increase of simulator sickness [10, 14]. Although we applied a rather short rotational stimulus it seems to suffice in duration and force to positively influence the experience of simulator sickness. We explain the results by avoiding a sensory conflict, which is assumed to cause simulator sickness [21], as we present visual stimuli synchronously with short vestibular stimuli and trick human perception into interpreting a rotational acceleration cue as forward acceleration.

Inducing Acceleration: Due to the short time of physical accelerating the chair, it also came to rest after a short time. We therefore used the same physical rotation stimulus for both kinds of acceleration, although they differed in terms of direction. Thus, braking was not simulated by actually reducing the velocity of rotation, but by increasing it in the inverse direction. Although participants gave lower values for the feeling of braking than for accelerating, they still had a stronger feeling of slowing down compared to the *visual only* condition. Participants also gave comparable values for realism of accelerating and braking when a physical rotation stimulus was applied. While vection can occur during longer phases of constant velocity, the feeling of acceleration is different. It is harder to induce by visual cues only, since acceleration is – in contrast to constant velocity – also measured by the vestibular system. Our results show that even acceleration can be perceived using our approach.

Less is More: While fine tuning our impulse, we were surprised how little movement actually was physically needed to simulate the acceleration that happens visually (see video). We only had to rotate for approx. $8^\circ/s^2$ with a short burst to mimic this form of visual forward acceleration. When we used a longer impulse we found several side effect that were considered unpleasant (e.g. when spinning for too long and too fast moving the head resulted in the perception of the gyroscopic effect). However, applying our short bursts resulted in a more realistic experience. We argue that this is even an advantage since it implies that to simulate this form of locomotion a 360 degree rotational platform is not necessary. To counter simulator sickness it could be enough to have 180 degree or even less.

CONCLUSION

In this work we presented *VRSpinning*, a seated locomotion approach based around stimulating the user's vestibular system using rotational impulses to amplify the perception of forward or backward self motion. We designed the feedback in a user centered design approach, involving participants early in the process and iterating the feedback mechanism. We found that participants preferred the *wiggle* mechanism as a form of feedback of the environmental impact. We further found that using a short burst of rotation with a corresponding visual forward acceleration leads to a significantly increased perception of self motion and reduces simulator sickness. Our work shows that to tackle the problem of simulator sickness and vection in virtual reality we can leverage the inaccuracy of the human vestibular system. We showed that a rotational acceleration during a visual forward acceleration can induce a perception of self motion. Based on our results we argue that different forms of "non-matching" stimuli should be tested synchronously to visual linear motion to generate the perception of self motion and fight simulator sickness.

We plan to test our approach in a self-controlled racing game to measure long term effects on simulator sickness and the effect on presence and enjoyment.

ACKNOWLEDGEMENTS

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Rethinking Redirected Walking: On the Use of Curvature Gains Beyond Perceptual Limitations and Revisiting Bending Gains

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Rethinking Redirected Walking: On the Use of Curvature Gains Beyond Perceptual Limitations and Revisiting Bending Gains

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Abstract

Redirected walking (RDW) allows virtual reality (VR) users to walk infinitely while staying inside a finite physical space through subtle shifts (gains) of the scene to redirect them back inside the volume. All prior approaches measure the feasibility of RDW techniques based on if the user perceives the manipulation, leading to rather small applicable gains. However, we treat RDW as an interaction technique and therefore use visually perceivable gains instead of using the perception of manipulation. We revisited prior experiments with focus on applied gains and additionally tested higher gains on the basis of applicability in a user study. We found that users accept curvature gains up to $20°/m$, which reduces the necessary physical volume down to approximately 6x6m for virtually walking infinitely straight ahead. Our findings strife to rethink the usage of redirection from being unperceived to being applicable and natural.

Index Terms: Human-centered computing—Human computer interaction (HCI)—Interaction paradigms—Virtual reality; Human-centered computing—Human computer interaction (HCI)—HCI design and evaluation methods—User studies

1 Introduction

Technologies like virtual reality (VR) and augmented reality (AR) are more and more becoming a topic of interest for the consumer market. One open problem is the navigation in such virtual environments. Real walking is the most natural and simple way of moving around in a virtual environment [34], but it is also the most difficult one to realize since it requires the real world providing the same space as the virtual one. One idea to overcome this limitation is redirected walking (RDW) [27]. RDW is a technique where the path walked in the real world slightly differs from the virtual one by manipulating the user's orientation, or other features during walking. As long as this manipulation is designed subtle enough, users do not even recognize the manipulation. According to Steinicke et al. [31] the manipulation may not exceed a gain of $2.6°/m$ or according to Grechkin et al. [12] $4.9°/m$ to prevent its detection. When applying such gains it is possible to virtually walk straight forward while walking on a circle in the real world without perceiving the shifting. Though, the diameter of the walked circle would be around 44 m [31] (or 22m [12]), which is far too much for most applications. It was also suggested to enhance the concept of RDW by guiding users to walk on curved paths [19]. The virtual curve adds to the curve induced by the gain and therefore results in less required space. Forcing users to walk curved paths reduces the desired tracking space, but requires a special design of the virtual environment and therefore strongly limits the application.

The current state-of-the-art of navigation in a roomscale VR is the *point and teleport technique* (eg. [8]). Teleporting solves different problems of VR navigation. On one hand, it solves the problem of limited space, since real walking is only used for short distances, while longer distances are traveled by using the teleport metaphor. Some other techniques, like indirectly controlling movements by a controller, cause motion sickness, a problem assumed to be caused by the conflicting visual and vestibular information during accelerations [20]. Since there is no acceleration when traveling between two points without animating the motion, motion sickness does not occur during teleporting. Nevertheless, there are also some drawbacks of teleportation. It might break the sense of feeling present in a virtual environment, but primarily, teleportation decreases the spatial orientation and the knowledge about the surrounding [1, 6, 10, 29].

Similar to metaphors like teleportation, we assume, that redirected walking may be designed beyond the perceptual limitations and could be accepted as navigation technique even if the manipulation is detected. We therefore conducted an experiment including higher gains then the already proposed ones. In contrast to prior works, we did not target our experiment to get insights on perceptual thresholds, but on participants preferences. We asked participants how natural the walking was and if the gain would be applicable to realize movement in VR. Since a stronger manipulation of the rotation could also induce motion sickness, we also asked participants to state if they suffered related symptoms.

To allow a fair comparison of prior works, as well as to compare detection thresholds to our results we propose the use of a unified metric being $°/m$ for curvature gains. Using this metric, we rerun the experiment of [19] and propose corrected perceptual thresholds that are much lower to the prior reported. Our proposed applicability metric showed that it is possible to apply twice the detection threshold without influencing the perceived naturalness or increasing symptoms of motion sickness. Participants even accepted four times the detection threshold of around $5.2\ °/m$ to be applicable. This way, the required space for infinitely walking a straight line can be reduced to 6x6m.

Our main contributions are:

- The approach of treating RDW as an interaction technique and evaluating it based on applicability metrics and not on the basis of perception.
- Proposing a unified metric to represent curvature gains in RDW and rerun a prior experiment showing how to apply our new metric.
- Findings from a user study showing that by treating RDW as an interaction technique $20°/m$ was acceptable for users, while they detected the manipulation at a gain of $5.2°/m$.

2 Related Work

2.1 Navigation

Navigation in VR can be separated into the cognitive and physical components way-finding and (active or passive) travel [5]. While way-finding is the spatio-cognitive process of finding a way from one location to another, travel denotes the actual movement within the virtual environment. Travel can be carried out passive, e. g. by

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using a joystick, or active, i. e., the user moves physically, which is often denoted as *locomotion*. While real walking is considered to be the most natural way of moving through a virtual world [34], other locomotion techniques were introduced due to the spatial limitations of the real world [32]. These include a wide range of approaches like omni-directional treadmills (e.g., [3,4]) or even robot controlled moving floor parts ([15]). Furthermore, walking-in-place techniques (e.g., [17,23]) and redirected walking [27] were investigated.

2.2 Redirected Walking

The idea of RDW is to compensate the limited tracking space by manipulating the user's orientation, position or other features. The manipulation of the user's orientation during walking is called curvature gains, which let's the user walk in a circle instead of straight forward as she does seemingly in the virtual world [27]. When the discrepancy between the virtual travel path and the actual travel path in the real world is small enough, this redirection is not detected by the user [31]. Beside these curvature gains, it was also suggested to apply gains on the velocity during walking (translation gains) [14], or to apply rotation gains while standing on the spot and turning around [16]. Suma et al. [33] introduced a taxonomy of different redirection and reorientation methods ranging from discrete to continuous, and subtle to overt.

Because the physical tracking spaces are usually not large enough to enable unlimited undetected redirected walking, different strategies are needed to keep the user inside the boundaries. Originally, Razzaque presented three different algorithms for that: Steer-to-center, steer-to-orbit, and steer-to-multiple-targets [26]. If the user still collides with the boundaries of the tracking space, a reorientation phase is started in which the user is turned around towards the tracking space. To make these reorientation phases less obvious, Peck et al. introduced distractors [25]. To avoid interruptions like this, Hodgson et al. [13] presented an algorithm for very large spaces, i. e., 45m× 45m. Another solution, which limits the required space was suggested by Langbehn et al. [18]. They propose to force the user to walk on already curved paths. In addition, they claim various detection thresholds to realize such a setup without being perceived.

2.3 Curvature Gain Detection Thresholds

When applying curvature gains, Razzaque [26] found that a manipulation of $1^\circ/s$ is the detection threshold under worst-case conditions. In other experiments, the strength of gains is applied depending on the walked distance. For example, it was suggested, that a redirection should not go beyond $2.6^\circ/m$, since participants perceived higher gains and therefore noticed the manipulation [31]. Such a gain would require a circle with a diameter of 44m to infinitely walk virtually straight forward. Grechkin et al. [12] regarded the influence of using translation gains while applying curvature gains. They found that the detection thresholds of curvature gains were not significantly influenced by translation gains. According to their results users are less sensitive to curvature gains than reported by Steinicke et al. and state a required radius of around 12m.

While detection thresholds of curvature gains are not significantly influenced by translation gains, it has been shown that other factors influence the detection thresholds. This is for example the presence of cognitive tasks [9], the velocity of walking [22], or the presence of passive haptic feedback [21]. The visual density of the virtual environment seems to have no influence on the detection of rotation gains [24].

Another kind of curvature gains were proposed as *bending gains* [19]. These gains are defined as the relation between real and virtual radius. As we show in the following, they can be directly converted to curvature gains and are unsuitable to measure perceptual thresholds.

3 CONVERSION OF OTHER NOTATIONS

Detection thresholds are often provided in various and even incomparable ways. In the following we show that stating the radius, although being a proper way of communicating the required space, is no adequate way of comparing gains. We therefore suggest to use a uniform way of describing gains, provide formulas to convert priorly reported gains and compare them by converting them into the proposed metric.

The most prominent factor that a user perceives during RDW is to be rotated by a certain amount of degrees after walking a certain distance. We therefore argue to use the notation angle per walked meter ($^\circ/m$). This unit can be interpreted as: *after a user walked a distance of 1m, he will be rotated by x degrees*. A similar metric was already used in the experiment by Steinicke et al.: They calculated the curvature gains g_C based on the scene rotation after 5m walking distance [31].

A lot of literature in the field of detection thresholds for RDW uses radii to describe curvature gains. But radii do not scale linearly to the perceived manipulation (see figure 1 b). While for example the gains proposed by Grechkin ($4.9\ ^\circ/m$) result in a radius of around 12m, the ones provided by Steinicke et al. being little lower ($2.6\ ^\circ/m$) result in a radius of 22m – a difference of 10m regarding the radius (while the degrees per meters differ by 2.3). Adding the respective difference of $2.3^\circ/m$ to Grechkin et al.'s $4.9\ ^\circ/m$ leads to a gain of $7.2^\circ/m$ and to a radius of around 8m – a difference of only around 4 m with the same difference of $2.3^\circ/m$. Radii do not increase or decrease in a linear way with the perceived manipulation and are therefore no adequate metric to compare gains. We therefore argue, that the use of radii to state the required physical space using a redirected walking gain is though useful to communicating the effects of a gain, are no proper way for comparing gains. We encourage further reports on curvature gains to state the radii as well as gains in the unit $^\circ/m$ to allow a fair comparison with prior works. Figure 1 b) shows the relation of radii to the perceived gain in $^\circ/m$.

We are aware that using the rotation after walking 1 m as unit might not be the perfect solution, too, since we already know that e.g., walking velocity or acceleration also influence the perception of RDW gains [22]. The unit $^\circ/m$ does not consider such temporal effects. However, we argue that they are a more precise way to compare the already proposed detection thresholds, since they increase linearly with the perceived manipulation. Additionally, we can assume that participants walk more or less in a same speed and can also be instructed to do so.

We therefore propose formulas to convert prior gains into the proposed unit. A simple radius can be converted into *angle per meter* by considering the perimeter of the respective radius (which is $P = 2\pi r$). Since a circle comprises a full 360° rotation, the rotation per meter is given by $\frac{360^\circ}{P}$. This principle is illustrated in figure 1 a).

The notation used e.g., by Steinicke et al. [31] which describes the gains as degrees per overall walked distance can be easily converted by dividing the gain by the walked distance.

Grechkin et al. [12] draw their psychometric function in the unit m^{-1}, which is interpreted as how much a user is redirected (in m) after a walked distance of 1m. To translate this unit into the proposed notation, one has to imagine a right triangle with the adjacent side being the walked distance and the opposite side being the gain (g) which is walked sideways. Since the walked distance and therefore the adjacent side is always 1 (in their notation), the gain can be calculated by $\arctan g$.

The *bending gains* proposed by Langbehn et al., are defined as a scale between virtual and real radius. They can be converted by translating both radii to $^\circ/m$ (as already described) and then subtracting both values. This can be interpreted as the difference of the curvature between real and virtual curve in the unit angle per meter.

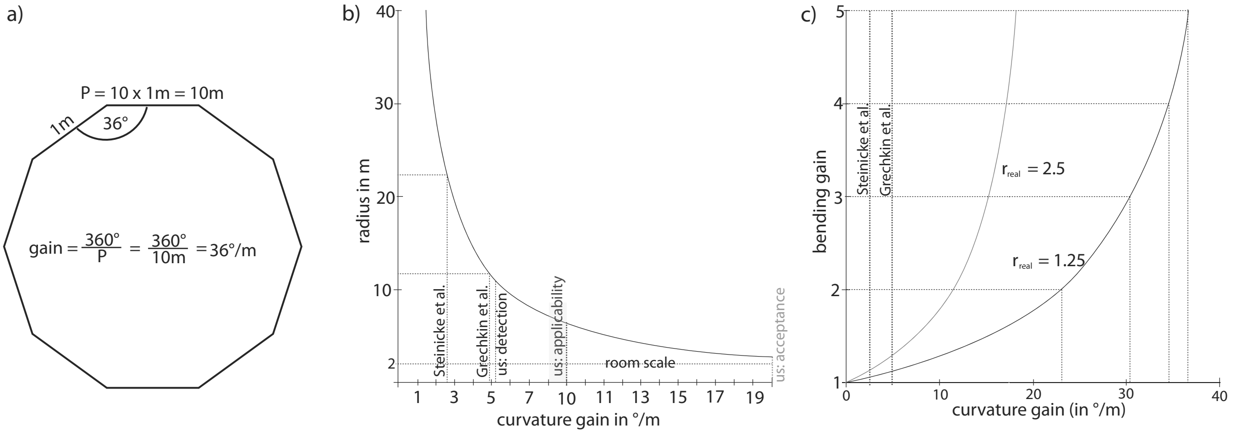


Figure 1: a) The principle of converting radii to degree per meter can be simplified as follows: A circle can be split in an endless amount of segments. When splitting the circle into 10 segments with the length of 1m, a user will be rotated after this meter by 36°.
b) Radii do not scale linearly to the perceived gains. The illustration also shows how high gains would be needed to reach a room scale radius.
c) The bending gains proposed by Langbehn et al. do not scale linearly with the perceived manipulation. They also depend on the underlying real radius (compare orange and black curve). Note: the drawn bending gains were used in their evaluation. Even the first tested ones are much higher then the prior reported detection thresholds.

4 EXPERIMENT 1: REVISITING CURVATURE AND BENDING GAINS: VALIDATION AND COMPARISON

When comparing the different detection thresholds in a unified metric, we found the proposed values to be exceedingly differing. Steinicke et al. [31] propose $2.6^{\circ}/m$), Grechkin et al. [12] $4.9^{\circ}/m$) and Langbehn et al. [19] $15.4^{\circ}/m$ or even $31.7^{\circ}/m$, depending on the condition. We therefore decided to not only run the experiment testing the applicability, but also revisiting prior experiments to get a valid ground truth for comparing applicability with detection. With revisiting we do not mean reproducing the exact study setup and experiment but rather tried to reproduce the stated results, which should be independent to minor variations. These differences are discussed in the *Method* section.

4.1 Setup

The study took place in a 10x8m laboratory room. As HMD we used the Oculus Rift and realized the tracking via the respective sensors. We used 3 Sensors that were placed in a triangle around the tracking space. This way we span a tracking space of around 5x5 meters.

4.2 Method

For the reassessment of the results of Langbehn et al. as well as the results of prior gains for straight walking, we stick to the most common method: a two-alternative forced-choice (2AFC) task. In the following we discuss the differences between Langbehn et al.'s and our experiment design.

Number of repetitions: The validity and expressiveness of such a test is strongly depending on the number of repetitions per participant. We therefore decided to use 10 repetitions equally distributed in left and right curves in contrast to Langbehn et al. who repeated two times per gain and direction.

Tested gains: We decided to test the gains 2, 4, 8 and 12 $^{\circ}/m$. We aimed at testing the same gains for walking a straight line and a curve to allow a comparison between both conditions. This is why we substituted bending gains by the given gain and the instruction and visually guiding to walk a virtual curve with 12.5m radius (4.6 $^{\circ}/m$) or 5m radius (11.5 $^{\circ}/m$).

Question: Most important, was to choose a question which should be about the detection of manipulation instead of the direction of manipulation (as it was done in e.g. [19]). Though it is possible to ask whether a participant could perceive a manipulation, such yes/no tasks can be highly biased, since there is no validation. A participant may really detect the manipulation or just claim to perceive it. We therefore decided to let the participants walk there and back again, while only one way was manipulated. We then asked the participants to state whether they were manipulated on the way there or back.

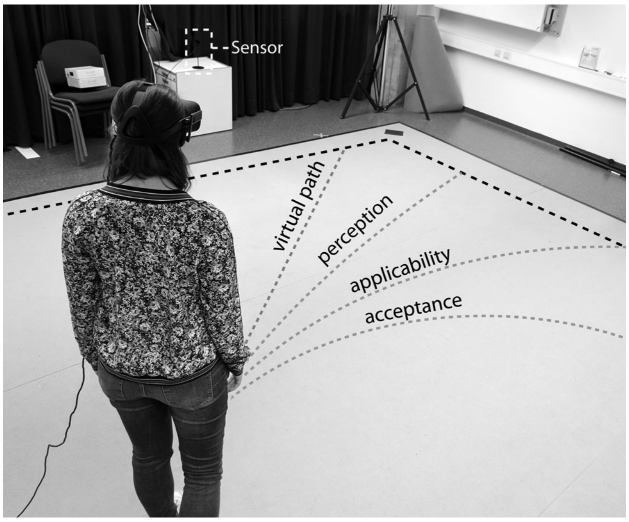


Figure 2: The laboratory including the tracking space. Illustrated is the virtual path (without curve), as well as the detection threshold of around $5^{\circ}/m$, the applicability gain of $10^{\circ}/m$ and the acceptance gain of $20^{\circ}/m$

The experiment was conducted as within-subjects design with two independent variables (gain and virtual curve).

4.3 Procedure

We first informed the participants about the target of the evaluation, being navigation in virtual environments. We then asked the participants to sign a declaration of consent and to fill in a demographic questionnaire.

For each test, the participants walked 4m there and 4m back again. When the target was reached, the participants answered the described question while remaining in the virtual environment. The participants were then visually guided to the next start position without any gains. When the participant was ready, the next condition started. This sequence was repeated until the end of the study. The order of the 120 trials (4 gains x 3 curves x 10 repetitions) was randomized. The participants could break or abort the study at any time. The whole study, including the 2AFC and applicability task, lasted between 1,5 and 2 hours, depending on the participants velocity of walking and number of breaks.

4.4 Participants

We recruited 16 participants (most of all students and employees of our university). The participants (5 female) were aged between 20 and 30 (mean: 26). There were four novice VR users who never experienced VR before as well as two very experienced users with more then 50 hours of experience (mean experience with VR: 15 hours). Each participant was compensated with 10 €.

4.5 Results

The results of the 2AFC task are illustrated in figure 3. The virtual curvature had only little effect on the detection of being manipulated. Our results of walking a straight line, with a detection threshold of around $5.2^{\circ}/m$ confirm the results of Grechkin et al.'s $4.9^{\circ}/m$. Though our results cannot be directly compared to Langehn et al.'s results due to the difference of the tested gains and the different 2AFC task, our results obviously differ. While their results for detecting the direction of manipulation suggest detection thresholds of up to $30^{\circ}/m$, our results show that the detection of manipulation is quite similar to walking a straight line ($5.5^{\circ}/m$ or $5.7^{\circ}/m$). We also compared the probability of detection of the two critical measuring points being 4 and $8^{\circ}/m$ (the ones below and above the detection threshold) between the three tested virtual curvatures. A Friedmann test for dependant variables showed no significant difference when comparing probability of detecting a gain of $4^{\circ}/m$ (*p=.68; F=.76; r=.11*). Comparing the probability detecting a gain of $8^{\circ}/m$ proved to be not significant as well (*p=.88; F=.26; r=.04*).

4.6 Discussion

We argue that the detection thresholds are close to independent from but slightly increasing with the virtual curve being all around 5 or $6^{\circ}/m$. Our results are inline with prior results, like those of Grechkin et al. [12]. Though, as can be seen in figure 3, there were large variances considering the detection of the different participants. This could either be due to perceptual differences between the participants or it could be originated in random effects caused by too less repetitions.

4.7 Revisiting Bending Gains

Our results stand in great contrast to the ones proposed by Langbehn et al. [19]. While they even stated detection thresholds of more than $30^{\circ}/m$ when virtually walking a sharper curve (which is around 6 times higher then the yet reported detection thresholds for walking a straight line), we found the detection threshold to be close to independent from the virtual curve (still around $5^{\circ}/m$). In the following we explain how this enormous difference arose.

Bending gains were defined as a factor scaling the real radius to the virtual one. As we already described, bending gains can directly be converted to the already known curvature gains. But we further argue, that the proposed *bending gains* should not be used for psychometric experiments. Depending on the relation of two radii which do not increase in linear way to the perceived manipulation (see figure 1 b), the resulting curvature gain strongly depends on the real radius on which the *bending gain* is applied. Therefore the same *bending gain* will result in different curvature gains when applied to different real radii. The *bending gain* of 2, for example, applied to the real radius of 1m results in a curvature gain of around $29^{\circ}/m$, while applied to a real radius of 2m leads to a curvature gain of only around $14^{\circ}/m$. A function that illustrates the correlation between bending and curvature gains is shown in figure 1 c).

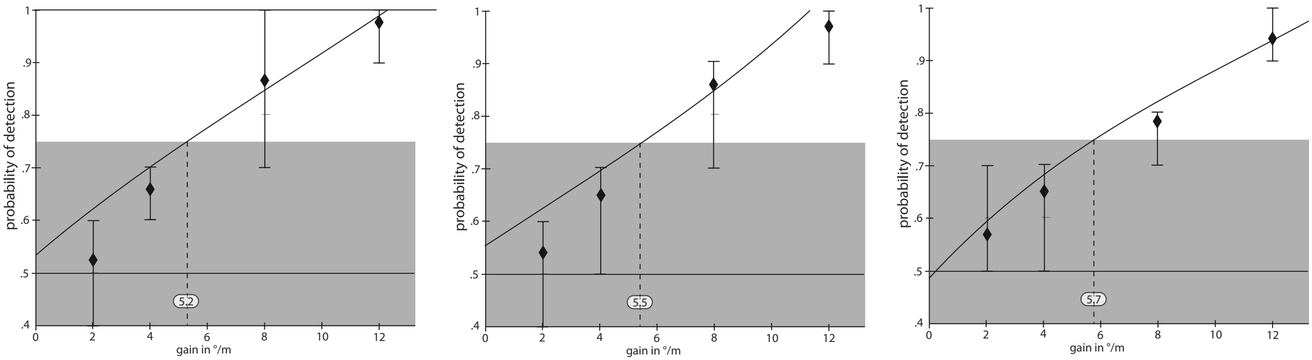
Comparing the detection thresholds of Langbehn et al. with the ones presented in prior works, the proposed detection thresholds are dramatically higher. Even while walking on a 12.5m radius in reality, which is close to walking straight forward, the proposed detection threshold of around $15.4^{\circ}/m$ is three or even six times higher then the priorly proposed ones of 2.6 [31] or $4.9^{\circ}/m$ [12].

A first reason for these higher gains might be the used two-alternative forced-choice (2AFC) task. The question that was asked was *"At which side from the virtual path did you walk physically in the real world?"* and the participants had the options to answer *left* or *right*. Grechkin et al. [12] already pointed out that this method is not necessarily the optimal way to estimate detection thresholds. Though this might still work for detection thresholds of straight virtual paths, it is very hard to estimate the direction of manipulation when walking a curve while being re-orientated by gains. Further, the ability of estimating the direction is strongly influenced by disorientation, which increases with higher gains. Therefore, higher gains might even lead to lower probabilities of detection. This is due to the discordance of the direction of gain and virtual curve. Since the authors asked explicitly for the direction of manipulation, their results cannot be interpreted as detection threshold for being aware of a manipulation.

As already described, radii do not scale in a linear way with the perceived manipulation. This leads to another problem of the proposed *bending gains* when creating psychometric functions. When, for example, using the suggested 1.25m radius for the circle walked in the real world which is stretched by the factor 2, the resulting virtual radius is 2.5m. The proposed gains of 1, 2, 3, 4 and 5 therefore result in the gains of 0, 23, 30, 34 and 37 $^{\circ}/m$. This example is also illustrated in figure 1 c). While the difference between the first two gains is $23^{\circ}/m$, the difference between the last two is only $3^{\circ}/m$. Assuming a linear distribution of these gains in a psychometric function leads to errors when calculating the detection threshold. In addition, there is a risk of testing gains, which are unrelated to the level of detection. In the case of the presented study, even the lowest tested gain of $23^{\circ}/m$ was already close to five times the priorly stated detection thresholds.

The nonlinear distribution of the proposed gains though leads to another problem. The authors also assumed their gains of 2, 3, 4 and 5 to behave symmetric to the gains $\frac{1}{2}, \frac{1}{3}, \frac{1}{4}$ and $\frac{1}{5}$, though they are not. Comparing their proposed real world radii of 6.25m and 1.25m which were modified using their proposed thresholds, they assume the following gains to be equal: 23 to $9^{\circ}/m$, 31 to $18^{\circ}/m$, 34 to $28^{\circ}/m$ and 37 to $37^{\circ}/m$. The proposed psychometric function, drawn in a symmetric way and assuming the described gains to be similar, can therefore not be considered as valid.

Furthermore, the validity of a 2AFC task increases with the number of repetitions per condition. The underlying assumption of such a test is that if a participant is unaware of a stimulus, but has to decide between two options, he will choose each of them just as often. When the stimulus gets stronger, the participant will tend to one of the answers. If for example a coin is flipped 100 times, head and tail will be most likely be equally distributed. The probability of head and tails are therefore both .5. If only flipping four times, the risk of random probabilities (e.g., three or even four times head) is quite high. The second problem using too view repetitions is the resolution of the sample space. When repeating the experiment four times the resolution of probability is in .25 steps. A participant can either give one of the possible answers no single time ($p = \frac{0}{4} = 0$), one time ($p = \frac{1}{4} = .25$), two times ($p = \frac{2}{4} = .5$), three times ($p = \frac{3}{4} = .75$) or four times ($p = \frac{4}{4} = 1$). When aiming at measuring the threshold of detection as accurate as possible, the resolution has to be higher. Such an experiment therefore requires more then four iterations to consider the results as significant.



a) b) c)

Figure 3: Results and fitted curves of the 2AFC task. a) for walking a virtual straight line; b) for walking a virtual radius of 12.5m and c) for walking a virtual radius of 5m.

Overall, we argue that the results of Langbehn et al. rather measure the estimation of the direction of the manipulation and not the overall detection of a manipulation. Since participants had to walk a virtual and physical curve this turned out to be quite difficult and participants already reported symptoms such as nausea and disorientation without being able to tell the direction of the manipulation. Further, we showed that the use of the proposed *bending gains* are unsuitable for the use in psychometric functions when assuming the *bending gain* to be increasing linearly with the perceived manipulation.

5 Towards the Applicability of Curvature Gains

Since our goal was to treat RDW more as an interaction technique (e.g., teleport) rather than designing it to be unperceivable, we looked into fields beyond RDW using different forms of evaluation metrics.

The following are experiments focusing on the quality of movement strategies. These experiments e.g., measured speed (e.g. [2,7]), accuracy (e.g. [7]) and asked for spatial awareness (e.g. [7]), ease of learning/simplicity/cognitive demand (e.g. [7,9,34]), ease of use (e.g. [7]), information gathering during navigation (e.g. [7]), naturalness (e.g. [34]), simulator sickness (e.g. [2,28]) or presence (e.g. [2,7,28,30]).

These metrics were used to compare the quality of walking techniques such as walking in place or controller input. There are no results on comparing redirected walking gains beyond the ability to detect the manipulation. Since our goal is to find how strong a user may be manipulated, before a gain is no longer subjectively perceived as applicable.

We therefore build a set of items which we refer to be contributing towards the applicability based on these prior experiments. We deliberately did not include measures like accuracy or speed, since we do not see them contributing to applicability.

Our first applicability item is based on the main motivation for redirected walking: the naturalness compared to other navigation techniques. If the walking is no longer regarded as natural, the main advantage compared to other navigation techniques is no longer complied.

Applying too high gains can disturb our sense of orientation and lead to symptoms of nausea. We therefore used disorientation and nausea as second item. Nausea, disorientation but also the enforcement of walking curves can decrease the comfort of locomotion. Though we assume that comfort will most likely be highly negatively correlated with the symptoms of nausea and disorientation, we used this item as well. The last item is the most obvious one and targets towards the applicability of gains itself. Considering the applicability, the practicability of gains is highly dependant on users' willingness to have such a gain inside a VR application.

6 Experiment 2: Applicabililty Study

Since both, the 2AFC and applicability study were part of the same session, participants and setup were the same as for the first experiment. The 2AFC task was always done before the applicability study.

6.1 Method

Since our aim was to get insights on how far the visual manipulation could go before the movement is no longer pleasant or becomes unnatural, we used seven point Likert scales that were presented directly after the participant reached the target without taking off the VR headset. Since we did not measure the detection thresholds, we did not need to repeat the measurements. Though we tested each condition four times, since we aimed at getting insights on potential customization effects.

We used the applicability items as described earlier. The participants were asked after each condition how much they agree to the following statements: *Walking like this through a virtual world is natural.*, *Walking this way through a virtual world is pleasant.*, *I could imagine using this walking technique to move inside virtual worlds*. The participants should answer on a scale from *1: totally disagree* to *7: totally agree*. In addition, we used a single item to measure potential symptoms of motion sickness by asking *How strong was the feeling of nausea or disorientation during walking?* on a scale from *1: non-existing* to *7: I wanted to abort the test*. Though we already included the item of acceptance as 7-point item, we decided to additionally force the users to either accept or reject a certain gain using the same question (*I could imagine using this walking technique to move inside virtual worlds*) but only with the options *yes* or *no*.

We used the same virtual curves with the radii of $r = \infty$ (straight line), r = 12.5m and r = 5m, but different gains for this experiment. As ground truth we tested walking without gain ($0°/m$). In addition, we tested a gain around twice the detection threshold ($10°/m$) as well as two very high gains of $20°/m$ and $30\ °/m$.

In addition to the quantitative measures we also asked the participants to provide feedback in textual form.

6.2 Procedure

For each condition, the participants first walked to a visually provided start point and walked the way to the target position. When the target was reached, the participants answered the questions while remaining inside the virtual world (as suggested by [11] to mitigate effects of interruption) by using the Oculus touch controller. After all questions were answered, the participants were guided to the next start position and the next condition was presented. The next task started as soon as the participant reported to have no symptoms of motion sickness. The experiment used a within-subject design with the independent variables being the virtual curve and the applied gain, as it was also done in the 2AFC task. Since we tested three virtual curves and 4 gains and repeated each condition four times, the participants had to walk 48 times (3 curves x 4 gains x 4 iterations).

After finishing all tasks, the participants were asked to fill in a final questionnaire which included textual feedback.

6.3 Results

Boxplots of our applicability items are shown in figure 4. While the median rating of the gains remained positive until 20°/*m*, we found a strong decrease of all scores when applying a gain of 30°/*m*. These results are mirrored in the rating of nausea and disorientation, which strongly increased for the 30°/*m* condition.

We first regarded the influence of the virtual curves on each score using separate Friedmann tests for dependant variables. Non of the ratings differed significantly, nor showed any noteworthy effect sizes. We therefore argue that the applicability scores, as well as the priorly stated detection thresholds, are not influenced by walking a virtual curve.

For the following analysis we therefore ignore the variable of the virtual curve's radius, since they did not influence the ratings. We therefore only compare the ratings considering the different tested gains.

We compared the sickness scores of the gains (0, 10, 20 and 30°/*m*) using Friedman's variance analysis for dependent variables. Since we found a highly significant difference (p=.00), we performed pairwise comparisons using Wilcoxon's signed rank test and adjusted the significance values using the Bonferroni correction. We started with the comparison of nausea and disorientation scores. While the gain of 10°/*m* did not significantly increase the scores (p=.79), 20°/*m* (p<.01) and 30°/*m* (p<.01) did significantly increase the scores.

Regarding the ratings of naturalness, we also found significant differences between the ground truth without manipulation and 20°/*m* (p<.01) and 30°/*m* (p<.01), while 10°/*m* did not show any significant effect.

The same trend is observed regarding the item whether a gain is still pleasant. While 10°/*m* did not differ significantly, 20°/*m* (p<.01) and 30°/*m* (p<.01) significantly decreased the respective ratings.

The rating whether a gain is applicable also did not vary significantly between 0 and 10°/*m*, while 20°/*m* (p<.01) and 30°/*m* (p<.01) were significantly less applicable.

Customization: We split the yes/no item about the applicability of gains in two parts (the first two iterations and the last two ones). Since the participants were forced to either answer with yes (1) or no (0), the middle of two trials can either be 1, 0.5 or 0. We interpret the value of 1 to be a certain yes, the value of 0.5 as being undecided and 0 as a certain no. Since the ratings did not differ between the virtual curves, we ignored this parameter in this part of the evaluation. The results are shown in figure 5.

The results mirror the tendencies of the 7-point scales, but show more clearly that the 20°/*m* gain is still applicable. Comparing the first iteration with the second one shows a slight tendency of customization. The participants tended to accept higher gains more likely in the second iteration. Since we only tested four times, we assume that the acceptance could even increase with more trials. While only 9% (or 12% in the first iteration) of the participants did not accept a gain of 20°/*m*, 70% (or 50%) fully accepted the gain. 30°/*m* was though obviously seen as not applicable. Only 6% accepted this gain, while 88% stated a clear *no*.

7 DISCUSSION

Our results indicate that users accept gains, even far beyond the level of detection. While our results, as well as prior results, state detection thresholds (though slightly varying) of around 5°/*m*, all of our participants accepted twice this gain. The applicability ratings proved that the ratings were not influenced by applying a gain of 10°/*m*. We argue that higher gains (up to 20°/*m*) can be applied, since they are still perceived as applicable, though they significantly increased nausea and disorientation and decreased the other applicability scores. So even increasing the gains to four times the detection threshold was accepted by 70% of the participants, while only 9% did absolutely deny their applicability.

The presented results are in strong contrast to the results priorly stated by Langbehn et al., who suggest that gains of up to around 32°/*m* are not perceived by users. Our results indicate that such high gains are far beyond being detected and even inapplicable and lead to a strong increase of nausea and disorientation. The other gains suggested by Langbehn et al. are though being far beyond the detection threshold, still around or below our applicability scores. Though we dissent with their detection thresholds, which were not based on measuring the perception of manipulation, we could prove their provided application scenarios. All, except one, of the used gains can be used from the perspective of applicability, though being obviously detected as manipulation.

7.1 Limitations

Though our participants accepted gains of up to 20°/*m*, we argue that this gain should not be used constantly. We only tested small sequences of walking and no longer application. In addition, the acceptance ratings have to be regarded with considering other tested scores. They all show, that such high gains are on the edge of being unnatural or unpleasant. In addition, we could observe an increase of disorientation. The 10°/*m*, which are still twice the detection threshold, though did not show any significant difference to the ground truth without any gains.

8 IMPLICATIONS

Our results show that gains can be applied far beyond the limitations of detection. Applying twice (or even around 4 times – depending on the source) the detection threshold as gain did not even show any influence regarding the perception of naturalness, comfort, applicability or nausea and disorientation. Applying higher gains like 20°/*m*, which is 4 times (our result and [12]) or even 8 times [31] the detection threshold, significantly reduced the applicability scores and increased nausea and disorientation, but were though still perceived as applicable. We therefore argue that redirected walking should not only be considered by measuring detection thresholds, but by considering other ratings which are related to the applicability of gains. We suggest to run similar experiments on other gains, such as translation gains, to allow an even higher compression of the virtual space.

Our results, however, should not be interpreted as hard thresholds. We found that a gain of 10°/*m* can be applied without influencing the respective scores. Though we did not aim at finding an exact point where the scores will be influenced stronger. Therefore gains of 15°/*m* could still be as usable as 10°/*m*.

While our detection thresholds of walking a straight line support the results of prior experiments, our results disagree with the results proposed by Langbehn et al. [19]. As we already described, this is due to the unsuitable use of *bending gains* for measuring detection thresholds and due to the different design of the 2AFC experiment (measuring detection of the direction of manipulation instead of the manipulation itself). The suggested use of gains up to 30°/*m* without being detected is even beyond the limit of our proposed applicability metric. We could not find that the virtual curvature does significantly influence detection nor our proposed applicability metric. Therefore, we argue against using bending gains over curvature gains.

We want to emphasize, that we could validate their proposed application of redirected walking in room-scale dimensions based on applicability metrics. Our proposed limit of applicability (being

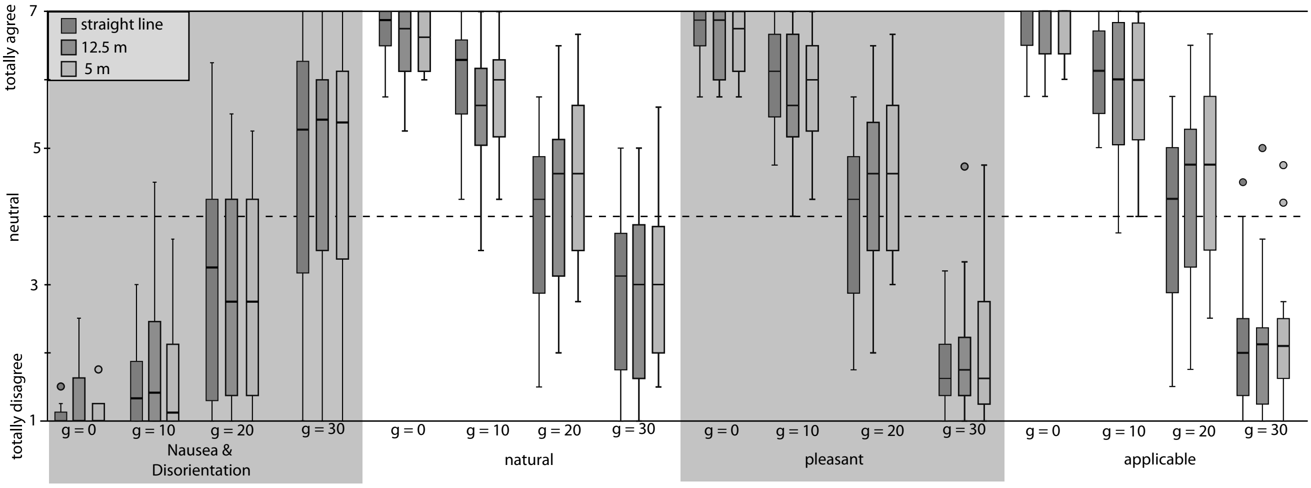


Figure 4: Boxplots of the used applicability items. All gains (g) are provided in the unit $^{\circ}/m$.

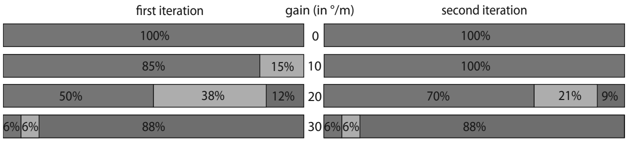


Figure 5: The percentage distribution of accepting the gains (green: yes, gray: undecided and red: no).

around $20^{\circ}/m$) still requires a space of around 6x6m to infinitely walk a straight virtual line. Forcing the user to walk curved paths can reduce the required space, since the angle of the virtual curve adds to the applied gain. The proposed room-scale application can therefore be realized not under the assumption of letting a user being unaware of the manipulation, but by having the user accept the manipulation. Only one of the proposed gains (which was around $32^{\circ}/m$) was even too high to be accepted by the participants and should be adjusted accordingly.

9 CONCLUSION

In this paper we propose a new metric for stating the quality of redirected walking (RDW) gains. We propose several items, based on related work, which we consider to be contributing to the applicability of gains. While prior works focused on designing such gains as subtle, to be not perceived by the user, we found that much higher gains can be applied before reducing the perceived naturalness or applicability, and without increasing nausea or disorientation.

Further, we show that the *bending gains* proposed by Langbehn et al. [19] are unsuitable for psychometric experiments and should be converted to curvature gains. For this we revisited their experiments and found that the proposed detection thresholds are far beyond the actual detection of manipulation. Yet, we could confirm their application to realize RDW in a roomscale setup of 4x4m, though not under the assumption of not detecting the manipulation, but under consideration of our proposed applicability metrics.

We argue that applying applicability metrics is a promising approach to reduce the required real world space, and that similar experiments should be conducted to get insights of the applicability of other RDW gains.

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Virtual Muscle Force: Communicating Kinesthetic Forces Through Pseudo-Haptic Feedback and Muscle Input

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Figure 1. We propose to enrich pseudo-haptic feedback with the additional input of muscle tension.

ABSTRACT

Natural haptic feedback in virtual reality (VR) is complex and challenging, due to the intricacy of necessary stimuli and respective hardware. Pseudo-haptic feedback aims at providing haptic feedback without providing actual haptic stimuli but by using other sensory channels (e.g. visual cues) for feedback. We combine such an approach with the additional input modality of muscle activity that is mapped to a virtual force to influence the interaction flow.

In comparison to existing approaches as well as to no kinesthetic feedback at all the presented solution significantly increased immersion, enjoyment as well as the perceived quality of kinesthetic feedback.

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CCS Concepts

•**Human-centered computing** → *Virtual reality; Haptic devices;*

Author Keywords

Virtual reality; pseudo-haptic feedback; muscle input; evaluation

INTRODUCTION

Virtual reality (VR) as a consumer accessible tool is a rapidly evolving technology. It offers a high level of presence and immersion for users even though consumer hardware provides only visual and auditive stimuli. Haptic features are also available in the form of vibration but do only play a minor role in VR hard- and software. While interaction inside the virtual environment has become much more natural by using dedicated controllers tracked in three-dimensional space, it is still limited to pressing buttons as input modality and vibration as output modality.

Multi-sensory feedback has shown to enhance the feeling of presence [8], but usually the inclusion of an additional stimulus requires a whole new set of additional hardware. Real kinesthetic feedback for instance, is hard or impossible to implement without the help of a real world counterpart that is able to restrict user's motion. Hardware-based solutions range from the use of tethered objects [32] to exoskeletons [3] or dedicated robots [31].

Current VR devices, however, usually consist only of the HMD and two controllers that are tracked in 3D space to interact with virtual objects. Building on such hardware, a completely different approach is pseudo-haptic feedback, that aims at delivering the illusion of haptic features solely by an altered visual feedback [38, 41]. The downside of hardware-based solutions, that pseudo-haptic feedback is not affected with, is a limited resolution and especially size and complexity of the systems. Fully natural kinesthetic feedback always requires a grounded counterpart in the real world. Pseudo-kinesthetic feedback – though different levels of kinesthetic forces can be displayed without additional hardware – is more or less a metaphor of forces that otherwise could not be displayed with available systems. Since such approaches only consider the feedback side of the interaction flow, one implication of such metaphorical feedback is that it does not involve the user's muscles for the interaction. Independent of the strength of kinesthetic forces, the user does not necessarily have to exert.

While prior works on pseudo-haptics concentrate on the output, this paper extends this concept to an input component that is embedded in the entire interaction flow. As long as only the output is considered, the user may lose some control over his actions. We propose to combine pseudo-haptic feedback with the additional input modality of muscle tension. By additionally using muscles as input devices it is possible to realize both input and output of haptic interaction without a physical counterpart and hand back control to the user. Pseudo-haptic feedback weakens the bond between tracked controller and virtual hand representation. By reaching through or into a virtual object the hand representation is blocked by the object and an offset to the controller's position results. It was proposed to use the offset between tracked controller and the virtual representation of the hand as a force [40]. This way, a virtual object (even if there is no physical reference) can resist the user (or at least their visual representation) and the kinesthetic feedback results in a visual offset depending on the virtual physical properties of an object. Though such an approach also affects the interaction, since a user has to stretch further to move heavier objects, it does not necessarily involve a real tensing of the user's muscles. We suggest to add a supplementary virtual force into the pseudo-haptic interaction cycle that is dependent on the measured tension of action related muscles. While pseudo-haptic tracking offsets can be used to visually communicate the forces, the measured muscle activity can be used as a countering force to these offsets. A higher weight can thus be communicated via an increasing offset, which decreases as the user begins to exert himself. In this way we want to communicate pseudo-haptic forces more clear and provide users greater control over their actions.

The advantage of the presented approach is, compared to already introduced solutions which used muscle contractions as input, the latter no longer has to be realized as a hard threshold. Previous works have designed muscle input in such a way that a certain threshold must be reached, e.g. to lift a virtual object. In this case there is a hard threshold from which an object can be lifted and held. If the measured values fall below this threshold, the object is dropped or cannot be moved. This hard threshold is no longer needed in our presented approach, since the measurement of muscle contractions can be integrated as an additional force inside the VR application. A weak muscle contraction therefore leads to a high tracking offset, but does not prevent virtual objects from being lifted or moved.

In a user study we found that such an approach can significantly improve immersion as well as enjoyment in VR applications. The use of muscle tension as additional input channel further increased the illusion of kinesthetic feedback as well as the perceived realism of the VR experience we implemented.

The main contributions of this work are:

- The concept of enriching pseudo-haptic feedback with an additional input modality and a concrete implementation using muscle exertion as input and visual manipulations as feedback channel
- A study showing increased enjoyment and immersion, as well as an increased level of the perceived quality of haptic feedback using such an implementation.

RELATED WORK

Multi-sensory feedback in general [8, 12] – and haptics being one of them – plays a major role for the feeling of presence in VR. Humans can differentiate various object properties like texture, hardness, temperature and weight by our haptic senses [26].

Hardware solutions

Our work concentrates on kinesthetic feedback, which is used to display directional forces. One way to achieve this goal is to make use of handheld [32] or stationary mounted tethers around the user [17]. More complex is the use of exoskeletons on the hands [3, 4, 10, 14] or on the arms of users [34]. Exoskeletons can also be attached between two body parts [49].

Passive-Haptic Feedback

The virtual and physical world are differing, but this mismatch can be compensated. There are several approaches to partially recreate the virtual world inside the real one. Robots [13, 31, 50] or other humans [7] can be used as helpers or actuators. There are also approaches on passive haptic feedback using props as physical counterpart for the virtual ones [16, 21, 46]. The mapping of real world objects to virtual objects can also be supported by slightly manipulating the user's motion to match surfaces [20, 45] or objects [2].

Pseudo-Haptic Feedback

Beside dedicated hardware and passive-haptic feedback there is a third strategy for the communication of kinesthetic feedback: Pseudo-haptics. The basic concept is to circumvent the real stimulus by another stimulus (most of all using vision). This way, object properties can be *faked* by synchronously presenting visual stimuli to support the performed interaction.

Various properties like friction [23, 24], stiffness [47] or tactile feedback [37] can be displayed without the need for a real world counterpart. There are also works on simulating directional forces [25, 22] on external displays or the subtle resistance of airflow [38, 39] in VR. The aim of all these approaches is to slightly manipulate the virtual representation of the hands without being recognized by the user. Unlike the naive vision of perfect illusion, such manipulations may also be applied with the user being aware of being manipulated and therefore breaking with proprioception. Though not relying on forces, it was suggested to support the feeling of slow-motion in VR by visually slowing down user motions [42]. In their proposed solution, depending on the user's velocity, there was an obvious difference between proprioception and the visual feedback.

Such obvious dissent between proprioception and visual feedback was also used to communicate kinesthetic feedback. This way even virtually heavy objects could provide respective feedback when being lifted [41]. Samad et al. [43] further explored the range of the control/display-ratio to simulate weight in virtual reality. A similar approach was presented for kinesthetic feedback in general [40] where also a multi-sensory pseudo-haptic feedback approach, which combines visual and vibration feedback, was presented.

Our approach and implementation is built on these presented works and the concept of pseudo-haptic feedback with perceivable offsets in general.

Muscles as input or output devices

Muscles have already been used for input and output for interaction. Electrical muscle stimulation (EMS) was used as feedback channel [11, 28, 29, 35, 48]. Lopes et al. used this approach to provide ungrounded kinesthetic feedback by actuating opposing muscles [30]. They actuate an opposing muscle to force the user to tense the desired one . Our approach has some similarities but while our proposed interaction also relies on exerting the user, we do not force the user to tense their muscles by electrically stimulating the opposing muscle. In our approach, the user is encouraged to tense a muscle to support the intended interaction.

Nacke et al. [33] investigate the effects of using physiologically controlled games. They argue, that respective sensors have to be mapped intuitively and matching to the desired action for direct interaction. Electromyography (EMG) was used for other interaction techniques such as e.g. pointing and clicking [15], same-side hand interactions [18] or hand gestures (e.g. [9, 19, 52, 51]), however often using algorithmic or learning-based solutions to derive other biomechanical parameters like hand pose from muscular activity before.

Ponto et al. used biofeedback to interact with virtual objects with a certain mass [36, 6]. In their system, users require to exert a calibrated amount of exertion to grasp and hold objects.

Hirooki Aoki [1] examined effects of pseudo-haptics on muscle activity to support exercising. He found that such approaches can indeed increase the amount of measured muscle activity.

COMBINING PSEUDO-HAPTICS WITH MUSCLE INPUT

Prior works that utilized exertion for interaction in VR implemented their approach in a way, that a certain threshold of force was required to lift and hold virtual objects. Pseudo-haptics, on the other hand, was implemented as discrete and barely noticeable feedback as well as by treating it as some kind of metaphor for kinesthetic forces using perceptible tracking offsets. We propose to include muscle activity as additional input for pseudo-haptic feedback to let virtual forces influence the whole interaction cycle. While prior approaches always require a minimum amount of force to keep the object grabbed, we utilize pseudo-haptics as additional feedback. In this case, offsets are used to indicate the weight of an object. As the user exerts, the amount of offset will be reduced according to the force a user applies.

Humans are able to tense their two opposing muscles, even without applying forces to physical objects. This allows the user to actually influence the applied strength of forces in the VE using the same medium as in the real world, which is the tension of muscles.

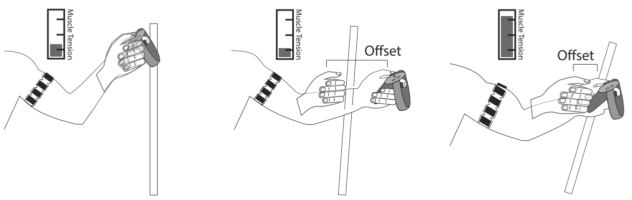

Figure 2. The offset between real hand and virtual hand representation, which is used for passive-haptic feedback, is dependent on muscle tension. When the user flexes his biceps, he is able to reduce the offset and therefore, apply higher forces in the virtual world.

The basic idea of pseudo-haptic feedback is to simulate kinesthetic forces by offsets between real limbs and their virtual representation. For greater expressiveness, this offsets can reach magnitudes where they become perceptible to users [41]. Depending on the movement the user performs and the resistance of the virtual object, the offsets vary in size. By combining pseudo-haptic feedback and muscle tension as input, this offset can additionally be influenced by the tension the user creates. The more a user flexes their muscles, the greater the applied force in the VE. Therefore, the offset is scaled by the physiologically created muscle tension.

IMPLEMENTATION

Our implementation consists of two separate virtual forces that are applied when a user interacts with, pushes or pulls an object. One is the *offset force* which was implemented as proposed by prior work [41, 40]. In this approach the the visual representation of the controller in the form of virtual hands are decoupled from the actual tracked position of the controller and are therefore treated as ordinary objects by the physics engine. The virtual hands are always pulled by an attraction force towards the position of the tracked controllers. With no further restrictions, the virtual hand representation is in the exact the same position as the corresponding controller in the real world. As soon as the real hands reach behind or inside a virtual object, the virtual hands collide with this object. As a result, the virtual hands apply their attraction force to the virtual object and may manipulate it, dependent on physical properties. The force that is applied to the virtual object depends on the size of the offset between virtual hand and tracked controller. Therefore, heavier objects with a higher inertia and friction require a larger offset to be manipulated. If the offset reaches a specified threshold (e.g. in case of a static object), clipping is used as escape strategy.

The *muscle force* is the second virtual force we included as a novel addition over previous works. The direction of the *muscle force* acts in the same direction as the *offset force* and its magnitude dependents on the measured muscle tension. As long as the user does not flex his muscles, only the offset force is effective. As soon as the muscles are tensed (and depending on the measured intensity) the offset force acts as support (see figure 2). This allows e.g. a heavier object to be lifted with a lower offset as long as the muscles are flexed.

Since the offset force was already described in prior works [41, 40], we will not discuss the respective implementation and only discuss the implementation of the muscle force in the following.

The Muscle Force

We used the Thalmic Myo armband to measure muscle tension. The armband consists of eight EMG sensors and is connected to a computer via bluetooth. In our implementation, we did not aim at distinguishing between different muscles (e.g. biceps and triceps to separate pushing from pulling) since when tensing muscles without real world counterpart, two opposing muscles must be tensed to keep the posture. Therefore, pushing a virtual object results in the tension of biceps and triceps as well.

Since the hardware we used possesses eight EMG sensors, our implementation takes all EMG signals into account, but only the largest factor is considered for further calculations. In this way, the Myo wristband itself does not need to be calibrated and can be attached in any rotation. Our approach could also be implemented with a single EMG sensor on one of the muscles.

Since the measured EMG signal is very noisy, an OneEuroFilter [5] is applied to smooth the measures before any further calculations.

Calibration: Since the minimum and maximum of the measured EMG signal strongly varies between users, a calibration of strength is inevitable to utilize muscle tension as input device. We perform a two point calibration. The user is first asked to relax their upper arm for 2 seconds. During this time frame, data is collected from the EMG sensors and a mean is calculated after excluding outliers. This procedure is then repeated with a flexed muscle for the maximum value.

Normalization: We then normalize the measured EMG values based on the calibrated maximum and minimum by subtracting the minimum from the current measure and dividing it by the maximum. We further restrict the range to values between 0 and 1.

Conversion to force: Based on the normalized measures a force is applied inside the VR application as long as the user interacts with an object. In our implementation, the conversion from the normalized EMG signal to a force was done in a linear way, multiplying the normalized EMG signal by 110N. This value was chosen according to [44] as the force a human can apply standing with her primary arm and shoulder muscles. The resulting scalar is then multiplied by the normalized direction vector between tracked controller and virtual hands (the direction of the offset) and applied as additional force.

The muscle force ($F(m)$) is therefore calculated using the current measurement (m), the minimum (min) and maximum (max) of the calibration and the direction of the offset ($\hat{O}$) as follows:

$$F(m) = \frac{m - min}{max} \cdot 110N \cdot \hat{O} \tag{1}$$

If a more realistic application is desired, we suggest to measure and use this maximum force for each user to let the application react on each individual according to his or her real strength. Furthermore, different operations, such as pushing, lifting and pulling, could be distinguished and treated differently. It is also possible to substitute the proposed linear interpolation by a more complex one. One suggestion is to use several calibration objects that are lifted by the user while measuring their muscle activity. Depending on the number of calibration objects a more or less reliable curve could be fitted to replace the linear function.

STUDY

To evaluate the proposed approach against state-of-the-art pseudo-haptic feedback approaches and a system without kinesthetic feedback (as used in most common VR applications) we designed a VE in which a user is asked to directly manipulate objects to progress and reach other locations inside the environment. We used an Oculus CV1 as HMD and two Touch controllers for the input.

Participants

For our study we recruited 21 participants (5 female) aged between 22 and 29 years with a mean of 25 (SD: 2.7). Most of them were students or employees of our university since we recruited on campus. We asked the participants to state how many months of experience they have with VR devices. The responses varied between 0 and 36 months ago with a mean of 6 month ago (SD: 9 months).

Method

We designed our study as a within-subject design having three conditions: no pseudo-haptics (*none*), pseudo-haptic feedback only (*PH*) which was implemented similarly to [40] and pseudo-haptic feedback with muscle force (*PHM*) that used the same implementation for the offset force as the *PH* condition but also the described implementation of the muscle force in addition. The differences and effects on the test applications are discussed in more detail in the *Study Application* section. All conditions were presented in a counter balanced order using a latin square.

We compared the three conditions in regard to immersion and enjoyment which were both assessed by the E^{2}I questionnaire

[27]. Additionally, we used five single item questions to get insights on the perceived quality of the haptic feedback as proposed by prior work [40]. We asked the participants to state how much they agree with the following statements on a scale from 1 (=strongly disagree) to 6 (=strongly agree): *"I could feel a resistance"*, *"The representation of physical constraints felt realistic"*, *I had the feeling of manipulating real objects* and *"I could influence the behavior of objects with my actions"*.

To get further insights on the personal preferences of each implementation we also included the item: *"I liked this representation of physical constraints"*.

Study Application

Our test application was a virtual environment in which participants had to interact directly with virtual objects. The participants were automatically teleported to the next task, after they completed the prior one. Since one of the study's goal was to find out whether the respective interaction techniques felt natural and fit the visual impressions of virtual objects we decided to implement a visually rich virtual environment. The visual appearance of objects the participants interacted with should have a realistic character to create expectations about their behaviour and physical properties.

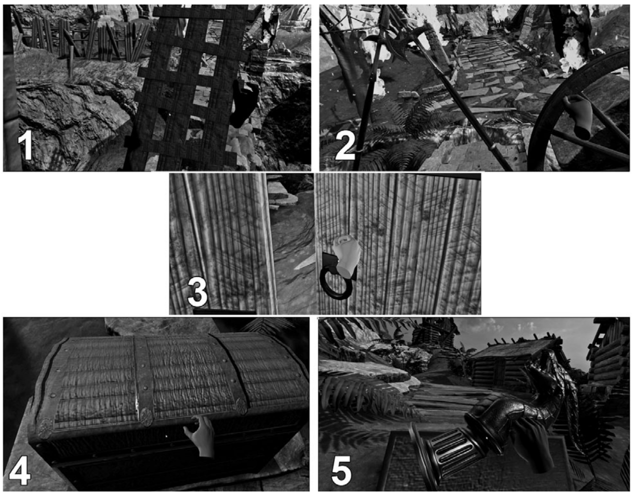

Figure 3. The five different interaction tasks that were implemented for this evaluation. Participants were asked to push [1,3], turn [2] and lift [4,5] objects while applying varying amounts of force for each of them.

Tasks: We chose tasks that do not necessarily require kinesthetic feedback but could benefit from it. Depending on the condition, the behavior of these objects varied as soon as they were touched. The differences will be discussed in more detail in the *Conditions* paragraph.

The first task to accomplish was to push a wooden structure, so that it tips over and falls into a small chasm where it completes a bridge in front. The wooden structure was defined lightweight and was easy to move in all conditions.

After the completion of the first task, participants were automatically teleported to the second location at the end of the provisional bridge just created. Here, they needed to unblock the path by cranking a wheel that slides the barrier (two spears) out of the way. Since the wheel had to be pulled towards the user, this task demanded the opposite direction of motion as task one. As the gate opened up, the user was again teleported – this time to a wooden double-winged door which was already in user's line of sight. As a third task, the participants needed to open both wings of this door. This required, much like the first task, a push operation. The difference was, that the doors were designed to possess a much higher resistance compared to the wooden structure in task one. This difference though, could only be observed in the two pseudo-haptics conditions (*PH* and *PHM*) since the respective forces cannot be displayed without (similar to current state-of-the-art VR games). Once both wings are wide open, the user was teleported to the last location.

Here, the user faced a large wooden chest. First, the heavy lid had to be lifted beyond the point, where gravity takes over and the lid falls back. The second part was to grab and lift a golden dragon statue which was placed inside the chest. When compared to the lid of the chest, this statue is designed more lightweight. The last two tasks therefore consisted of two different lifting operations, one heavy and one lightweight.

By getting to the golden dragon statue, the user has achieved his quest and the experience was over.

Conditions: Depending on the condition, the interaction with objects slightly differed, since the *PH* as well as the *PHM* condition introduced different challenges (reach further due to the offset force and additionally tense the muscles to move an object). The impact of these differences were then assessed and compared using the described questionnaires. The following paragraphs summarize the differences.

The **none** condition is the state-of-the art of most VR applications and did not provide any kinesthetic feedback at all. The task of moving virtual objects could be solved without any additional challenge, since the objects and the virtual hands moved as the real hands of the users did, by following the tracked controllers without any manipulation.
The **PH** condition relied on already proposed implementations of pseudo-haptic feedback ([40, 41]). To solve their tasks, the participants had to put more effort into moving the objects, since the force applied to a virtual object dependent on the offset between tracked controller and the virtual hands. Depending on the weight of an object, the user had to reach farther to move it.
The **PHM** condition used the same implementation as the *PH* condition but made use of the described *muscle force*. Depending on the measured tension of the user's muscles, an additional force was applied to the virtual object. This resulted in potentially less offset and more exertion compared to the *PH* condition.

Independent from condition the maximum offset didn't exceed 42 cm as proposed by Rietzler et al. [41]. In this case, clipping was used as escape strategy.

Procedure

The participants were welcomed and introduced to the topic of the study. We only communicated that the study was on interacting with virtual objects. None of them was further informed about the details of the underlying implementations but informed about what they had to do to move heavier objects (e.g. exert their muscles or reach farther). Each participant then completed a demographic questionnaire and signed a consent form.

Before any condition started, participants were introduced to the five tasks and what they needed to do to accomplish the task. Ahead of the actual experience, participants found themselves in a virtual training environment, where they could interact with a sample object to try out and get used to the current condition. In case of the *PHM* condition we calibrated the EMG sensors before starting the training. After completing the experience with one condition, participants were asked to fill the questionnaires described in the *Method* section.

After completion, this procedure was repeated for the remaining conditions in a counterbalanced order.

Results

We compared each of the scores and items described in the *Method* section using Friedman's variance analysis. If a significant difference was present, we used Wilcoxon's signed rank test to make pairwise comparisons. All stated significances were adjusted by the Bonferroni correction. Boxplots of all values are shown in figure 4. Significant values below 1% are referred to as highly significant and values below 5% are referred to as significant in the following.

Immersion differed highly significantly (p <.01) within the three conditions. Pairwise comparisons showed a significant difference between *none* and *PHM* (p <.01; r = .28) and between *PH* and *PHM* (p <.05; r = .16).
Enjoyment scores differed highly significantly. We found the differences between *none* and *PHM* (p <.01; r = .30) and between *PH* and *PHM* (p <.01; r = .22).
Realism ratings revealed significant differences between *none* and *PHM* (p <.01; r = .26) and between *PH* and *PHM* (p <.05; r = .16). While the feeling of **touching real objects** highly significantly differed between all conditions: *none* vs. *PH* (p <.01; r = .19), *none* vs. *PHM* (p <.01; r = .33) and *PH* vs. *PHM* (p <.01; r = .14).
The **feeling of resistance** also differed highly significantly between all conditions. The strongest effect sizes were found between *none* and *PHM* (p <.01; r = .38), and between *none* and *PH* (p <.01; r = .21). The *PHM* condition provided a significantly stronger feeling of resistance then the *PH* condition (p <.05; r = .17).

The feeling of being able to **influence objects** was highly significantly stronger in the *PHM* condition compared to *none* (p <.01; r = .28). Though not differing significantly, we found small effect sizes comparing *none* and *PH* (p >.05; r = .14) as well as *PH* and *PHM* (p >.05; r = .14).

Though we found a significant difference comparing all conditions regarding the results of the single item questions whether the participants agree to **like** the presented approach, we did not find any significant differences when comparing pairwise.

Discussion

Immersion: Though the boxplots as shown in 4 do not indicate strong variations between conditions, the results support the assumption that the inclusion of muscle tension as an additional input for pseudo-haptics can increase immersion.

The **enjoyment** scores were very high for each condition, though there is a clear tendency towards the *PHM* condition resulting in a higher enjoyment. Interestingly, the variances of the scores differed most in the *PHM* condition. While most of the participants had most fun with the proposed approach, few did like it less. In informal discussions after the study was finalized, some participants stated that they just wanted to complete the challenge. They saw the pseudo-haptics as some kind of disturbance, that limited them to complete the challenge as fast as they could do without such modifications. We could not observe similar ratings considering immersion. We assume that the additional input was more compelling for almost every participant, while some saw themselves constrained in managing the tasks. However, this additional challenge was not perceived as negative by every participant. The majority stated that they felt more involved in the virtual world because of the possibility to influence the objects with their own muscle power. Due to the additional challenge, some participants stated that they were more pleased with the success.

Perceived haptic quality and realism: The item that was influenced most by pseudo-haptics in general was the feeling of *resistance*. While the respective scores are obviously quite low without additional feedback (median: 2 out of 6), participants rated it much higher with the proposed combination of pseudo-haptic feedback and muscle input (median: 5). The approach also strongly influenced the feeling of interacting with *real objects* (median 3 vs. 5) and the overall realism of the application. Interestingly, the ratings whether participants *liked* the presented approach did not vary strongly, though all other ratings were improved by pseudo-haptics, including enjoyment. This could be due to differences in characteristics of the conditions. In the *none* and *PH* condition, the users might feel that they have a super power to move every object without having any fatigue or resistance from objects. As soon as the muscles get involved, this is no longer the case. The user must tense his muscles, which may make the interaction more realistic and intense, but also more strenuous and difficult. As mentioned before, there were some participants who liked the additional challenge, while others, who were most of all into completing the challenge stated that it would make the virtual experience more intricate. We assume, that if these participants only knew a single version of the experience, the ratings would differ more strongly.

Limitations

We did not compare our approach to hardware-based solutions which provide physical kinesthetic feedback. As the boxplots in figure 4 show, we achieved very high ratings in *feeling of resistance* and *feeling of touching real objects* with our proposed approach. However, the absolute scores of these results should be interpreted with care. We assume that the rating would be much lower when comparing a pseudo-haptic approach with real physical stimuli.

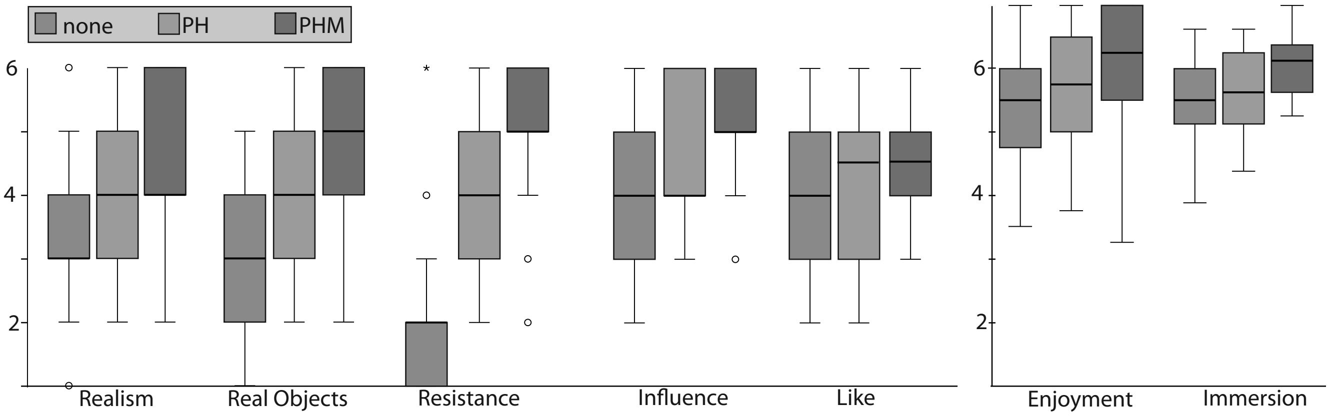

Figure 4. Left: Boxplots of the answers of our single items as described in the *Method* section. Right: Boxplots of the E^2I enjoyment and immersion scores.

The enjoyment scores are little difficult to interpret. While the scores were higher in both pseudo-haptics conditions, there were also some low ratings (see the boxplot's whiskers). Considering the informal verbal feedback which we collected by talking to the participants after the study, the pseudo-haptic feedback as well as the proposed muscle input was perceived ambivalent. While most of the participants liked and enjoyed such feedback, others saw themselves restricted in their actions. When playing without the pseudo-haptic feedback or muscle input, every task could be solved much faster, since there was actually no challenge at all. We therefore assume, that the respective ratings were very much influenced by the basic attitude of the participants: if they just wanted to complete or whether they wanted to be challenged.

IMPLICATIONS

Using muscle tension as input has shown to be a promising way to enhance pseudo-haptic feedback. Most of the participants liked the approach and valued their additional influence on manipulating the virtual environment. Based on the feedback we got from the participants as well as by our own experience during implementing and testing we suggest to consider the following when designing applications with pseudo-haptic feedback with muscle input:

Familiarization is a very important factor. Some participants had no problem in tensing their muscles without a real world counterpart, while others needed some time to get used to it. We therefore suggest to include a tutorial, where users can try to interact with an object based on their own muscle tension.

Exhaustion is a factor that should be considered as well. Though there is no real object that is pushed, pulled or lifted, participants stated that it was indeed exhausting to interact with the virtual objects. We therefore suggest using the approach with care. Not every action a user performs in the virtual world should be based on strong muscle tension. Such high exertion levels may be used best to design additional challenges that make use of physical exhaustion, while lower levels (that could also be easily compensated by the pseudo-haptic feedback's offset force) can be used without limitations.

Challenges, though, have to be designed in an adequate way. In our tests, we found that some participants just wanted to finish as fast as possible. Compared to the alternative of having some kind of superpower (which was given in the *none* condition, where the user could manipulate objects without effort), some interpreted the additional challenge as limitation.

Applications can range from more realistic (like simulations) to unrealistic game effects. If the goal is high realism, the function which converts the measured values into virtual forces could be adapted to the individual and calibrated more fine-granularly. Real reference objects could also be included in this calibration step.

On the other hand, the approach is also suitable for displaying game effects. If a character becomes stronger, the virtual muscle strength could become stronger and less muscle tension would be required to lift heavier objects. If a character is weakened it could be scaled to be smaller. In the latter case, each action in the virtual world would be associated with more effort.

CONCLUSION

The ability to interact directly with virtual objects via controllers tracked in 3D space is becoming of great importance in VR applications. Though the ability of having a natural interaction, one with haptic stimulation, within such scenarios is still limited. Since it is very hard to develop hardware solutions that are suitable to communicate the broad range of possible kinesthetic feedback, we propose to enhance pseudo-haptic feedback with muscle activity as additional input. Neither pseudo-haptic feedback nor the measurement of muscle tension demand actual forces, and therefore neither haptic props nor complicated hardware are required. Our proposed approach uses priorly presented pseudo-haptic feedback techniques, where physical properties are communicated by offsetting the virtual hand from the tracked controllers. We propose to use the user's muscle tension as additional input to enhance respective interactions, make them more natural and give the user more control.

In a user study, we found that such an approach is suitable to enrich the interaction with virtual objects. We found a significant increase of immersion as well as enjoyment. Participants also rated the approach to be more realistic compared to no pseudo-haptics at all, as well as compared to pseudo-haptic feedback only. Additionally, we found an improvement of the feeling of physical resistance.

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Telewalk: Towards Free and Endless Walking in Room-Scale Virtual Reality

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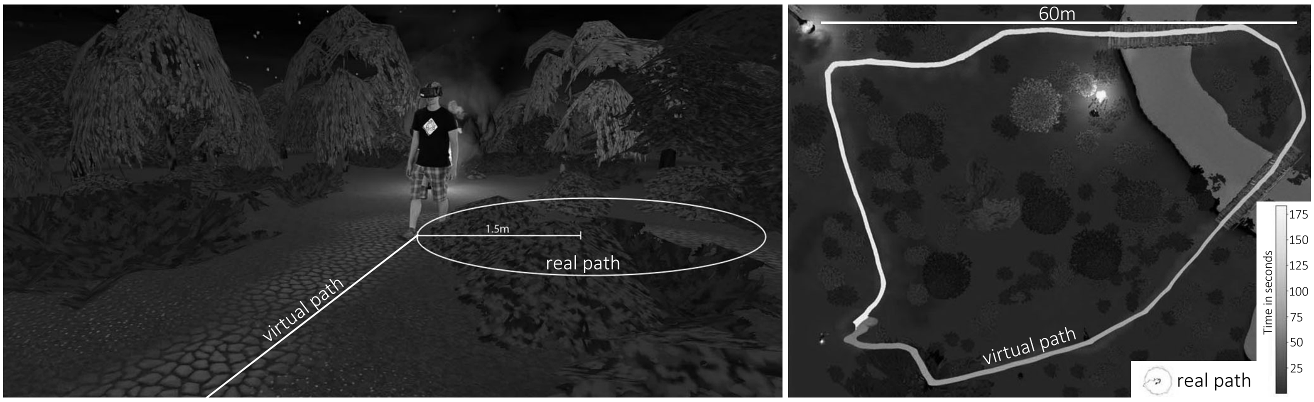

Figure 1: The concept of Telewalk: The combination of perceivable curvature and translation gains along with a head based camera control allows to compress any virtual space to a pre-defined real world radius (in our case 1.5m). (Left) illustration of walking paths and (right) plots of the virtual and real path walked in our study application.

ABSTRACT

Natural navigation in VR is challenging due to spatial limitations. While Teleportation enables navigation within very small physical spaces and without causing motion sickness symptoms, it may reduce the feeling of presence and spacial awareness. Redirected walking (RDW), in contrast, allows users to naturally walk while staying inside a finite, but still very large, physical space. We present Telewalk, a novel locomotion approach that combines curvature and translation gains known from RDW research in a perceivable way. This combination enables Telewalk to be applied even within a physical space of 3m x 3m. Utilizing the head rotation as input device enables directional changes without any physical turns to keep the user always on an optimal circular path inside the real world while freely walking inside the virtual one. In a user study we found that even though motion sickness susceptible participants reported respective symptoms, Telewalk did result in stronger feelings of presence and immersion and was seen as more natural then Teleportation.

CCS CONCEPTS

- **Human-centered computing → Virtual reality**.

KEYWORDS

Redirected Walking; Virtual Reality; Telewalk

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1 INTRODUCTION

Navigating inside virtual worlds is challenging to realize, since the scale of the virtual world does not necessarily match the one of the real world. When consuming VR content in a room-scale application, the available real world space does seldom exceed 3m x 3m. The current solution to allow navigation within such a small space is

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the use of point and teleport, where a user instantly changes their position without actually moving inside the real world. Though this solution is suitable to allow navigation in VR, it still comes with drawbacks, such as the missing feeling of actually moving or the loss of spatial awareness [6]. However, teleportation also has advantages over natural walking that go beyond pure feasibility. Even long distances can be covered in a very short time. For many applications such a technique is a pleasant and comfortable way to move through a virtual world.

An alternative to teleportation is the use of manipulations to trick the user to walk within a given real world space while walking a different path inside the virtual world. Such manipulations are summarized under the term redirected walking (RDW). To design the manipulations of a RDW technique in a way that it is suitable or even unperceivable for users, the required space is still far to big to be realized within a 3m x 3m tracking space.

We propose Telewalk, a novel navigation technique that is based on very strong RDW manipulations to allow infinite and free walking within a 3m x 3m tracking space. Telewalk combines the advantages of RDW and teleportation. The proposed interaction technique has only low demands on the physical space, is based on natural walking (in order to convey a stronger sense of space) and also enables rapid movement within the virtual world. Telewalk essentially works based on three main mechanisms. (1) Perceivable RDW gains: translation gains scale the user's velocity, which leads to a slow pace and smaller steps. As a result, higher curvature gains can be applied, which lead to a smaller radius of the circle, the user walks on. As soon as the user continues to walk faster in the real world, however, an unnaturally fast movement can be achieved. (2) To ensure the user always remains on the optimal path around the tracking space's center, we use the head of the user as input device to allow virtual direction changes without actually turning the body. (3) As a last feature, we included a visual guidance to keep the user aware of the optimal path and direction.

Telewalk also offers great potential for expansion. While the technique presented in this paper is based on a real path around the center of the physical tracking space, it is also possible to define a path that takes into account the individual room geometry including obstacles such as tables and chairs.

We implemented Telewalk in several iterations and optimized it based on user feedback. In a user study, we compared our final implementation of Telewalk to the state-of-the-art locomotion approach: Teleportation. The results show that Telewalk leads to a significant increase of presence and was seen as more natural then teleportation. On the other hand, Telewalk also lead to an increase of motion sickness symptoms, most of all to motion sickness susceptible participants. Overall, half of the participants preferred to navigate through a virtual world using telewalk, while the other half preferred teleportation. A further advantage of Telewalk is the exact predictability of the path taken in the real world. This way, the available space can be optimally used and walking on small areas can be realized.

The contributions of the paper are the following:

- The description and implementation of the Telewalk locomotion technique, which allows for continuous movement in space as small as 3x3 meters
- A user study showing that Telewalk can enhance the feelings of presence and immersion
- Implications for future Telewalk implementations and suggestions based on our own experience and participant's feedback

2 RELATED WORK

2.1 Overview

One of the goals of many virtual reality applications is to provide realistic navigation through the simulated world. Here both of the two main components, the cognitive way-finding and the physical (active or passive) travel [6] need to be available for users. Way-Finding here denotes the spatial-cognitive process of finding a route from one location to another, while travel encompasses the actual movement through the virtual environment. This movement can be carried out in a passive manner (i.e. using a joystick) or active (i.e. moving physically). Latter case is often denoted as locomotion.

Walking is considered to be the most natural way of moving through a virtual world [38], but due to the real world spatial limitations of current virtual reality setups, other locomotion techniques were introduced [35]. Boletsis et. al [2] provide a topology of such techniques, grouping them into four categories (motion-based, roomscale-based, controller-based and teleportation-based). Their categorization is based upon factors like physical or artificial interaction, continuous or non-continuous motion, and limitations of the virtual interaction space.

One common factor amongst most of these locomotion techniques is the occurrence of the so-called simulator or cybersickness with certain users. These are in general considered to be subsets of motion sickness and therefore the symptoms of both are related, including eye strain, headache, sweating, vertigo and nausea [21]. The most accepted theory about the cause of motion sickness is the sensory conflict theory [28]. It states that the body is not able to handle dissimilar information from different sensory systems. When locomotion techniques create such a conflict, due to them presenting different visual stimuli from vestibular ones (e.g. showing visual motion to a standing observer) they can possibly cause motion sickness to occur.

2.2 Walking-in-Place

One technique that aims to be realized within a small real world space while moving through the virtual world is the so-called walking-in-place approach [20, 25]. Here users only move their arms, head or legs up and down, while standing on a spot. The system translates said movement into a virtual forward motion. This approach was rated worse compared to actual walking, but better compared to virtual flight [38] or movement based arm-swinging [39].

The walk-in-place (WIP) approach can be enhanced by using a passive or active platform beneath the user, that allows for step movements to be performed more naturally while still staying in one spot. Such treadmills [3, 4] or larger even robotic moving platforms [17] still show less performance compared to real walking [23], as full physical movement increases the efficiency of any navigational search, due to better spatial memory [30].

2.3 Teleportation

The approaches mentioned above all cause some form of sensory conflict, as the presented virtual motion does not match the physical motion and can therefore lead to motion sickness symptoms. One locomotion approach that avoids such sensory conflicts is Teleportation – used in nearly all current VR applications. It avoids the conflict by never presenting any kind of motion, instead instantly transporting the user to the target. Teleportation therefore does not suffer from motion sickness [7].

There are however disadvantages to these instant location changes, as they might influence spatial awareness and presence in virtual world negatively [1, 5, 10, 31]. Bowman et al.[6] found that these changes cause spatial disorientation in users, while Christou et al.[9] suggest the overall impact of disorientation on the experience to be negligible, though the potential of missing elements along the route is not.

2.4 Redirected Walking

Unlike the WIP or teleportation approaches, redirected walking (RDW) aims to provide unlimited natural walking in VR while still requiring a limited physical space. In order to achieve this, RDW manipulates the users orientation, position or other features. The manipulation of the user's orientation during walking is called curvature gains, presenting the user with a straight virtual path, but manipulating them to walk in a circle in the real world instead [27]. Suma et al. [36] introduced a taxonomy for redirections and reorientations, ranging from subtle, as above, to overt manipulations. Using overt manipulations keeps the discrepancy between virtual and real travel path small enough, so that users may not be able to detect any manipulation. The redirection can occur in different ways, with the two main types being through curvature or translation gains.

Curvature gains are described as a rotational manipulation that is applied during walking. It can be described in the unit degree per meter and can be interpreted as a change of the user's coordinate system while walking. Using curvature gains Steinicke et al. [34] have been able to redirect users onto a circular path with 22m radius without the users being able to detect the manipulation. Another solution, which reduces the required space was suggested by Langbehn et al. [20]. They propose to force the user to walk on already curved paths and additionally apply curvature gains.

Translation gains do not manipulate the orientation, but the velocity during walking. Interrante et al. [16] introduced a system that applies moderate gains onto the users motion, but only in the direction of travel, allowing for a much faster and preferred method for traversing linear corridors. Grechkin et al. [12] used a combination of curvature and translation gains and were able to improve the detection radius down to 12m. It has been shown that translation gains do not influence the detection thresholds of curvature gains, however the velocity of walking during the redirection does [24]. It was also proposed to redirect a user while standing still and turning around. This kind of gains was called rotation gains [18].

While the gains described were examined from the point of view of the perception of manipulation (detection threshold), Rietzler et al. propose to examine gains for their acceptance [29]. They report that curvature gains could be increased up to $20°m$instead of the perception threshold (which was reported between $2.6°m$ [34] and $4.9°m$ [12]).

As long as the users remain on a straight, fixed virtual path, redirection has not to contend with any further factors, but in order to allow for virtual direction changes, further redirection mechanics have to be introduced, to keep users within the physical boundaries. For this problem, Razzaque presented three redirection algorithms that adjust the gains dynamically based on the current position of the user: Steer-to-center, steer-to-orbit, and steer-to-multiple-targets [27]. If the user still collides with the boundaries of the tracking space, a reorientation phase is started in which the user is turned around towards the tracking space's center. In a comparison between these algorithms, steer-to-center was found to be the best performing, while steer-to-orbit is best used for long straight virtual paths [13].

To make all these reorientation phases less obvious distractors were introduced [26, 33]. To avoid interruptions like this, Hodgson et al. [15, 33] presented an algorithm for very large spaces, i. e., 45m 45m. Sometimes though the boundaries cannot be fully avoided and the user needs to be reset. Here Wilson et al. [39] introduce several resetting techniques, that ensure the users' reorient themselves back into the tracked space. Sun et al. [37] propose a technique that utilizes eye-tracking to detect saccadic eye movements in which the user is temporarily blind to apply higher manipulations.

Telewalk uses some results of the presented works. The basic mechanism is based on combining translation and curvature gains. While these are mostly hidden for the user, for Telewalk they are obviously and deliberately used as an interaction technique. Similar to teleportation, the user is always aware that real movement is different from virtual movement. This circumstance allows a stronger compression of the virtual space. Furthermore, a higher virtual walking speed can be achieved in order to overcome greater distances in a shorter time - similar to teleportation. As described in the following, new visualization metaphors will be introduced, which should enable the user to keep control at all times.

3 DESIGNING THE TELEWALK

Current VR navigation approaches, which are based on real walking, basically place demands on the real or virtual space. While for example the use of unperceivable gains still requires a huge physical space to be applicable, other approaches, such as the proposed circular paths [20], require a specific path the user walks inside the virtual world. Currently there is no real walking technique that can be applied within small tracking spaces without limiting the VR application or the way a user walks within the virtual world. With Telewalk, we aim at proposing a solution that overcomes these limitations to allow a more natural navigation inside VR applications.

Telewalk is a novel concept for navigation that consists of three parts: (1) Manipulations (RDW gains), (2) a camera control that realizes directional changes based on head rotation instead of physical turns and (3) visual guidance.

3.1 Overview of the Challenges

The required real world space of a RDW technique most of all depends on the strength of the gains that are applied. These gains have their limits, since too high gains would lead to cybersickness, disorientation and would at some point no longer be pleasant for the user. In a preliminary work we propose a maximum of acceptance for curvature gains at a level of around 20°m [29]. This reduces the required physical space to around 6x6m for walking a straight path. But there is an additional challenge when implementing RDW: the technique that ensures the user keeps within the available real world space. Most tests on RDW were done on walking a short straight line. Curvature gains, for example, keep the user walking on a circle with a certain radius, but as soon as the user turns around, these gains would have to be increased or decreased to keep the user within the available space. Since such turns are unpredictable, the actual implementation of a RDW approach would require additional space and variable gains.

3.2 Curvature and Translation Gains

The first problem we tried to solve with Telewalk was the limitation of gains. Depending on the source, it was suggested to use gains of a maximum of 2.6 °m[34] or 4.9°m[12] because users will be aware of the manipulation. Problematic with the use of such gains is the enormous space requirement which is 44m x 44m (for 2.6°m) or 23m x 23m (for 4.9°m) to realize only a constant forward motion – if the user changes the direction, this space requirement would increase even further. The suggested maximum gain considering acceptance instead of detection still requires around 6m x 6m for infinitely straight walking [29]. To realize walking on a space of 3x3m, gains of around 38°m are required. To further further increase the acceptance of higher gains, Telewalk is designed to use curvature gains in combination with translation gains (as suggested by Grechkin et al. [12]). It has been observed that walking at reduced speed leads to fewer detection rates for curvature gains [24]. We assumed that with higher translation gains the walking speed would decrease and thus the acceptance of higher gains would increase. While Grechkin et al. evaluated the influence of low translation gains (scaling the velocity by a factor of 1.4) we applied much higher gains with a maximum scale of 5. Since such high translation gains proved to be confusing when being designed as a constant, we decided to design them dependent on the current velocity a user walks. The higher the pace the higher the applied gains. With this mechanism we aimed at forcing the user to walk slowly, as small steps are sufficient to cover greater distances.

For the concrete implementation of Telewalk we take the available tracking space, fit the biggest circle and use its diameter to calculate the required curvature gain (G_c) as follows:

$$G_c \quad \frac{360}{\pi \cdot d} \tag{1}$$

The first implementation of translation gains considered the current velocity of the user or the translation between two frames respectively and scaled this translation according to the current gain. We found this scaling to be causing motion sickness, since when applying the translation gain on the translation vector between two frames, the bouncing of the head while walking is scaled as well. In case of the maximum (being scaled by the factor 5), bouncing 3cm to the left and right would lead to bouncing 15cm. This was reported to be uncomfortable by several test users. We therefore decided to apply the translation gain not as a scaling factor for the actual translation, but as an additional translation into the current optimal direction the user should walk given their current position inside the tracking space. This optimal direction (V_o) can be computed as the normalized orthogonal vector of the one between user and tracking space center and can be imagined as the tangent of the circle the user should walk on.

Test users additionally reported that the use of the current velocity let the gain alternate very strongly. We therefore decided to use the velocity calculated by the user's translation in the last second. The result was a slowly increasing but still responsive gain when starting to walk. The concrete implementation used this distance minus 0.2m (to exclude motions of the head while standing still), divided by 0.2 and clamped to a value between 0 and 1. The result is than multiplied with the defined maximum gain (which was in our case the constant of 5).

The maximum gain is therefore applied at a velocity of 1.44 km/h or higher. With a velocity of 0.72 km/h or lower the applied gain is 1 (no manipulation). With a velocity between 0.72 km/h and 1.44 km/h the gain linearly increases from 1 to 5.

The final implementation to calculate the current translation gain (G_t), with v being the velocity within the last second, was as follows:

$$G_t \quad \frac{\|v\| - 0.2}{0.2} \cdot 5 \cdot \|v\| \cdot \overrightarrow{P_c - P_u}^{\perp} \tag{2}$$

with P_u being the position of the user; P_c being the center of the tracking space and $\|v\|$ being the magnitude of the translation of the user within the last second and $\frac{\|v\|-0.2}{0.2}$ being clamped between 0 and 1; All calculations are done in 2D space.

3.3 Using the Head as Controller

The second problem we tackled was the directional changes a user performs to walk freely inside the virtual world. We implemented the *steer to center* as well as the *steer to orbit* approaches as suggested by Hodgson and Bachmann [14]. Since our approach relies on applying very high gains, the suggested approaches proved to be inapplicable for Telewalk, since they resulted in very high deviations of the curvature gains within a short time and too often required reset strategies since we aimed at implementing Telewalk within a 3m x 3m space. Test users stated that these deviations of the applied gains made it impossible to navigate and lead to strong feelings of motion sickness. We therefore required to find an approach that allowed constant curvature gains while still allowing the user to turn around inside the virtual space. This is why we used the head as input device to realize turning without any actual physical turn.

Directional changes are usually realized by rotating the virtual camera. In case of a VR application, camera rotation is triggered by rotating the head. If the full body is turned (e.g. to change the direction of walking) this directional change is still realized by a rotation of the camera, since the head rotates in line with the body. To allow body turns without any physical turn we needed to divide these kinds of camera rotation two parts: Looking around and turning around. In our implementation, the head triggers both of these actions. While the head rotation itself is mapped one to one on the virtual camera, rotating the head over a defined maximum triggers an additional virtual body turn, which is realized by rotating the virtual world around the the camera.

For the concrete implementation, we defined a region of ±10° from the optimal path (the tangent of the circle the user walks on) to be ignored for directional changes. For the region between ±10°

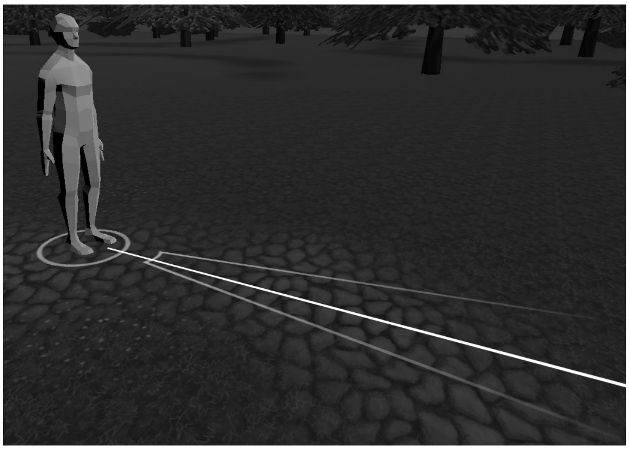

Figure 2: The visualization of the optimal path including the spot with the optimal distance to the tracking center and the two lines indicating the optimal direction. The user's viewing direction is visualized by a single line.

and ±35° we applied a linear increasing rotation (similar to turning a joystick to the left or right to control a character). The maximum rotation per second was defined as 80°. If the user exceeded the 35° from the optimal path, the virtual character was rotated by the maximum of 80°/s.

3.4 Visualizing the Optimal Path

Without any visual guide, this approach turned out to be uncontrollable, since the user was unaware of the optimal direction. We therefore decided to include a visual guiding system indicating the region in which no rotation is applied. It consists of the current gaze direction in form of a needle like a compass as well as a visualization of the optimal direction as two lines as triangle displayed in front of the use. Both were displayed on ground-level in front of the user (see 2). Though this visualization helped users to keep well oriented, they still tended to walk too far or too close to the tracking center. While walking to far obviously leads to leaving the tracking space, walking too close leads to very fast changes of the optimal direction since the circle the user walks on becomes smaller. We have therefore decided to separate the position of the optimal direction indicator from the position of the user. The starting point of the needle was always fixed at the point which intersects the circle of the optimal distance with the line between the circle center and the current user position. Thus the line served as an additional visual aid to follow the optimal path.

3.5 Turning the Telewalk On and Off

To ensure, the user always remains on the optimal path around the center of the tracking space, we turned the Telewalk off as soon as the user's distance to the optimal position passed 30cm. In this case the users could walk without any manipulations as long as they reentered the optimal position. We also included a button that could be pressed to manually turn the Telewalk on and off. If a user for example reaches a region of interest, they could deactivate the Telewalk to examine the region more closely. The visualization of the optimal position remained visible at the position where Telewalk was turned off, but the optimal direction was set to invisible until it was reactivated.

In the user study we noticed, though, that this feature was seldom used and that participants constantly walked using the Telewalk, and without turning it off.

3.6 Paths beyond optimal circles

In this work, the optimal path was realized as a perfect circle around the center of the tracking space. However, it is also possible to realize this path as long as the start and end points are equal. For example, you could define a path that makes optimal use of the room geometry and considers obstacles such as furniture. Since such paths do not have a constant curvature like a circle, it would be necessary to adjust the curvature gain to be applied as well as the visualization of the optimal running direction to the current curvature. This approach would make it possible to use Telewalk in rooms where not even 3m x 3m free space is available. On the other hand, in larger rooms it would be possible to have an overall longer path available. This would reduce the average required curvature gain.

4 STUDY

To get insights on the performance of the Telewalk navigation approach, we designed a small virtual environment that included several points of interest the participants could navigate through. We tested and compared two navigation approaches: Telewalk and Teleport, being the most commonly used navigation approach in VR for room-scale applications.

4.1 Participants

We recruited 18 participants (2 female, 1 non-binary) with a mean age of 25, ranging from 19 to 29. Most of them were students or employees of our university since we recruited on campus. The participants stated to spend 4 hours per week consuming VR content in mean, varying between 0 and 10 hours. Additionally we used the motion sickness susceptibility questionnaire (MSSQ) [11] to get insights on the general sensitivity of our participants towards motion sickness in general. We only used the MSB score (the one concerning the participants experiences over the last ten years). The mean score over all participants was at around 4.3 ranging from 0 to 7.9. Our sample therefore included both, motion sickness susceptible and non-susceptible participants.

4.2 Method and Procedure

Our study was designed as within-subject having the locomotion approach as independent variables leading to two conditions: (1) Telewalk and (2) Teleport. We compared both approaches concerning several attributes that were considered relevant for a navigation approach in VR. Our metrics follow the suggested quality metrics of Bowman et al. [6]. They propose that an effective navigation technique should implement the following attributes: (1) speed, (2) accuracy, (3) spatial awareness, (4) ease of learning, (5) ease of use, (6) information gathering and (7) presence. We used self-reports to measure the respective attributes, since we aimed at measuring the perceived quality of the respective locomotion approaches. Most of the named attributes were assessed via single questions using a five point Likert scale titled as *absolutely disagree*, *slightly disagree*, *neutral*, *slightly agree* and *absolutely agree*. The questions were formulated as follows:

(1) "*The speed with which I traveled through the virtual world was appropriate*", (2) "*I could navigate with a high accuracy*", (3) "*I never lost track of my position and orientation within the virtual environment*", (4) "*I could easily learn how to move inside the virtual world*", (5) "*The navigation technique was too complex*", (6) "*I could obtain information from the environment during travel*". In addition to these items, we included two further Likert scale questions: "*The way I moved through the virtual world felt natural*" and "*I had the feeling of truly moving through the virtual world*", which targeted at providing insights on additional features a locomotion technique should implement according to [38]. Since the Telewalk approach uses very high RDW gains which could lead to symptoms of motion sickness, we also included the simulator sickness questionnaire (SSQ) [19]. To get insights on the performance of Telewalk compared to Teleport regarding presence, we included the SUS presence questionnaire [32]. Additionally we included the E^{2}I questionnaire [22] to measure immersion and enjoyment.

In a post questionnaire that the participants answered after both conditions, we asked the participants to state which navigation approach they did prefer and asked them to write down general feedback of the navigation approaches as well as to state for which kind of application they would prefer Teleportation or Telewalk.

The order of the two conditions was counterbalanced over all participants.

4.3 Study Application

We designed the virtual environment in a way it provided both, longer walking distances without special events that captured the participants' attention as well as shorter distances. The path the participant needed to navigate through further included two passages where a high accuracy was needed (two small bridges that had to be crossed). On the way through the environment seven attractions or obstacles were presented. It was a fantasy world where the participants could find for example a wizard, a knight or a giant. The places where such creatures were displayed invited for closer exploration, which should lead to users moving beyond the intended locomotion mode during both Teleportation and Telewalk.

4.4 Results

The analysis described in the following was done using a Wilcoxon signed rank test for dependent variables. The results are interpreted as significant with p values below the 5% level and as highly significant with p-values below 1%. Boxplots of the results of the presence, immersion and enjoyment as well as the SSQ scores are presented in figure 3. The single item questions are presented as diverging stacked bar chart in figure 4.

A Wilcoxon signed-rank test showed that Telewalk and Teleport did elicit a highly significant change regarding the **SUS presence** score (Z = -3.11, p = .002, r = .52), with Telewalk resulting in more presence. Telewalk lead also to a significantly higher immersion (Z = -2.54, p = .011, r = .42). The E^2I enjoyment scores, though, did not show a significant difference (Z = -.80, p = .422, r = .13).

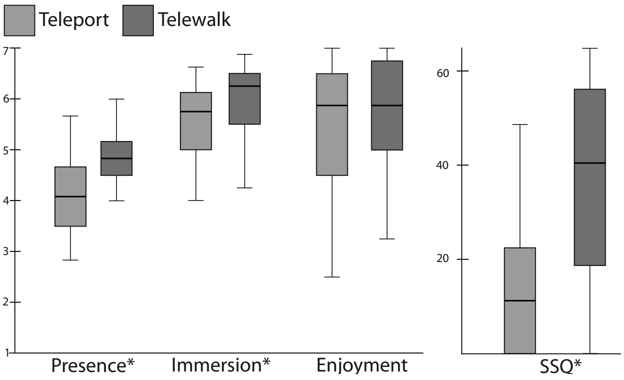

Figure 3: Boxplots of presence (SUS), immersion and enjoyment (E^{2}I) and simulator sickness (SSQ) scores. The marked comparisons were significant on the 5% level.

Regarding the SSQ scores, again a highly significant difference was found (Z = -3.41, p = .001, r = .57), with Telewalk being used for navigation resulting in stronger symptoms of simulator sickness. We also compared Telewalk and Teleport by the ratings of the single item questions as described in the method section using Wilcoxon's signed rank test. While Telewalk was rated as significantly more complex (Z = -2.11, p = .035, r = .35), it provided on the other hand a significant higher feeling of truly moving through the virtual world (Z = -2.33, p = .020, r = .39) and felt significantly more natural (Z = -2.01, p = .041, r = .34) and allowed to obtain more information from the surrounding (Z = -2.11, p = .038, r = .35). The remaining items, being whether the speed was seen as sufficient (Z = -.59, p = .557, r = .10), the perceived accuracy (Z = -1.00, p = .318, r = .17) and ease of learning (Z = -1.00, p = .317, r = .17), were not significantly differing between Telewalk and Teleport. The results are illustrated in figure 4.

To get insights if we could predict the feeling of motion sickness in the Telewalk condition using the MSSQ scores, we performed a Spearman correlation on the MSSQ and SSQ scores of the Telewalk condition. There was a positive correlation between MSSQ and SSW scores, which was statistically significant (r_s = .548, p = .045).

4.5 Final Rating and Textual Feedback

After both conditions were rated by the participants, they were asked to fill a last questionnaire containing one answer in which the participants were asked to state which locomotion approach they preferred. Both, Telewalk and Teleport were chosen 9 times as favorite locomotion approach. The additional textual feedback for both locomotion approaches gave further insights on these ratings.

Those who rated telewalk as preferred locomotion approach commended the naturalness and ability to closely examine the surrounding. Even some of those who preferred teleport reported that the feeling of walking through the virtual world "was a great experience". On the other side, Telewalk was criticized most of all for the head controller that was not smooth enough and too fast for some of the participants. One participant (who preferred the Teleport condition) stated that "Telewalk was actually way better for immersion [...] and one was actually able to walk for an extended

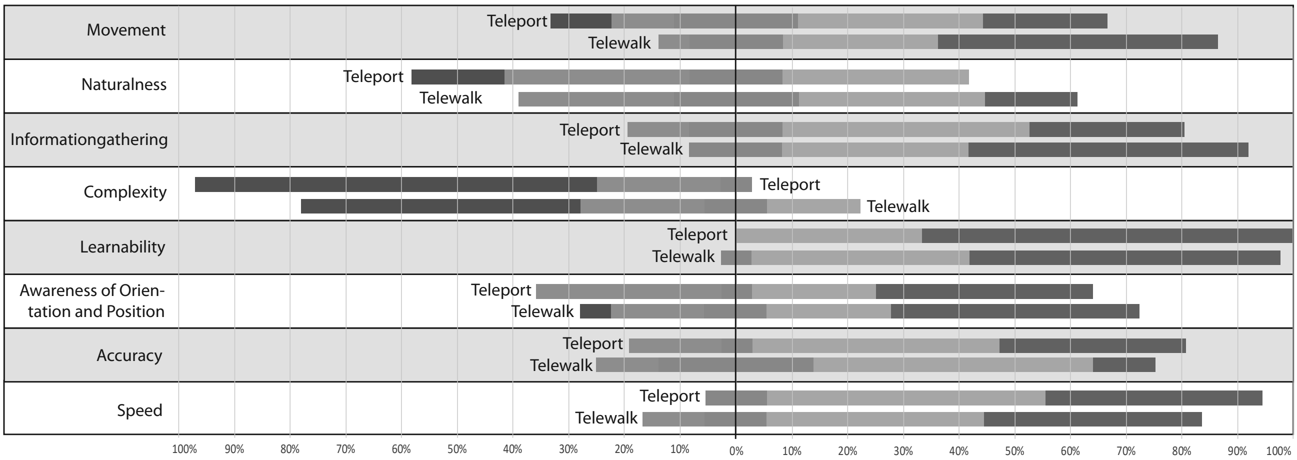

Figure 4: Diverging Stacked Bar Charts of the single item questions as described in the *Method* section.

period and with some speed. However, nausea was a real problem for me, reducing the quality of the experience." Similar feedback was given by multiple participants who preferred Teleportation. Besides the feeling of motion sickness, convenience and the increased complexity compared to teleportation were the main reasons why participants rated Teleportation as preferred navigation technique. Some also suggested to combine both approaches by offering both techniques at the same time.

We also asked the participants to state for which kind of application Telewalk or Teleport would be more suitable. Here we could observe clear tendencies. Teleport was most of all preferred for applications in which the world being traveled is not of interest or for traveling very fast between two points. Telewalk in contrast was seen as most suitable for applications that are designed for being immersive, explorations or for scenarios where both hands are needed. These insights support the desire of some participants to offer both techniques at the same time.

4.6 Discussion

With Telewalk we aimed at developing a locomotion approach that allows navigation in VR in a more natural way to increase presence and immersion, without limiting other factors that are considered to be relevant for VR navigation. As the significant increase in presence and immersion shows, Telewalk was able to meet these requirements – though not for all participants. The current implementation raised symptoms of motion sickness for some participants, while others showed no symptoms at all. We further found a positive correlation between SSQ and MSSQ scores, indicating that the susceptibility to motion sickness strongly influenced the respective symptoms of simulator sickness during Telewalk. Since motion sickness was named the most important factor to dislike or to avoid the use of Telewalk for our set of participants, we argue that most of all for motion sickness susceptible users further strategies to avoid motion sickness have to be found. In addition, Telewalk was considered to be more complex than Teleport. However, these results are difficult to interpret as the majority of the participants already had VR experience and were familiar with the teleportation metaphor, while being novices using Telewalk.

5 LIMITATIONS

5.1 Study

Since we used a within-subject design, we cannot guarantee that one condition did not influence the other, which is most of all important for the SSQ scores, since symptoms can last for a longer period of time. Though we told the participants to wait for the second test until they felt like before the first test, an influence by the within-subject design cannot be excluded. Further, our application was designed to be explored, including several points of interest and events occurring during the experience. This could lead to a decrease of the feelings of presence, immersion and enjoyment for the second trial (since everything was already discovered). The counterbalancing should compensate such effects, but there are still possible influences. The application design further could have lead to more positive ratings for the Telewalk condition (at least for some participants), since the exploration of a virtual world was considered to be one of the most suitable applications for Telewalk. We suspect that some of the ratings would have been different if a less spectacular world had been presented or if only reaching a certain point in the virtual world had been chosen as task.

5.2 Approach

The study results suggest two main assumptions. On the one hand, the Telewalk mechanism seems to be very well suited for exploring immersive worlds. How suitable the mechanism would be for other tasks would have to be shown by further studies. On the other hand, it has also turned out that the current implementation is not yet applicable for all users. The strong correlation between MSSQ and SSQ scores suggests that the Telewalk in its current state is particularly suitable for users without motion sickness susceptibility. We assume that by further optimizing the algorithms or choosing additional or modified gains, the motion sickness can also be reduced. Additionally we aimed at highly reducing the space requirements thus the used space was 3m x 3m. If more space is available, both gains could be reduced which assumably would decrease the feelings of motion sickness.

It might also be of interest to investigate long-term effects on motion sickness in the future. Recently it was shown that the sensitivity to notice curvature gains changes over time [8]. Similar effects could also occur in the field of motion sickness. In the present study, however, the duration of the VR experience was too short to be able to make any statements about this. Since motion sickness is currently the biggest limitation of the presented technique, we consider it useful to conduct further studies with the focus on the causes and possible prevention.

6 IMPLICATIONS

What we proposed in this paper is one of many possible ways of implementing a Telewalk technique. A future implementation of Telewalk could for example make use of different or additional RDW gains (like rotation gains), use a different way to realize directional changes, or include additional visual guidance strategies. Furthermore, the possibility of predicting the walking path could allow for adaptive paths to avoid obstacles (e.g. a table in a typical living-room situation).

Though, we found some requirements the different parts have to ensure to implement which we will describe in the following.

The most obvious is that the applied gains have their limits. In our implementation only curvature gains are used to keep the user inside the tracking space, while the translation gains are used to let the user move slower. Using the Telewalk, the user is always forced to walk on a perfect circle around the tracking center. This allows a perfect prediction of required gains as well as the required space. In our case using a tracking space of around 3m x 3m we applied gains of $38.2°m$. Testing other radii could lead therefore lead to less or more symptoms of motion sickness. Future implementation could make use of additional types of gains to either further reduce the required space or to reduce the symptoms of motion sickness.

In our application, turning around was realized by rotating the head. This constant change of the character's rotation while turning the had was stated to have the highest impact on motion sickness. In first tests, most participants had no problems walking a straight line, but some failed on turning around. This is the same problem as VR games have when played with a controller and when navigating with a joystick. A potential solution could be to apply no continuous reorientation, but a discrete one that e.g. rotates the user every 0.5s with an angle depending on how far she looks away from the optimal path. Similar to the instant translation that is applied during teleportation, such instant reorientation could lead to less motion sickness. Another approach could be to give the user more control (e.g. by using a controller). Our implementation that uses the head as an input device has the advantage of enabling hands-free navigation on the one hand, but can also lead to problems, as for example head movements when looking around can lead to unintentional rotations.

The visualization of the optimal walking direction goes hand in hand with the head controller we implemented. In earlier implementations we tried not only the used straight line but also the display of curves, which should rather correspond to the real path. For our implementation, however, the straight line turned out to be the best visualization. However, if, for example, additional gains or another camera control is used, the adaptation of the visualization could bring further advantages.

7 FUTURE WORK

With this paper we explored a novel interaction technique for traveling virtual worlds that combines perceivable RDW gains with a novel head based camera control. The current implementation and its settings were determined by informal user tests. The study can be interpreted as prove of concept of such a technique. We propose to investigate the observed effects more closely to get more insights on how the different interaction mechanics work and interact together. One example could be the relation between higher translation gains (as used by the presented Telewalk implementation) to the real world walking pace or step length. It is also of interest how strongly the translation gains interact with the acceptance of curvature gains. On the other hand it could be of value to determine the origin of motion sickness. Since in our study all concepts were combined to an overall system, the influence of the individual mechanics on motion sickness could not be examined in detail.

As already mentioned, a future implementation of Telewalk could not be based on just one pre-defined perfect circle. Through variable gains it is possible to use any predefined real path as a template to make optimal use of the available physical space. This would not only make the best possible use of the available space, but also extend the walking distances. This would make it possible to reduce the necessary curvature gain, which in turn could have a positive effect on motion sickness.

8 CONCLUSION

In this paper we presented Telewalk, a locomotion approach that allows infinite walking in VR on small tracking spaces. Telewalk utilizes high and perceivable curvature gains and forces the user to walk slower by scaling the user's translation. In contrast to general RDW, which is designed to be an unperceived manipulation, Telewalk deliberately uses perceivable gains. A further difference to general RDW is that the user is guided to walk an optimal path (in our case a perfect circle around the tracking center) by substituting directional changes by using the head rotation as input device. This makes it possible to fully predict the user's real world path and ensure that the tracking space will never be left and that there are no obstacles on the user's way.

In a user study we found that Telewalk is a good alternative to Teleportation that results in a stronger feeling of presence and immersion. Though, most of all motion sickness susceptible users struggled with respective symptoms. Future implementations of a Telewalk approach could investigate how such symptoms can be avoided by utilizing different gains or other mechanisms to realize directional changes.

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