Perception Design

Designing Multimodal Experiences to Transform Perception in Virtual Reality

Dissertation

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Abstract

Current research and development of Virtual Reality (VR) focuses on improving the appearance of the virtual world and replicating the real world as well as possible. The advancements in technology and experiences try to replicate our reality in a virtual space in the finest detail, thereby creating a doppelgänger for reality. VR is a new medium that needs to evolve beyond the mere replication of reality. Previous research has shown that simplified virtual environments and avatars are effective in bringing a person to remote worlds or enhancing one's self-perception in a way that is impossible in the real world.

This focus on the replication of reality is heavily focused on the field of haptic feedback, as shown by our literature review. Therefore, there is a need for research in Human-Computer Interaction (HCI) for novel approaches to designing VR that go beyond reality.

In this thesis, I discuss the design constraints and considerations involved in working with VR as a new medium that allows creating experiences that go beyond reality. I demonstrate how multimodal experiences transform the perception of the user through the use of simple elements such as haptics. To that end, I divide the perception of the user in relation to oneself, other characters or people and the embodiment of multiple bodies in the form of out-of-body experiences. Through iterative design, building systems, and conducting user studies, I show how changing one's step sound impacts gait; a computer-controlled character appears more human with a touch on one's shoulder; and changing the perspective lets the users embody in multiple bodies simultaneously. Further, I demonstrate a framework and application of a drone-based feedback system that facilitates haptic encounters. I also contribute to the technical design of a system that provides inertial feedback in VR through air resistance.

The work in this thesis builds a base for inquiries into VR systems that offer sensory experiences beyond what is possible in real life. I offer a theoretical framework to classify haptic experiences in VR as well as numerous design solutions for building illusions that expand the scope of perception in virtual worlds. Thus, I provide researchers and designers with the thinking tools and design solutions needed to build a new wave of VR research.

ZUSAMMENFASSUNG

Die derzeitige Forschung und Entwicklung im Bereich der virtuellen Realität (VR) konzentriert sich darauf, das Erscheinungsbild der virtuellen Welt zu verbessern und die reale Welt so gut wie möglich nachzubilden. Mit den Fortschritten in der Technologie und den Erfahrungen wird versucht, unsere Realität in einem virtuellen Raum bis ins kleinste Detail nachzubilden und so einen Doppelgänger der Realität zu schaffen. VR ist ein neues Medium, das sich über die bloße Nachbildung der Realität hinaus weiterentwickeln muss. Frühere Forschungen haben gezeigt, dass vereinfachte virtuelle Umgebungen und Avatare entscheidend dazu beitragen, eine Person in ferne Welten zu versetzen oder ihre Selbstwahrnehmung auf eine Weise zu verbessern, die in der realen Welt unmöglich ist.

Dieser Fokus auf die Nachbildung der Realität konzentriert sich stark auf den Bereich des haptischen Feedbacks, wie unsere Literaturübersicht zeigt. Daher besteht in der Forschung im Bereich der Mensch-Computer-Interaktion (HCI) ein Bedarf an neuen Ansätzen für die Gestaltung von VR, die über die Realität hinausgehen.

In dieser Arbeit erörtere ich die gestalterischen Limitationen und Überlegungen, die bei der Arbeit mit VR als neuem Medium, das die Schaffung von Erfahrungen jenseits der Realität ermöglicht, eine Rolle spielen. Ich zeige, wie multimodale Erfahrungen die Wahrnehmung des Benutzers durch den Einsatz einfacher Elemente wie Haptik verändern. Zu diesem Zweck unterscheide ich die Wahrnehmung des Benutzers in Bezug auf sich selbst, andere Figuren oder Menschen und die Verkörperung mehrerer Körper in Form von außerkörperlichen Erfahrungen. Durch iteratives Design, den Aufbau von Systemen und durchgeführten Nutzerstudien zeige ich, wie sich die Änderung des Schrittgeräuschs auf den Gang auswirkt, wie eine computergesteuerte Figur durch eine Berührung an der Schulter menschlicher erscheint und wie eine Änderung der Perspektive den Nutzer in mehrere Körper gleichzeitig schlüpfen lässt. Darüber hinaus demonstriere ich einen Rahmen und die Anwendung eines dronenbasierten Feedbacksystems, das haptische Begegnungen erleichtert. Ich trage auch zum technischen Design eines Systems bei, das durch den Luftwiderstand ein Trägheitsfeedback in VR ermöglicht.

Die Arbeit in dieser Dissertation bildet eine Grundlage für die Erforschung von VR-Systemen, die sensorische Erfahrungen bieten, die über das hinausgehen, was im realen Leben möglich ist. Ich biete einen theoretischen Rahmen zur Klassifizierung haptischer Erfahrungen in der VR sowie zahlreiche Designlösungen für den Aufbau von Illusionen, die den Umfang der Wahrnehmung in virtuellen Welten erweitern. Auf diese Weise gebe ich Forschern und Designern die Denkwerkzeuge und Designlösungen an die Hand, die sie benötigen, um eine neue Phase der VR-Forschung einzuleiten.

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Introduction and Foundations

Chapter 1

Introduction - The Fascination of VR

Reality is not what it used to be.

In the Mouth of Madness
- John Carpenter

By simply strapping a display in front of someone's eyes we are able to teleport them to different worlds. They can be sent back in time, teleported to the top of a mountain, or even explore the surface of the moon. Virtual Reality (VR) is often viewed as a solitary experience where the user is cut off from the real world and experiences a simulated environment. However, these activities can also be shared with others by bringing people across the world closer to each other, allowing distant friends or strangers to sit down at a virtual poker table, chat, and interact as they would just sit right next to each other.

Virtual Reality (VR) can be a tool to recreate history, visit distant cities or countries without the need to travel or play games. The users do not perceive these experiences as simply watching them on a display but actually have the feeling of "being there" as they substitute their surrounding reality with a virtual environment. In this virtual environment, the user is taking over a virtual body as their own. This virtual stand-in can range from a formless shape without any visual representation of the user, having virtual hands to a full body. While these virtual bodies (avatars) can serve as virtual representations in the virtual environment, they do not have to recreate the user's appearance [R30, R31] and even can let the user take over the role of another character [R36]. Therefore, I explore how this self-perception and perception of others can intentionally be altered and designed by the use of (haptic) impulses. Further, I show that the user cannot only perceive the virtual body as a representation of their own real body but also accept a virtual body that diverges from it.

In VR the users interact with the virtual world via these avatars. While interaction concepts in the form of point-and-click user interfaces are present as a holdover from 2D desktop computers or phones, VR allows for more direct and interactive ways of manipulation. From picking up objects, throwing them, opening doors, pressing buttons or even interacting with other characters, the interaction appears seamless to the user as they act like they would in the real world.

All elements, such as the appearance of the body, expectations of how an object can be interacted with, or how a character reacts to their actions, affect how the virtual world is perceived by the user. If expectations are not met, chances are the user is not simply disappointed, but this break in expectations changes how real, or rather believable, the virtual world appears to be. The perception does not only change from the quality of one experience to another, but it also heavily depends on the user itself. While one user is fully captivated by what they see and do, others might be irritated by elements that pull them out of the experience [R29, R30, R31]. While a high level of technical fidelity (Immersion) is beneficial to the human response of feeling of "being there" in the virtual world (Presence), it is not a prerequisite [R35].

Terminology such as immersion, presence, and embodiment are widely used in HCI to describe and discuss how design elements affect and change the user experience of the virtual scene. However, these terms are often used interchangeably or without a clear distinction (see Chapter 3). The level of perceived presence is often used as a rating of "how good" or "how realistic" the virtual experience is. However, it is unclear how design elements influence presence and how such elements are interconnected. Without this understanding, VR developers cannot deliberately design the virtual scene to effectively influence and improve the user's experience. Therefore, HCI needs to further understand the theoretical components (e.g., presence, co-presence, embodiment) of VR to utilise their effects on the user's perception. This understanding is essential to effectively build VR experiences and advance VR as a medium. As part of a literature review regarding haptic devices, I discuss a taxonomy for creating a structured framework that aids in concept development and design. The purpose of this taxonomy is to close the gap between a technical description of the system (e.g., Immersion) and the perceptual interpretation of the user (e.g., presence).

> Current research and development of Virtual Reality (VR) technology and experiences mostly focus on improving the overall presentation of the virtual world in the form of higher-resolution screens, rendering, tracking, and more accurate haptic feedback. In the current state, we try to replicate our reality down to the finest detail, thereby creating a virtual doppelgänger of reality. However, VR is a tool that lets us create and control every aspect of our environment and ourselves. To unlock the full potential of VR we therefore need to take into consideration that VR is not only a technical approach, but that indeed perceptual understanding and philosophical theories can offer valuable contributions in order to take the next steps.

1.1 VR as a Medium - A History of Paintings and Games

I argue that VR should be considered as a new medium, rather than a continuation of video games or computational images. While in its infancy it will take time to evolve like other mediums before. Similarly to other media that needed time to be explored in order to evolve and unlock their potential. Paintings started with simplistic cave drawings that convey information about hunting scenes presented in an abstract form [R17]. While the paintings started in a simplistic form on stone walls, paintings evolved, got more detailed, and got more sophisticated [R13]. Not only did the visualisation include wider topics but also changes in technique and materials. During the Renaissance (~1415) the style of paintings took another evolutionary step as the understanding of linear perspective in art came to be. This advancement of technique and aspired style kept moving forward and reached a point where artists could replicate reality in the form of photorealistic paintings. While one might suspect that this ended the further development of styles and techniques in paintings, it should rather be seen as an achievement in the technique of replication rather than perfection of the medium itself. However, this achievement marked a breaking point and artists became interested in more abstract forms of painting. Before the photorealism movement reached its height in popularity in the 1960s, Salvador Dalí discovered his interest in twisting elements of realism and thereby breaking the representation of reality. Thereby his paintings are often based on photorealism or the use of realistic elements to create paintings that show a surrealistic world. By invoking the feeling of dreams, and absurdity and exposing the viewer to fantastical scenes, therefore, allowing to make new experiences and gather new insights [R2]. Similarly, Picasso can convey content, themes, feelings, and invoke emotions with abstract forms (e.g., cubism) and unrealistic colours (e.g., blue period, rose period). He therefore was intentionally diverging far from reality and often showed a subject from multiple angles at the same time. Visual arts such as painting have long evolved beyond the point of recreating reality, indulging in various forms to convey content or emotions that might be only possible with the abstract.

A more recent medium that is closer to VR is video games (see Table 5.1). This medium underwent the same stages of development as other mediums, such as paintings, before it. Video games, similar to VR, do not simply present themselves to the user or player. Therefore, instead of a passive audience, games involve the audience with interactive elements, such as making decisions or controlling the movements of the character. The first video game "Tennis for Two" (1958) let two players compete via a simple rotary knob and a button input device on a virtual tennis court (similar to the popular game Pong). The tennis court and ball were visualised in an abstract side view of the court and ball, which was rendered on an oscilloscope. Showing that simplified controls and graphics can be enough to captivate and motivate the players, even to this day. Traditional video games went from an abstract representation (e.g., Pong, Space Invaders, Asteroids), limited by the display and rendering capabilities of its time, to a more detailed two-dimensional visualisation (Super Mario Bros. (1985), Commander Keen (1990), The Secret of Monkey Island (1990)). These colourful, more detailed graphics presented worlds, characters, and stories in more depth, while still leaving room for the imagination of the player to fill in the details that are only hinted at by the visuals. With the advancement of computational power developers aimed for the creation of three-dimensional worlds and higher details. While not being presented via a true 3D engine, Doom (1993) created the illusion for the player to explore a "realistic" three-dimensional world.

With these new 3D capabilities the trend, or rather race between developers, shifted towards presenting the player with the next level of "realistic graphics". However, games did not only try to closely represent the real world visually, but with the new graphical possibilities, games started to orient themselves more closely to the medium of movies instead of focusing more on the differences and therefore strengths of video games as a medium. Final Fantasy 7 (1997) strived to enhance the story with short 3D-rendered clips between gameplay sequences. While Metal Gear Solid (1998) presents the player with encounters unique to games by playing with the player's knowledge, expectations, and inputs, the story presentation is very cinematic and adapts the style of 1980s action and Science-Fiction movies. The 3D engine and voice recordings were used to present long non-interactive sequences in the game engine itself, without the need to pre-render the sequence.With these new capabilities, the generation of 3D graphic games started a trend to imitate movies for realistic looks and cinematographic elements.

As in media before, developers strived to achieve photorealistic graphics, models, and textures. Further, to make the games more cinematic developers often neglected the interactive element of games, taking away the control and agency from the player. Long cut scenes (with actors and elaborate predetermined camera movements) are often used to convey a level of "quality" of the game and present a story. However, these elements are not unique to games but copied from years of development of movie mechanisms that developed throughout decades of movie making (since the late 19th century). This strife for realism dominated the development of video games for years and the medium of video games struggled to find their own identity. With the rise of Indie developers (independent or low-budget developers) and resulting limitations, games started to explore mechanisms to tell stories and experiences that are unique to games in both mechanics and aesthetics (e.g., Braid, Dark Souls, Journey, The Stanley Parable). This development is an ongoing journey and video games only recently started to grow and find their unique voice as a medium.

Therefore, while already originating in the 1960s, video games first had to develop and the creators of games first needed to develop the needed technology, but especially to learn to understand the various elements of video games. In the history of over 60 years of development and learning tied to replicating movies. Games developed from abstract representations, to realistic graphics and cut scenes, but found their own voice by developing elements that are unique to and only possible in games.

In the same way, VR is currently trying to orient itself to video games and trying to replicate reality. While, VR also started with abstract graphics (e.g., Sword of Damocles, Dactyl Nightmare) and interactions (low-tech head tracking), in recent years the technical development drastically improved. Resulting in more realistic graphics and rendering, high-resolution displays, and more sophisticated room-scale motion tracking, including full-body reverse kinematics. Due to the immersive technology that allows the user to feel fully present in a virtual world, it might be even more tempting to recreate reality with VR than for other media.

As media are ever-evolving in their use, meaning, and technology, they often have a rather simple starting point and take time to develop. While the intention to replicate reality can be an important part of filling the repertoire of possibilities for a medium. In the case of VR having the option for realism is important to utilise the potential for training [R18], testing or studying future scenarios without danger to participant [R12]. As VR can induce the feeling of urgency and danger, and receive a high level of accuracy in training scenarios. However, focusing purely on realism is limiting when it comes to exploring elements that are unique to a new medium. **VR needs the freedom and time to develop like earlier media** before it. Therefore, exploring **VR experiences that are abstract or go beyond reality will** allow designers and researchers to **unlock new potential for future VR experiences**.

1.2 The Current State of VR as a Medium

In its current state VR is in the same position that computer games used to be in. The focus on imitation of the medium that came before it was more important than utilising the medium's own uniqueness. VR is currently still in a phase where imitation of reality is the main focus of developing and evolving the medium. While some developers use a simplified or abstract visualisation, either intentional as a stylistic choice or from necessity of graphical and processing limitations, the advancement of VR is currently linked to visual fidelity and used displays. The visual capabilities of VR developed extensively in recent years in the form of technical improvements and rendering. Therefore, the visual aspects are getting one step closer to replicating reality. However, VR is not only an immersive visual medium but interactivity is an essential part of it.

A large body of HCI research focuses on the technical development of having realistic input and output capabilities in VR (see Chapter 3). The aim of current research is to mimic not only the visual but also the haptic perception of the real world. These approaches range from hand-held shape and weight-changing controllers, haptic gloves or full-body suits, ultrasonic haptic feedback, or even shape-changing floors or environments. These approaches use physical changes in controllers or devices, however, there are non-physical approaches that utilise the capabilities of VR to present a "different reality" to the user. Pseudo-haptic feedback uses illusions by repositioning the user's virtual hands, without notice, to give the impression of different weighted virtual objects or softness. Pseudo-haptics therefore do not create a change in physicality but rather change and manipulate the user's perception. These illusions are not only used for haptic feedback but also serve as workarounds for limitations of VR systems. Issues such as limited tracking space can be mitigated by the use of redirected walking or translational gain, therefore giving the illusion of a virtual space that is larger than the actual physical tracking space. Such approaches already show the potential of how VR can be utilised beyond simply replicating reality.

Artists and creators of visual arts, movies, or games, keep challenging their medium and therefore keep evolving and changing it by applying and breaking their surrounding rules, in order to create something new. However, VR development and research still lack the understanding of how VR exactly works in its effect on the user's perception and what can be achieved with it. This understanding is currently being limited by the goal of simply recreating reality in the virtual space. The capability to being able to recreate reality can be a helpful skill to create virtual worlds. However, **VR technology and virtual worlds do not only need to be built and created, but its elements need to be understood in order to create experiences that go beyond reality and offer something truly unique to and only possible in VR.** Therefore, VR "creators" need to **close the gap between engineers** – who build a solid foundation while improving its quality – **and artists** who keep exploring and pushing the limitations of their medium.

II

Vision: Beyond Reality

Chapter 2

Visions of Simulacra - Beyond Reality

...she created her own reality. Her thoughts at the precise moment she was trapped determined its shape and form. - The Traveller

The Next Generation - Lee Sheldon

Virtual Reality research is focused on the improvement of the technology, systems, and interactions. The goal is to improve the fidelity of VR systems to achieve a high level of realism. The replication of reality (Simulation) is the first step in improving VR, however, going beyond what is possible in reality is important to understand and unlock the full potential of VR. Therefore, exploring the creation of something that does not exist in reality (Simulacrum) is needed to further VR as a new medium. To achieve this, HCI holds a key role in bridging the gap between building systems and evaluating their impact on perception.

Virtual Reality is considered a new and "hot" technology and is hyped as the next big thing. However, the first wave of what we nowadays would consider VR has already been available in arcades in the early 90s[1]. Different forms of VR devices go even back to stereoscopic picture viewers in 1838 and Link Trainer, which can be considered the first flight simulator in 1929. In recent years the technical development of cheaper components such as displays and sensors resulted in a resurgence of VR. At the same time, VR-related research reached an enormous momentum in HCI and is considered a hot topic[2].The technical development of headsets reached a point of affordable high-fidelity technology and a large consumer market with multiple available headsets. Therefore, it is even more important to understand how humans react to and interact with VR.

[1] `https://www.vrs.org.uk/virtual-reality/history.html`

[2] ACM DL Keyword "Virtual Reality" 198,326 results (1951-2012); 244,081 results (2013-2023) – last updated 17.10.2023

However, HCI research is still largely connected to the improvement of technology to create experiences of higher quality and more accurately recreate experiences from the real world. The focus lies on devices and implementations with the purpose of presenting a better experience to the user instead of investigating and understanding what actually makes a good experience. We need to ask ourselves where can, should and will VR go. If we consider VR as its own medium, then we need to understand how HCI can contribute to its further development. HCI's role should not be limited to fulfilling the dream of the ultimate display [R38], which is capable of perfectly replicating the real world. To consider and develop VR as a medium one needs to incorporate fields other than engineering.

I am convinced that HCI is suited for this task, as it bridges the elements, between technology and human perception. I see this fusion as essential for the future advancement of VR as a medium. Building the technology, such as displays and speakers and tracking, is a technical feat. While these will continue to improve VR is now at a point where other fields are needed for further advancement. We have the basic skills to place a user in a virtual scene and create the illusion that they are "there". Now it is important to understand how to design visuals (e.g., how body models should look like [R30]), interactions (e.g., how input can designed to be more performant [R24]), how we can improve the devices (e.g., haptics and pseudo-haptics [R41]) and to understand how the user responds to these (e.g., measurements of human response such as presence and embodiment [R9]). While there are theoretical models of being exposed to VR such as Slater and Skarbez [R35, R34] and technical descriptions of VR systems, there is not much in between and we lack an applicable theoretical model for researchers and designers. HCI research is perfect for tackling these challenges as VR is closely intertwined between technological advancement, human perception, and interaction design.

2.1 Research Questions

VR gives the designer control over every aspect of the user's environment. Consequently, as designers, we cannot only be the architects of virtual worlds but create ways in which users perceive digital worlds. However, it is unclear how VR will evolve, what developments it may bring, which goals we will set, and how we are going to achieve them. Currently, research seems to strive for a perfect recreation of reality, e.g., haptic devices that can simulate texture [R41], weight [R42], hardness [R40], etc. of objects (see Chapter 3). However, this limits the potential of how VR can be used. To further VR as a medium we therefore need to understand how we can uitilise the unique aspects of VR. I therefore challenge the status quo of current VR experiences and research. With my work, I explore how to go beyond what is possible in reality by developing specific experiences. For my dissertation, I pose two questions: RQ1 - "How can VR evolve from simulation to simulacra?" to utilise the uniqueness of VR as a medium and RQ2 - "How can we formalise operationalise the understanding of the theoretical design of perception in VR" to advance the theoretical concepts in HCI.

To explore these questions I investigate the concept of altering the user's body schema by small (haptic) impulses when interacting with the virtual world. The body schema not only entrails one's own body perception over a virtual body [R29] but also creates the feeling of co-presence [R7] with another virtual character or even body ownership over abstract bodies [R15, R3]. I concentrate on this aspect as the strength of VR is not only to induce telepresence, and "teleport" the user to a different world, but invoking the feeling of embodiment of virtual bodies. The virtual body serves as a vessel for interaction with the virtual world and is a strong indicator of how effective and believable the virtual experience is. This is not only reflected in the acceptance of the user over their virtual body as their own, but the body is often used to test the limits and therefore break the illusion of virtual worlds. Breaking the illusion can be achieved by touching non-interactable objects, walking through walls, to lovingly stroking the check of a scary character that does not react to the user's behaviour. Next, I examine the two RQs in detail.

2.2 Simulacra and Simulation - Jean Baudrillard

Currently, the expectation is that we create a virtual doppelgänger for reality and get even the smallest aspects "right". This includes graphics, physical simulations but also the virtual body the users slip into, and how the user can interact with the virtual world. We are creating a simulation, a copy and imitation of the real world, as defined by Jean Baudrillard [R4].

With a simulation and therefore recreation we do limit ourselves to what is already possible in our physical world. With VR however, we can go beyond mere replication and create something that does not exist in reality. We can envision a simulation of something that never existed or does not have an original anymore, a simulacrum[3]. By utilising the strengths of VR one can deviate from reality and create experiences that go beyond what is possible in reality.

Currently, a broad body of research investigates how to replicate reality and give users an "acceptable" experience, e.g. using haptics that can replicate as many physical properties as possible. A small body of research does not rely on replicating reality but explores VR's non-realistic aspects. Possible unrealistic skills such as giving people the ability to grow in size and bridge greater distances with the same number of steps [R1] or experience the feeling of phasing through a wall like a ghost [R23]. The projects that go beyond replication, however, do this without the awareness to intentionally divert from simple replication. This is expanded upon in Chapter 3.

While a simulacrum is a new approach to VR it would not overly challenge users as they are experienced with the use of methapors. While, metaphors can also be transfered to VR, we yet do not have the desing understanding to build VR simulacra.

[3] While I follow the definition and differentiation by Baudrillard, I deviate from Baudrillard's intention. Baudrillard argues that the reality constructed by human culture, media, etc. already is a simulacrum.

Using different levels of abstraction from reality and drawing on known elements is not new to HCI. When looking at a computer desktop, the analogy to a physical desktop is not in name only but resembles working at a physical desk. The user translates working on a desk to work on a computer. Navigation through folders and files, visualised by symbols of physical props such as a recycle bin. These analogies from real life made computer usage more accessible and understandable while lowering performance compared to console-based interaction and presenting the user with 1s and 0s. However, one of the most influential aspects of computers is not the simulation of a physical desktop with files and folders, but the internet. The internet can be described as a simulacrum and abstraction of reality [R22, R19].This development might not have been apparent from the beginning and the wide use and acceptance of the internet was quite late compared to the first computer.

However, when talking about VR specifically, the expectation seems to be the instantaneous creation of a "killer app", before we develop, explore and understand the medium first. As VR is a new medium and not an iteration of previous technology, the understanding of how VR really works and how it should be designed might not be apparent yet. VR is currently still in its infancy and in a phase where reality is the aspiration. Therefore, we need to set a research agenda for non-reality-based VR before there is a chance for building a killer app.

2.3 From Simulation to Simulacra

We have reached a point where we are able to effectively build VR technology and create virtual experiences that are able to transport users into virtual worlds. We are fascinated that by simply putting on goggles, people are transported into virtual worlds, feel present, and often forget what their real-world environment is and that the environment they interact with is only virtual. We have a basic knowledge of "what works" in VR and how to design experiences that are accepted by the user. Further, research has a basic terminology of how to describe the deployed concepts such as immersion, presence [R35], and embodiment [R14]. However, we are still lacking the knowledge and theory to describe how these concepts are connected.

In current VR research, we hold the assumption that more presence equals a better experience. However, we are still lacking an understanding of what impacts concepts such as presence and in which cases these are important. On one hand, HCI research focuses on making the experience better, improving interaction techniques, improving the quality of presentation, or building new devices for better input and output. Resulting in a large body of research filling the gaps of recreating a realistic experience, and thereby creating many haptic feedback devices to stimulate haptic sensations. On the other hand, researchers from a more traditional academic background, such as Slater, investigate the perceptual parts of VR from a physiological and cognitive neuroscience perspective.

The understanding of theoretical VR concepts and the development of haptic devices are two separate research fields. However, I see myself in the middle of these. On one hand, with my work I strive to create better and unique VR experiences, giving new design elements and tools to developers. On the other hand, I want to understand how these introduced factors truly change the experience and why they affect the quality of VR beyond inducing "more presence" in the user. As VR as a medium is computational in nature, I see that HCI has an important role in building a bridge between these disciplines.

2.4 VR theory in HCI

There is a need for theory in HCI to effectively build systems [R26]. A lot of HCI research focuses on improving the systems themselves. However, as soon as one puts on VR goggles, the system itself does not matter that much anymore. It does not matter if what one interacts with and feels is real (haptic 1:1 representation via haptic proxy) or if it is not even physical (illusions via pseudo-haptic feedback). As long as the interaction is perceived as "real" or rather believable, then the means of how this is achieved do not matter.The fidelity of the used device does correlate with its design goal (see Chapter 3). We found that there is a design space that does not reflect reality while still being beneficial to the user. However, we need a theory to understand simulacra in VR. Further, in HCI research we lack ways to describe how haptics are connected to the elements they represent in the virtual world. Therefore, we need to build towards a theory in HCI that helps us to improve VR experiences.

For HCI-focused VR research, Slater's work is the main strain of theoretical models behind VR research [R35]. However, these models originate from perceptual psychology, a scope of inquiry not concerned with design. Thus, these theories are often too disconnected or too broad to be directly applied by an HCI researcher or designer to build and/or evaluate a system. When comparing two haptic devices, the question of which invokes more presence only has limited value for a general discussion. From an applicable perspective, we need a way of describing and later on evaluating systems.

Current VR models are either theoretical or technical. Therefore, HCI is very important to bridge this gap between building systems and evaluating their impact on perception, as no other field is able to answer these questions. We need to be able to understand and describe how VR can affect the user in order to effectively build systems and improve the experience.

Therefore, in my thesis, I experimentally investigate these questions through a systems approach, by identifying a conceptual problem, building a system, and analyse how people are affected by the exposure to the system.

2.5 Summary of Dissertation

Knowledge, you see, has no uses without purpose, but purpose is what builds enclosing walls. - Leto Atreides II

Children of Dune - Frank Herbert

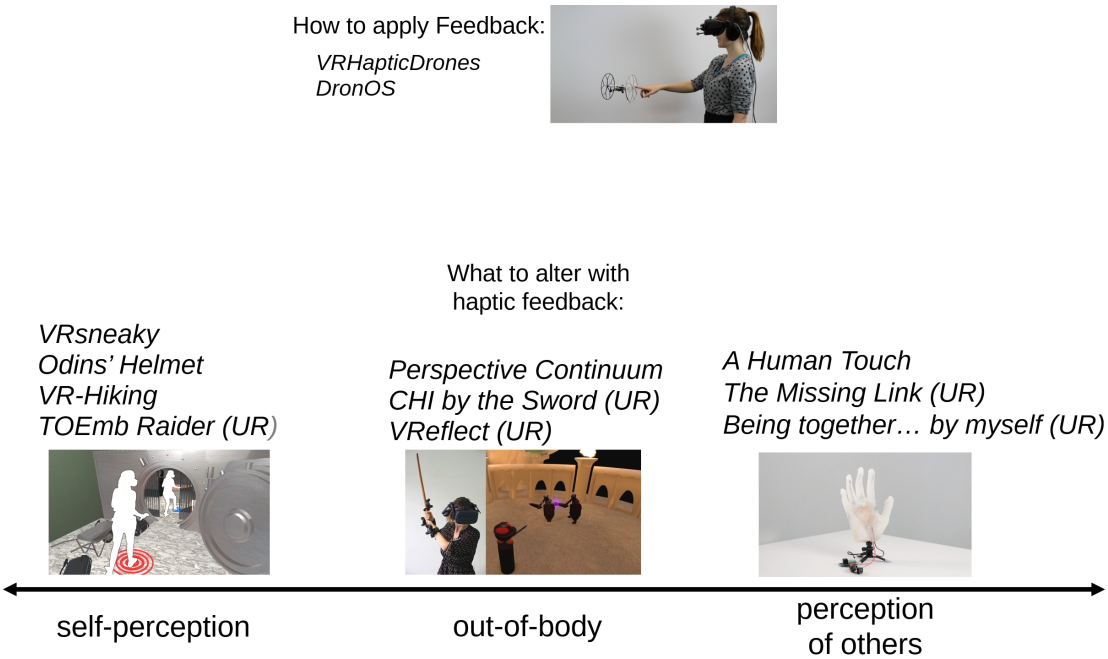


Figure 2.1: Overview of my publications divided by transforming the perception of the user in relation to oneself, other characters, or people and embodiment of multiple bodies in the form of out-of-body experiences. Haptic Feedback consists of drone drone-based system for rendering haptic feedback. All publications are published or under review (UR).

> A central part of any VR experience is how the user interacts and perceives the world around them and their own virtual body. In my thesis, I demonstrate how simple (haptic) feedback can be used to alter the user' self-perception, and the perception of others and create experiences only possible in VR. Further, I discuss how such elements can intentionally be utilised by developers and designers to design the perception of the user.

Recent VR research, games, and experiences show that for the creation of believable VR experiences replicating realism is optional. Simplified virtual environments and avatars are already effective in bringing a person to remote worlds. While this is often discussed in the form of graphics, current consumer handheld controllers are a great example of how simplified haptic feedback in the form of vibrotactile actuation achieves great results. Rendering

Table 2.1: Overview of my publications divided by transforming the perception of the user in relation to oneself, other characters or people and embodiment of multiple bodies in the form of out-of-body experiences.

Perception of Self	Perception of Multiple Bodies	Perception of Others
VRsneaky [P4]	Perspective Continuum [P9]	A Human Touch [P18]
TOEmb Raider [P13]	CHI by the Sword [P8]	Being by myself... together [P22]
VR-hiking [P7]	VReflect [P3]	
Odin's Helmet [P17]		

abstract feedback (vibrating controller upon touching a virtual object) is often used as a workaround as the rendering of more accurate haptic feedback is not plausible for a wide variety of objects. While vibrotactile feedback can present information about the environment it also gives the illusion of something "being there" that can be touched. To interact with the virtual world and its objects within, the user needs to embody a virtual avatar. However, in my research, we showed that (haptic) devices can not only give the illusion of a "physical" world that can be touched but that the devices can also be used to transform one's perception of oneself, others, and out-of-body experiences by the use of simple impulses (see Table 2.1). I, therefore, explore how haptic devices can be utilised to push and explore the boundaries and limits of human bodies and their perception in Virtual Reality.

The Body in VR — Body Schema and Body Image

The concept of body schema by Head [R11], defines that one's self-perception is based on sensory impulses that result in the perceived location of one's body parts in space. In HCI this is often referred to as proprioception. However, the body schema is not only limited to one's own body but is essential to the use of tools, as they are perceived as extensions to one's body. Schindler redefined the term in 1935 and suggested body image as "the picture of our own body we form in our mind, that is to say, the way in which the body appears to ourselves" [R27]. Therefore, defines self-perception in a more abstract form, as the body image includes the conscious perception of the own appearance. The differentiation between the two is an ongoing debate. In recent years Graziano suggested the "Attention Schema Theory", a neuropsychological concept that suggests that the brain is subjectively aware of itself and therefore able to monitor and control movements of the body [R10]. The theory suggests that the brain is an information-processing device that has a subjective awareness.

The Need for a Theoretical Model for Applicable Design Choices

The ongoing debates about definitions and concepts of body perception, while still unclear, suggest a connection between one's perception and interpretation of bodies. While there are discussions across different scientific fields, it is unclear how changing one's perception (e.g., by altering the virtual scene) influences one's body perception. HCI's contribution to explore and improve VR should therefore not be limited to how the user's body and virtual world is presented. HCI researchers should consider how it can be beneficial to intentionally change aspects of the virtual scene to alter the perception of the user. For this, HCI needs to have an understanding of the relationship between concepts, such as perception and embodiment. However, as the ongoing discussion shows, it might be impossible to fully prove a model on a purely perceptual level.

The components behind VR are not limited to technical and computational elements of how the virtual world is presented to the user. An important part of every VR experience is based on natural science and how the users perceive themselves and the world they are immersed in. Therefore, HCI should take into consideration philosophical, phenomenology, and psychological theories, as VR research needs a theoretical approach that helps to make applicable design choices.

In my dissertation **I present how one's perception of self and perception of how others can be transformed**. The unique nature of VR further allows me to present a fusion between self-perception and the perception of others, and create a form of out-of-body experience. This perspective continuum in VR describes a form of **embodiment of multiple bodies simultaneously**. Additionally, I present how **elements – such as haptic feedback – can be used to intentionally transform one's perception in VR** and explore the limits of embodiment, that serve as indicators for first steps towards a theoretical model for applicable design choices.

2.5.1 Perception of Multiple Bodies — Perspective Continuum

The nature of how VR devices (especially modern HMD) are designed, lets the users look into a different world, giving the impression of teleporting their real-world self into virtual environments. Via room-scale body tracking the user cannot only look around from a fixed viewpoint but actively move through the virtual environment and use hand-held controllers to interact with the virtual world. This technological setup and interaction methods favour VR experiences that present the user with a first-person perspective. The first-person perspective replicates how humans perceive and interact with their environment every day (be it visual, auditory, or haptic). While, in real life humans are limited to this perspective (excluding experiences such as medical or drug-induced out-of-body-experiences, etc.), VR gives us the ability to deliberately change this, e.g., by altering the camera position [P21]. By placing the virtual, stereoscopic camera not at the user's eyes but behind their body, we can create an out-of-body experience, where the user sees their own body from a bird's eye perspective. Similar to how many video games are played from a within-character view (first-person perspective) or the character is controlled from an out-of-character view (third-person perspective).

Modern games make creative use of First- and Third-person perspectives (FPP and TPP) to allow the player to explore virtual worlds. Traditionally, FPP and TPP perspectives are seen as distinct concepts. Yet, Virtual Reality (VR) allows for flexibility in choosing perspectives

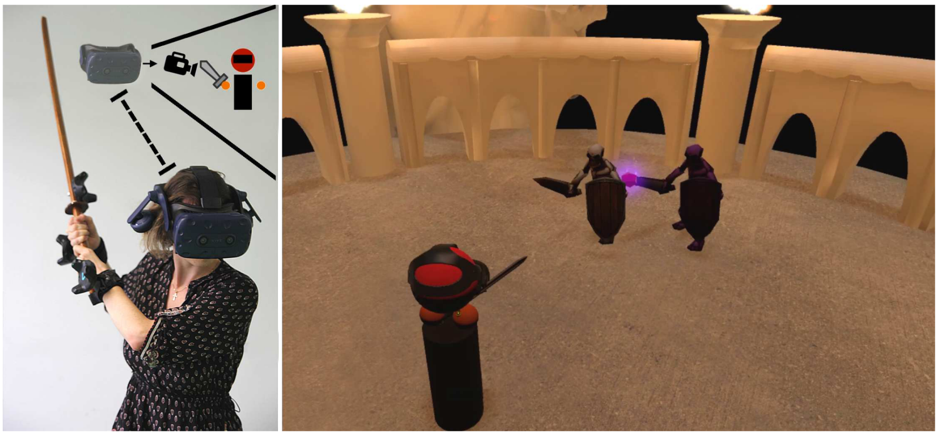


Figure 2.2: The presented scene (right) depicts the actual point of view of the VR user visible in the HMD (left). The concept of 1stPP and 3rdPP as known from traditional desktop games cannot be directly translated to Virtual Reality. While some users will perceive the scene as watching themselves from behind (similar to an out-of-body experience), others will perceive the scene as looking at another character that they control via their movement. Various design elements such as visualisations of the user's body and control schemes can impact this perception.

(see Figure 2.2). We introduce the notion of a perspective continuum in VR, which is technically related to the camera position and conceptually related to how users perceive their environment in VR [P9]. Unlike the clear distinction between FPP and TPP in traditional video games, VR is a continuum between FPP and TPP, rather than two distinct perspectives. Therefore, while some users might perceive themselves as an observer that is puppeteering a character, others might have an out-of-body experience, or have the feeling of being multiple characters at the same time.

This flexibility of perspectives broadens the design space of VR experiences through deliberately manipulating perception.While, changing the perspective allows user to get a different feeling for their body movement, by utilising camera positions instead of mirrors [P3]. Further, design elements such as haptics, control schemes, and avatar models have the potential to intentionally induce shifts of perception [P8]. These intentional shifts along the perspective continuum could be used to control the level of embodiment. Thereby, enabling a form of "easy mode" for horror games that are too intense or for exposure therapy where the patient slowly gets more intense exposures. Therefore, VR can be used to push the boundaries of perception of oneself and remove the limits of having a single body.

2.5.2 Perception of Oneself — Altering Behaviour

While Virtual Reality continues to increase in fidelity, it remains an open question of how to effectively reflect the user's movements and how providing congruent body feedback in virtual environments changes the perception of the user. With room-scale tracking and redirected walking techniques the possibility and therefore importance of walking in VR gets more important. A lot of research prototypes present the user with haptic feedback for feet. This helps for better representation and understanding of the virtual world, in this case walking surfaces. However, even simple tools such as giving auditory characteristics [P4] or visual deformation of the surface [P13] can change how the user perceives them while walking.

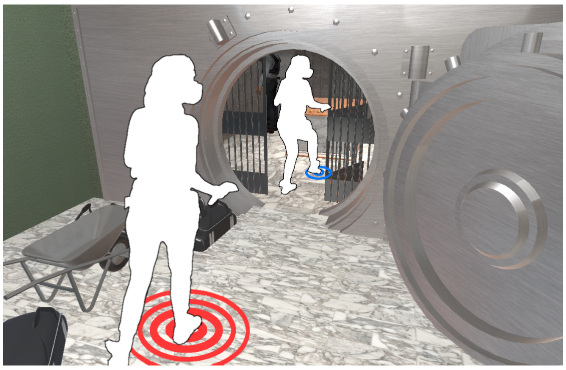
Our work shows that gait-aware audio feedback is a means to increase presence in virtual environments while making the users more aware of their own body posture and gait [P4]. Unsurprisingly, previous work showed that multimodal feedback is an effective way of increasing the perceived level of presence, as it further improves the realism and expected behaviour of the virtual world. However, we found that gait-aware auditory feedback significantly influences characteristics of participants' gait, number of steps taken, and stride length.

Giving interactable objects, such as floors, adequate multimodal characteristics [P13] not only changes the level of presence but can be utilised as a design element to alter users' self-perception. Users with synchronised and gait-aware step sounds reported that they have a better feeling of their impact on the virtual world. The self-perception in VR goes beyond the felt embodiment of an avatar based only on visual avatar characteristics (e.g. Schwind et al.). Such as adding physical exertion to a virtual scenario produces significantly more positive emotions and mindfulness [P7].

Therefore, feedback can strengthen bodily representation and self-reflection in VR beyond the perceived embodiment and presence of a user. Further, changes in the type of applied feedback can be utilised to intentionally change the user's perception and behaviour, e.g. slowing down the user when needed. Systems such as VRsneaky offer opportunities and design elements for scenarios where users walk through immersive virtual worlds. Future developers will be able to leverage the direct input of a user's gait. This offers creative opportunities for immersive virtual environments and provides the capabilities to raise the user's feeling of "being in another world" to a new level.

2.5.3 Perception of Others — Social Touch

A potent element of VR is the social aspects of displaying other computer-controlled characters (agents) or a virtual representation of real people (avatars). The interaction with in-game characters, be it scripted computer-controlled agents or human-controlled avatars joining a remote session, is an important part of VR experiences. Being in a room with another person involves more elements than perceiving them via visuals and auditory signals. Behaviour, context, previous history with said person, own expectation, and empathy are all coming into play. Therefore, how the social aspect is perceived has many factors and components that are harder to recreate beyond the obvious senses. The atmosphere and dynamics of a live audience during a concert involve complex social components making it difficult to measure



(a) Depiction of a user in the virtual environment. VRsneaky detects the user's gait — heavy (red) vs. light (blue) footsteps — and provides congruent auditory feedback.

(b) A Raspberry Pi Zero W control unit is mounted on a participant's leg. Force-sensing resistors (FSRs) used for gait awareness were placed under the shoe.

Figure 2.3: The stride length and number of steps taken can be influenced by changing the auditive feedback.

and recreate such events in VR [P22]. Therefore, both the evaluation and recreation of such events demand new ways of measurement and inducing the same response in the VR user.

In the case of agents, developers go a long way to create believable NPC characters that interact with the world and the user. Pre-captured motion sequences, Voice recordings, facial expressions, movement animation, 3D models, behavioural scripting, are all aimed at increasing the visual humanoid resemblance and creating a character that is perceived as human. However, similar to traditional desktop games, it is quite easy to spot computer-controlled characters when interacting with these agents for a short period. These unrealistic and undesired behaviours are often highlighted and ridiculed on online forums as a mark for low quality.

Most of these efforts for recreation preclude realistic social interactions (complex forms of eye contact, imitation of body language), particularly for agents. The recreation of social interactions is immensely challenging. Therefore, we explored how simple haptic impulses can be used to smooth over these irregularities. We bypassed these irregularities or missing details of social interaction via the use of social touch [R39, R5]. Social touch is non-verbal and conveys feelings and signals (coexistence, closure, intimacy). In our research, we created an artificial hand to apply social touch in a repeatable and controlled fashion to investigate its effect on the perceived human-likeness of avatars and agents. While we used an artificial hand for the visual appeal and potentially more complex interactions (such as handshakes), we are sure that similar results can be achieved by simpler means such as a tennis ball on a stick. Our results show that social touch is effective in further blurring the boundary between computer- and human-controlled virtual characters and contributes to experiences that closely resemble human-to-human interactions.

Social interactions possibly are the aspect where VR benefits the most from the recreation of even the smallest element. While, VR developers might invoke similar responses as during social events by the use of abstract visuals of recorded biometric data [P22], for direct interactions with characters this is not feasible. While immense effort is put into improving such character and behaviour, haptic feedback can be used to trick the user into perceiving a character as a human-controlled avatar. By inducing social touch, a social context, and intent behind a physical contact, via a simple haptic interaction, one perception of another person or character can change [P18]. With a social touch event, the perception of a character therefore can be alert by simple haptic feedback. Therefore, the perception a user has of another virtual person can be intentionally altered and computer-controlled characters can appear more human.

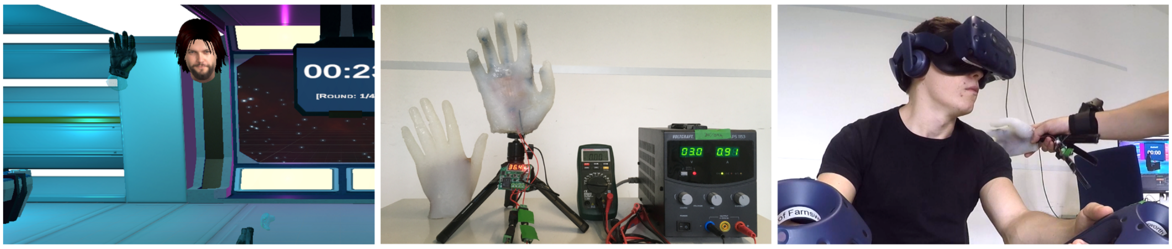


Figure 2.4: Is the presented character a human-controlled avatar or computer-controlled agent? If the character reaches out and physically performs a social touch on a user, it will blur the boundaries between avatar and agent. For this we used a heat-able hand prototype with flexible joints, to recreate a touch sensation that is indistinguishable from a real hand.

III

Degrees of Mimicry - Literature Review

Chapter 3

Degrees of Mimicry - A Literature Review of Haptic Feedback for VR

There's pain sensation in VR, and even a sense of reality and urgency. The only difference is that it isn't actually happening. - Raiden

Metal Gear Solid 2 - Hideo Kojima

Haptic feedback is highly focused in HCI related VR research. In a literature review of 3414 CHI publications (filtered to the corpus of 113 haptic feedback-themed works), we identified the main goal of current haptic research: to create haptic feedback that recreates real-world haptics. Therefore, there is a lot of potential for novel approaches that go beyond the replication of reality. Further, we developed a classification that is independent of the subjective perception of the user or the haptic quality of the system.

The related work section of each of my listed publications contains an extensive analysis that is tailored to the topic and contribution of the paper. In this section, on the other hand, I present an analysis of the available related work that deals with the consideration of how haptic feedback for virtual objects is being provided and the design concept of how the haptic feedback is used. This literature review contributes to a theoretical model of perception in VR beyond the level of fidelity for haptic feedback devices. All included papers present a haptic feedback system or concept that is categorised in the context of the application.

Recent publications in HCI contributed a large body of research on improving VR systems. The majority of VR-related research tends to concentrate on the lack of haptic representation of virtual worlds, as interactions within these worlds are an integral part of the experience. The focus within haptic research concentrates on how to use technical systems to improve haptic feedback itself. Designing haptic devices dedicated to VR is enjoying unprecedented popularity in research. While new devices are developed, HCI should also aim to understand the limits and possibilities of feedback in VR.

As VR research progresses, numerous haptic devices are being introduced, each promising to improve user interaction in its own unique way. For HCI researchers, understanding the intricacies of these devices is crucial. By doing so, we can gain deeper insights into how people perceive and interact within VR environments, ensuring that our technological advancements align with user needs and preferences. The first step to such an understanding is establishing a coherent terminology. Yet, current terms that describe haptic feedback have unclear uses and distinctions. Terms such as tactile, haptic, force feedback, and kinesthetic feedback are not distinct or even, potentially erroneously, used interchangeably.

The complexity and overlapping definitions in the realm of haptics likely stem from its interactive and multimodal characteristics. Unlike other technological facets of VR—like graphics, display, and audio—which are primarily output-focused, haptics encompasses a dual role. It not only serves as an output mechanism, such as in the case of delivering vibrotactile feedback, but also integrates input functions, especially when users interact with virtual objects. Consider the tactile exploration of objects in VR. Depending on the nature of the interaction, different physical properties must be replicated. For instance, when a user grabs a virtual object, they should ideally feel its shape and weight. In contrast, merely touching that object should simulate sensations like texture and temperature, as illustrated in Figure 3.1.

This review seeks to standardise terms by introducing specific labels for haptic feedback in VR: Mimics and Design concepts. Our intention is to make the field more accessible and coherent. Using these classifications, we mapped historical VR research in HCI within a structured design space. This approach provides clarity on past work, while also setting a clear path for researchers to follow and build upon in future studies. The core contribution of this chapter is deriving a lingua franca for VR research in HCI, defined by Mimics (true, semi, and false) and Design concepts (abstract, real, and beyond).

In the remainder of this chapter, I first motivate our review, then define the key terms in our design space for haptic feedback in VR and lastly present how these terms accurately describe current research in the field.

3.1 Motivation—Conceptualisation of Haptics in VR

As haptics are often still low in fidelity, vibrotactile controllers remain the state-of-the-art approach in consumer devices. They are effective for giving abstract feedback and signals when the user’s hand collides with an object or upon receiving a notification. HCI research aims to improve rendered feedback and generally tries to improve the quality and amount of feedback to more accurately replicate the expected physical attributes of the virtual object. While providing more multimodal feedback can lead to a better, richer experience, it is not a prerequisite. However, researchers strive to improve VR by providing "more" haptic

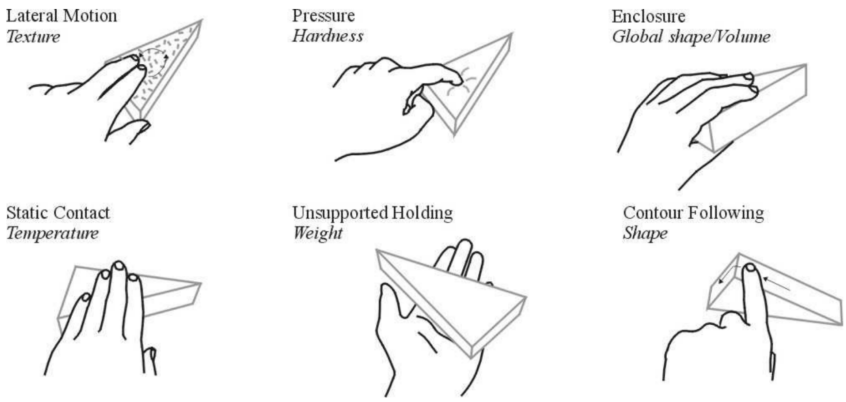


Figure 3.1: Object properties can be identified through haptic exploration [R16] (Figure by Allison Okamura).

feedback. The assumption is, that the more realistic the haptic feedback is, the better the virtual world will be.

Depending on the type of haptic interaction that is to be improved, different kind of stimulation is needed. Therefore, resulting in highly specialised haptic devices to render a specific haptic experience [R41]. For an interaction where the user is pressing different types of buttons made of multiple materials different physical attributes need to be combined, e.g., combining rendering the texture of a surface with the hardness of the material. While the texture is perceived via tactile sensations the hardness is perceived predominantly via kinesthetics. For the development of such devices, the distinction between haptic, tactile, kinesthetic, etc. is important for the implementation of feedback devices.

However, for this literature review, I do not wish to distinguish the types of stimulation needed and therefore not the specific actuation implemented in the feedback approach or device. Instead, I am interested in the interactive and perceptual properties of VR experiences. Our research is driven by the following questions: 1) How do solutions in HCI research generate feedback (the degree to which the properties of a virtual object are being mimicked) and; 2) What can be achieved by current systems, i.e. how the perception of the user is affected or altered?

This conceptualisation of the rendering and usage of haptic feedback can benefit HCI as it focuses on the representation goals and methods used to achieve this representation, rather than the specific technical implementation or used technology.

Within the HCI community, there's a noticeable gap in a shared understanding and consistent terminology concerning the application of haptic feedback in VR. This ambiguity, particularly in terms such as "haptic," "tactile," "kinesthetic," and "force feedback"—which are frequently used interchangeably—makes a shared understanding of the concepts complicated. It is unclear whether the technology's primary objective is to emulate reality through novel interaction methods or to introduce abstract tools that serve various purposes. Our aim is to introduce a taxonomy, creating a structured framework that aids in concept development and design.

3.2 Method

To address this gap, we conducted a structured literature review of work on novel VR feedback techniques. Following a structured process, we analysed a corpus of 3.414 papers sourced from the top venue CHI, identified through a survey of active VR researchers. Based on our literature review, we contribute a design space for haptic perception in VR, defined by degrees of mimicry of used devices and design concepts of the application. We present a systematic understanding and design recommendations to address the research gap regarding the design of haptic feedback in VR.

3.2.1 Method details/steps

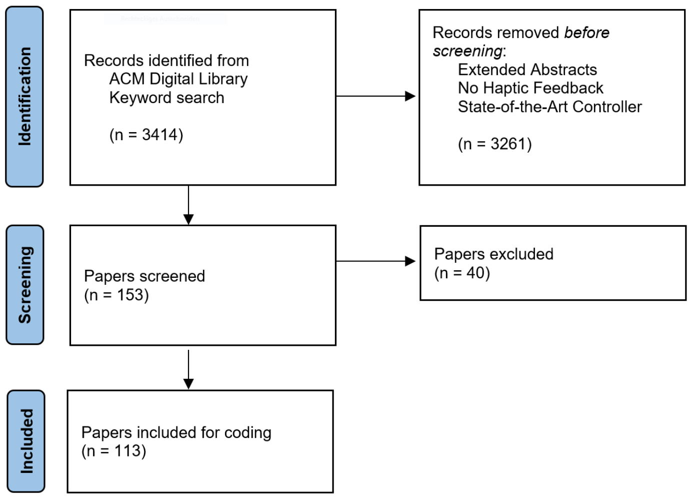


Figure 3.2: PRISMA flow diagram for haptic feedback in ACM Digital Library. Keyword search was performed for ACM CHI up to the year 2023

To identify the venues that are relevant to our literature review we interviewed 15 junior and senior researchers that previously published in the field of haptics and/or virtual reality. Among questions about their expertise and research focus we asked them to mention and rank the top HCI venues for haptics (see Table 3.1).

Both in the number of mentions and rankings, the ACM Conference on Human Factors in Computing Systems (CHI) was rated as the top venue.

Table 3.1: We interviewed 15 junior and senior VR and haptics researchers and asked them to mention and rank their top HCI venues for haptics. In both the rankings and number of mentions ACM CHI was rated as the top venue.

Conference	Place Ranking	Points (Sum Ranking)	Place Mentions	#mentions
ACM CHI	1	129	1	14
IEEE VR	2	110	2	13
ACM VRST	3	83	3	11
IEEE ISMAR	4	79	4	10
ACM DIS / ACM UIST	5	29 / 29	5	4 / 4

We selected CHI as the venue of choice, as it is not only ranked highest by experts but also represents VR research in a diverse area, as VR publications at CHI not only focus on technical hardware aspects or virtual designs but cover a wide variety of specialised papers that could not be found at more focused conferences. We aimed to build a meta-understanding of the kind of VR haptic feedback research performed in the HCI community, rather than build a comprehensive summary of the field. Therefore, we selected all CHI publications available from the ACM Digital Library that contained the keywords *Virtual Reality*; or *VR*; or *Mixed Reality* [R21]; or *MR* up to the year 2023 (see Figure 3.2). We chose to not filter any keywords related to haptics, as our expert interview showed that the used terminology regarding haptics is manyfold at potentially could exclude relevant papers. Instead, we screened all publications that could potentially be important, as some papers could not have used the terms related to haptics while contributing to the overall field.

The search of the ACM Digital Library resulted in a selection of 3.414 publications. These were then screened by three researchers according to a set of criteria.We identified these publications and excluded 3261 publications. We excluded extended abstracts and workshop proposals as we aimed to analyse full papers. Additionally, we excluded papers that did not present any type of haptic feedback device, experience, or haptic interaction. Papers that used state-of-the-art standard controllers with vibrotactile feedback (standard feedback patterns) were excluded if they did not present a novel approach. They needed to include a system, that is not based on pure audio or visual feedback. However, pseudo-haptics and similar illusions were included as they are a valid multimodal method to generate the illusion of haptic sensations. While ultrasound can be considered audio, as it is being produced via sound waves, papers were not excluded as in this case audio is used to stimulate tactile sensors. Papers including walking or redirected walking proved to be an edge case, as they always involve a haptic contact with the floor. These were excluded if they did not involve any changes in the perception of the ground or the user (texture, weight, height). The first screening resulted in a body of 153 publications.

In the next step, three researchers thoroughly reviewed the 153 publications and then discussed the identified common themes. This resulted in the distinction between multiple degrees of mimicry of the actuation (device or concept) that was used to render haptic feedback. This does not include a rating of the quality and accuracy of the approach, but which strategy was used. Further, we identified that different "levels" of goals can be achieved by these actuation approaches. Similar to the degree of mimicry, these design concepts do not reflect a rating of the quality, but the levels of abstraction that can be achieved by the application of the mimics.

During this step, 40 publications were excluded as they did not fit the criteria upon closer inspection. Papers were excluded that do not present a system (such as literature reviews) or approach or do not provide enough descriptions about the prototype or approach to be classified, this included cases where multiple systems were presented simultaneously. This coding step resulted in a corpus of 113 publications.

3.3 Findings and Definitions

Our analysis showed that a wide variety of research projects use different approaches to render haptic feedback. We divide these approaches into different degrees of mimicry, as in how feedback is rendered or achieved. These categories describe two nominal scales without hard borders, therefore the suggested classification can vary with the implementation of specific application scenarios. The Design Concepts were conceived and used as a nominal scale during review and rating of the papers. However, the Design Concepts can be considered an ordinal scale from abstract, over real to beyond, as the range represents the levels of control the designer behind the system has over the user's perception.

3.3.1 Mimics

We define Mimics as devices, systems, or approaches to provide haptic feedback in different forms. The degree of mimicry describes how a virtual object is represented. While it describes how feedback is provided, it does not depend on the fidelity or the type of technology used. Nor to what level the sensory properties of the corresponding real-life object are provided.

- **True-Mimics:** render "all" properties of a virtual object by approximation of all sensory properties of real-life objects, e.g., in the form of haptic proxies such as a wooden apple.
- **Semi-Mimics:** represent a subset of sensory properties of a real object in the virtual environment. E.g., EMS can render touching a virtual apple by restricting movement of arms or fingers (kinesthetic feedback) however it cannot render the texture of the virtual apple.
- **False-Mimic:** map sensory properties of a real object into different sensory properties of the virtual object. For example, vibrotactile feedback of hand-held controllers,

where vibration represents the surface location instead of having resistance in the form of kinesthetic feedback. E.g., feeling vibration upon touching a virtual apple.

A mimic that renders the perception of movement for a user that is driving a car in VR could therefore be implemented as three different types of mimics: a real car the VR user sits in which follows the same directions as the virtual car (True); a cable-based driving simulator that is able to render the same forces of acceleration but is limited in its range or rotational acceleration[1](Semi); a system such as EMS or head-worn actuators [P17] that stimulate the vestibular system of the user, thereby creating the illusion of self-motion (False);

The type of mimic does not represent a ranking of the absolute fidelity of the system. While the car (True) would be closest to the real forces of driving, it still has its limitations as it could not simulate slopes or different track textures on demand. The cable simulator would be able to simulate slopes and track textures but might run out of room to simulate all ranges of acceleration for a prolonged time. While the EMS (False) might make all forces perceivable by the user, the mapping of one sense to another might reveal the illusion.

3.3.2 Design Concepts

We define design concepts as the goal of what the used mimics are representing. The design concepts of the haptic representation can be: abstract, real, beyond. It is important to note that while these categories differ in the level of abstraction of the goal, they are neither ordered nor are they rated. However, the design concepts can be considered an ordinal scale from abstract, over real to beyond, as the range represents the levels of control the designer behind the system has over the user's perception.

- abstract: representation of abstract concepts such as notifications, and text input. e.g., using one's leg as a surface for input, however not the recreation of a real keyboard.
- real: imitation of the representation of real-world objects. e.g., the virtual recreation of a physical object as real as possible. haptic perception that is based on illusions are included.
- beyond: representation of things that are not possible in real life. e.g., out-of-body experiences or amplifying humans by creating new reflexes;

The design concept changes the requirements of the mimics. In a scenario where the user wants to interact and alter the system, an abstract design concept represents the abstract concept of text input. These abstract concepts are often translated from desktop systems, such as input or notifications. For real this demands the replication of a physical keyboard that the user can interact with, touch, and move in VR. For a beyond design concept this could be a form of holodeck that automatically adapts to users' needs without the need to program scenarios or specify small details.

[1] https://www.cyberneum.de/CableRobotSimulator

3.3.3 Results - Categorisation

The categorisation of the mimics resulted in 39 TRUE-mimics, 39 SEMI-mimics and 35 FALSE-mimics (see Figure 3.3). The categorisation of the design concepts resulted in 15 ABSTRACT, 90 real and 8 BEYOND. The cross-categorisation between mimics and design concepts result in 3 TRUE/ABSTRACT, 1 SEMI/ABSTRACT, 11 FALSE/ABSTRACT; 33 TRUE/REAL, 38 SEMI/REAL, 19 FALSE/REAL; and 3 TRUE/BEYOND, 0 SEMI/BEYOND, 5 FALSE/BEYOND.

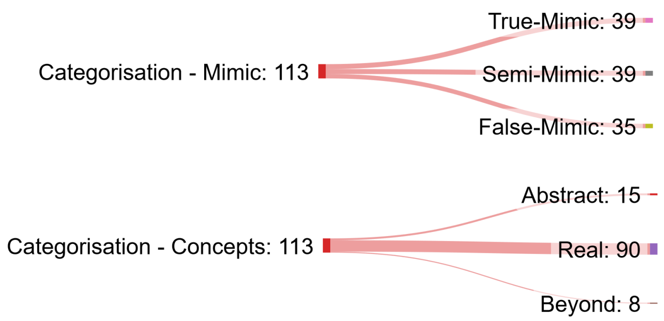


Figure 3.3: Categorisation of 113 publications into mimic and design concepts. Mimics are equally distributed, design concepts favour the REAL design concept.

3.3.4 Categorisation Criteria and Examples

Definitions of complex systems such as haptics generate a lot of corner cases and dependencies on details. Such details might be missing from the papers or are too extensive to be considered for general categorisation, such as presenting multiple combined systems. To give a better understanding of the definitions we explain corner cases and give examples to better guide the reader.

- (TRUE/ABSTRACT): a haptic proxy that mimics the same virtual object. The object is augmented with micogestures such as volume control [R32].
- (TRUE/REAL): a haptic controller with the purpose of mimicking the same haptic properties (in this case weight distribution) as the virtual handheld object (e.g. a sword or a gun) [R33].
- (TRUE/BEYOND): a haptic proxy that mimics the same virtual object. However, the proxy is used to create an out-of-body experience by connecting the real-life object to a character that holds the virtual equivalent of said object [P9].
- (SEMI/ABSTRACT): touchable drones are used as hovering input surfaces. While not representing a full virtual object they are able to create a collision with the user's finger [R8].

- (Semi/Real): representation of virtual objects or walls by restricting movements of arms by EMS. However, it can only render parts of the object such as the position of the surface by stopping the arms from moving, but lacks the ability to simulate touch/pressure and the hands surface [R20].
- (Semi/Beyond): no publication with this combination was found.
- (False/Abstract): any surface is used to give haptic feedback to typing a letter. However, the surfaces are used for the concept of text input instead of creating the illusion of a physical keyboard [R37].
- (False/Real): changing the perceived properties of the virtual object by making handheld proxies or controllers appear heavier by the use of pseudo-haptic illusions [R25].
- (False/Beyond): as the user walks through a virtual wall, the illusion of a haptic sensation occurs. As the virtual wall has no physical representation, the wall cannot be perceived via contact. However, the wall is "felt" by the user while traversing through it [R23].

Many of the selected papers present a haptic feedback device that is supposedly used for providing feedback in VR. However, often descriptions about the virtual application itself or haptic qualities are lacking. In such cases, the assumed goal is to improve the Virtual Reality and create the perfect 1:1 reality, which we see as a stance and not a a priori goal. Therefore, such papers are categorised as Real [R6].

For papers with multiple prototype variations or iterations we asses the highest fidelity prototype featured in the paper. For cases when a paper features not only a system but also a user study, we ranked the system and not the study. For example, while VRsneaky [P14] reports results of the system being able to change the user's gait (Beyond), the system itself recreates gait-aware steeping sounds in VR (Real), therefore the paper would be categorised as Real.

Haptic retargeting or haptic illusions can be considered an oddity in terms of haptic feedback as they per se often do not provide any haptic stimulation. These approaches trick the user's perception by, e.g. visually (re)mapping the user's movement, thereby creating the illusion of haptic properties. For this reason, we classify such approaches as False. Additionally, we categorise systems that impact the proprioceptive perception (e.g. by the use of EMS) as False, as they also create the illusion of change in the proprioceptive system by mapping simulated forces to different senses.

3.3.5 Cross-categorisation Mimics-Design Concepts

Here, we look at the combinations of mimics and design concepts, as illustrated in Figure 3.4. The cross-categorisation between Mimics and Design Concepts shows that True- and Semi-

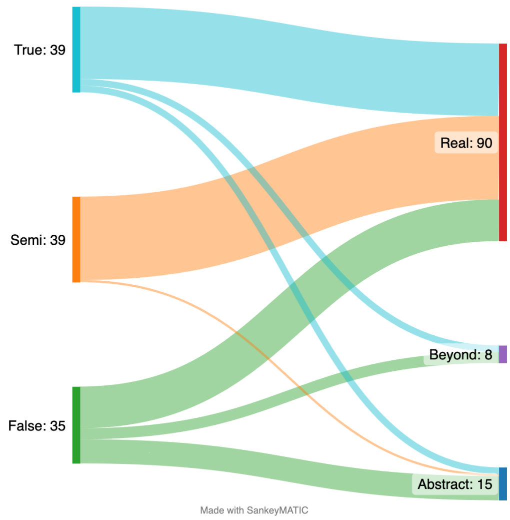


Figure 3.4: Combinations of mimics and design concepts in our review. SEMI/REAL is the dominant category.

Mimics are a popular choice (33 TRUE/REAL, 38 SEMI/REAL) to create the perfect replication of reality, the ultimate display [R38].

This, however, is a complex task and the technology is sometimes limited in its range. In many cases such complexity is not needed, and SEMI-Mimics might be enough to achieve the illusion of reality. Therefore, the remapping of a characteristic of the device to another characteristic of the virtual object is a favourable alternative (38 SEMI/REAL).

As this demands the use of additional technology pseudo haptics are a viable solution for either creating the illusion of a haptic sensation or altering the perception of haptic properties of existing objects or devices such as handheld controllers (19 FALSE/REAL) For the same reasons FALSE-Mimics are also used for ABSTRACT to improve text input or mid-air gestures (11 FALSE/ABSTRACT).

The remaining cross-connections (3 TRUE/ABSTRACT, 1 SEMI/ABSTRACT) do not offer enough data to asses how the mimics are used for the Design Concepts.

3.4 Discussion

The reviewed publications from CHI (up to 2023) contained a wide selection of technologies and different approaches used to generate haptic feedback. We found three different approaches to how haptic feedback is generated and categorised them into three types of Mimics: TRUE-Mimics, SEMI-Mimics, and FALSE-Mimics. Further, we found that the different forms of Mimics were utilised in three Design Concepts that describe the application area and goal of rendering the haptic feedback.

While there is an even distribution across the types of Mimics, the Design Concepts have a strong focus on the (re)creation of realistic haptic feedback for virtual objects (REAL).

Our work gives a conscious overview and **design recommendations** for designers' needs when building a new prototype. Our Design Space for Haptic Perception supports the decision if a TRUE-Mimic, of a full haptic proxy, is needed or if SEMI-Mimic, that maps the important haptic characteristics, provides enough adequate feedback for the use case, or if FALSE-Mimics, in form of illusion, are enough. Further, we present a **research gap** for future researchers of cross-combinations that are not equally explored yet.

3.4.1 Understanding Mimics

The hardware and approaches used to generate haptic feedback is many fold. They range from vibrotactile actuators, over electrical muscle stimulation, and even pseudo-haptic illusions created by retargeting objects or the user's body. We found that the used Mimics are evenly distributed among the publications (39 TRUE-Mimics, 39 SEMI-Mimics, and 35 FALSE-Mimics). Suggesting that overall no type of Mimic is favoured and their use is equally applicable. Therefore, depending on the object that needs to be represented one type of technology or approach might be better suited for that object. It also suggests that a pseudo-haptic approach is equally applicable as a full haptic proxy. Therefore, designers of haptic devices can chose a variety of implementations for the needed task or object.

The scope of our review, suggests that researchers are aware of the potential of implementations of different levels of complexity and abstraction. The prototypes do not rely on a full replication of the real-world haptic experiences in the way they are implemented, as not all tactile and haptic senses are stimulated equally for different types of mimics. E.g, EMS might represent an object by kinesthetics but intentionally omits tactile perception on the hand surface.

3.4.2 Using Design Concepts

The purpose of the reviewed prototypes heavily favours the recreation of reality with 90 publications (REAL). The main goal of haptic research therefore is the recreation of reality by rendering better haptics that align with the real-world properties of objects. However, the quality of the render feedback does not need to fully match the expectations of how a virtual object "feels like". While the shape of a proxy might perfectly match the virtual object, the perceived weight might differ. Therefore, to achieve the ultimate display [R38] a combination of multiple approaches might be needed.

We found that 15 publications were classified as ABSTRACT. ABSTRACT design goals often translate concepts from the real world/computers into VR, such as the need for text input. However, even concepts such as text input do not necessarily demand the haptic recreation of a physical keyboard but rely on haptic impulses.

With 8 out of 113 publications Beyond is rarely explored. While, the recreation of reality (Real) is highly explored, Beyond offers the biggest potential for innovations. VR gives the designer full control over the virtual world and what the user perceives. Therefore, while recreating reality is important, VR offers different uses and benefits that are not possible in real life, such as having multiple bodies [R28] or experiencing new sensations [R23][P9]

3.4.3 Ways forward

It is important to highlight that Beyond offers the most potential for novel approaches, as only a limited number of publications tackle Beyond (3 True/Beyond, 5 False/Beyond). Additionally, no publications used a Semi-Mimic for this Design Concept (0 Semi/Beyond).

Overall, future researchers can use this as design recommendations when building new systems and approaches. However, it is important to note that it is unclear if the distribution between Mimics and Design Concepts presents the best available solution. The distribution could be caused by pragmatic choices or even limited possibilities or availability of technologies.

3.5 Research Gaps

Haptic feedback is a highly focused category in VR research. However, HCI does not have a systematic understanding of how researchers tackle the development of haptic feedback in VR. Terminology of what sensors are involved in and how they relate to the presented prototypes are often unclear and terms, such as haptic, tactile, or force feedback, are even used interchangeably.

We present a terminology and classification that is not limited to what sensors in the user's body are stimulated. Instead, we focus on what approach is being taken to create haptic feedback and the goal of feedback. Therefore, our classification is independent of the subjective perception of the user or the haptic quality of the system.

Our literature review of 3414 CHI publications led us to the classification of 113 haptic feedback publications. This classification demonstrates that the main goal of haptics for VR (and Mixed Reality in general) is to create haptic feedback that recreates real-world haptics. Only a few (15 of 113) use for Abstract concepts such as text input or metaphors from desktop computers. On the other hand, only a few publications (8 of 113) explore the creation of experiences that go beyond what is possible in real life and are only possible in VR.

We present a systematic understanding and offer **design recommendations** for the available choices and **research gaps** to render haptic feedback in VR in relation to their design goals. Therefore, we see a lot of potential for novel approaches and future publications. Our presented **Design Space for Haptic Perception** and literature review will help future researchers to conceptualise novel ideas, and also use it for the design process for the creation of haptic devices.

These insights strengthen my assumption that even "simpler" haptic impulses can be used to achieve a high impact on the user's perception of the virtual world and themselves. Further, it identified that there is a research gap of applications that go beyond the mere recreation of reality. This, therefore, supports my claim that the potential of VR is not fully identified and future VR researchers should consider going beyond reality.

IV

Exploration of Perception

Chapter 4

Exploring Perception Design

In this chapter, I discuss the journey of my PhD[1], how I started building haptic devices to improve VR and discovered the untapped potential of haptic feedback beyond the representation of virtual objects. I hope this chapter inspires the novice researcher and helps the curious reader to understand why I decided to tackle the main topics in my thesis to investigate how haptic signals are affecting user perception in VR. For a more detailed discussion and inspiration for any topic, please refer to each of the papers, as this chapter serves as an overview of how my publications are connected.

4.1 The Origins of Perception Design

With the "rebirth" of VR in the form of the Oculus Rift Developer Version and HTC Vive, my chances to explore and work with VR opened up. The room tracking of the Vive setup enabled a "full" experience, compared to other earlier HMDs, that were full games with interactions via vibrotactile handheld controllers. Playing a space simulation with a full cockpit and HOTAS setup teleported me into a dream I had since playing Wing Commander in the early 90s: sitting in a spaceship, being able to freely look around the cockpit and wildly flipping mechanical switches. In many local gatherings and meetups of VR enthusiasts, I had the chance to see how many people perceive a strong sense of presence and feel like being in another world. While, vibrotactile feedback created stunning illusions of, e.g. drawing a bowstring to shoot arrows, people quickly realised its limitations, e.g. reaching through objects, the missing weight, etc.

When I started working towards my PhD the interest in the research of haptic controllers quickly became my focus. I found that there is a wide variety of different controllers, with

[1] The pronoun "I" is used when describing the meta-commentary of what inspired me and led me to tackle the next project. As all projects were a cooperation with my coauthors I will use "we" to refer to the projects themselves.

different functionalities, for different types of haptic feedback. These extraordinary technical systems achieve what they were designed to do in an effective way, creating believable experiences of haptic explorations. Be it walking on surfaces with haptic shoes son2019realwalk, an exoskeleton for hands choi2018claw, or handheld controllers that create the feeling of different weights heo2018thor. However, these devices were designed to do one specific task very effectively, thereby, limiting their applications to single tasks or types of interactions. This would require the user to either stick with them throughout the experience or require them to switch between the devices during the experience. Therefore, either the experience needs to be fully tailored to the used device or limit the user's options and openness to interact with the virtual world.

People tend to explore and figure out the limits of the experience, which results in breaking the illusion of being present in another world in one way or another. One of the easiest ways of perceiving a break in illusion is when wanting to interact and touch virtual objects. In current VR setups, the user commonly holds a hand-held controller in each hand. The controllers are a decent solution for interacting with virtual objects and give vibration signals as feedback for interaction or collision. These controllers are suited for representing objects like a gun or sticks. Comparing this to real-world devices, a hammer is a very useful tool when one is putting up picture frames, but running around with two hammers during the rest of the day might be quite limiting. But after performing the task the tools are suited for, you want to put them down and interact with different objects or your environment with your own hands.

The continuous development of improved haptic devices and approaches such as pseudo-haptics are therefore essential for convincing VR experiences. However, HCI should get a deeper understanding of VR and its components and human response to it. While we have full control over the virtual environment, we do not fully utilise or understand it. Therefore, VR as a subject needs to be investigated, and HCI has to play a key role in developing a deeper understanding of VR.

4.2 Building Haptic Devices: VRhapticDrones

As I started with haptic feedback as my research focus I of course also needed to create my own haptic feedback device. While researching related work on haptic devices I noticed that most of them implement a different form of handheld-controller. However, for VRhaptic-Drones [P15] we wanted to provide haptic feedback for hands-free interaction. Thereby, getting rid of the need for handheld controllers, and letting users explore with their own, empty hands. I still think this is a great solution, even if it currently comes with its limitations that offer unique new challenges (e.g. noise, complexity). I continued developing haptic feedback devices throughout my PhD. Including a Drone Framework DronOS [P11, P16, P19], and Odins Helmet [P17]. Building a drone system for haptic feedback taught me a lot about haptics, creating a system, and working with its limitations and advantages.

However, I did not want to build "yet another device" over and over again during my time as a PhD student. I realised that a simple haptic signal when the user touches a virtual object can already create the impression of "it being there". Therefore, when a device, such as a drone, can represent a handful of virtual objects it might already be enough to build up a mental model of infinite possibilities of interaction in the user.

At this point, I got curious and wanted to explore what else could be done with such simple (haptic) interactions. How can the initial exposure prime the user and change their impression of the virtual world? Is this impression of a "full world" only possible for inanimate objects, by the feedback of "it" being "there"? Does this exposure simply make them feel "more present" in the virtual world, as it seems to be fuller than before or does the exposure change the user's perception itself? Simple signals or priming often can be enough to shape the experience and therefore allow to design the perception of the human. Therefore, I started to explore the effect of haptic interaction on the user's self-perception and perception of others.

4.3 Exploration of How Exposure can Affect the User: VRsneaky

Hm. Hä?! Fußspuren?

Metal Gear Solid - Hideo Kojima

Many VR publications focus on the impact of adding different forms of haptic feedback for hand interaction. A limited number of publications investigate haptic feedback for feet, as this is quite complex and challenging. While these prototypes offer a great feeling for the ground son2019realwalk, they are often cumbersome to walk in. We on the other hand wanted to give users a feeling for sneaking in VR on a normal floor surface.

We were wondering what happens when we give back gait-aware stepping sounds in VR. Therefore, we explored how the user's way of walking and perception changes instead of pressing a sneak-button. For the study we wanted the participants to hurry and run, but at the same time try to tip-toe and be as silent as possible. Due to the limited tracking space, we had to encourage a fast switch between running and tip-toeing. We therefore created a mini-game where the participants had to rob a bank. The participant could run outside the bank vault but had to be silent in the vault to not startle the guard. The guard was standing with his back to the vault entrance and mumbled when the user got close to getting gold.

VRsneaky unsurprisingly increases the sense of presence, due to more exposure to multimodal feedback. We also found that the walking sound changes the user's gait, stride length, and number of steps depending on the used condition of audio feedback. Users also reported that it gave them a better feeling about the world and their impact on it. Therefore, adding gait-aware sounds gives designers options to impact and alter the user's gait when needed. While the investigation was quite limited, it is possible to intentionally change the user's self-perception and behaviour.

To continue to investigate the impact of feedback systems on the user's perception we formed follow-up projects based on the potential we saw in VRsneaky. In the next step of exploring gait-aware systems, we continued to develop TOEmbraider, which uses pseudo-haptic feedback by deformation of virtual floors to represent various levels of softness without changing the real-life floor [P13].To reduce motion sickness by inducing the illusion of self-motion in VR we implemented Odin's Helmet. Further, the system potentially can give the user a better judgment for physical forces such as acceleration in virtual surroundings [P17].

VR research's common aim is to improve interaction and comfort for the user. However, we are curious "negative" elements such as exertion have their merits and potential for improving VR. Does the need for intensive physical activity, such as walking up a virtual mountain, gives more meaning to the user when reaching the mountain top? Therefore, we ran studies on how physical interaction can alter the experience of VR scenarios and the user's self-perception. VR-hiking shows the impact of exertion on self-awareness, as adding physical exertion to a virtual scenario produces significantly more positive emotions and mindfulness and taking in a virtual scene [P7].

4.4 Exploration of the Perception of Others: A Human Touch

You took my trust for granted
You shook my hand and smiled
I walked away believing
In a world that never was.

The Curtain Fall - Tom S. Englund

We found that simple feedback, such as VRsneaky, can already change how the users perceive themselves and help to judge their impact on the virtual world. To encourage the participants to stay as quiet as possible we tricked them into the impression of the bank guard to be aware of their actions. The guard was muttering sounds shortly after the participants picked up one of the gold items. While this simple implementation was aimed at reminding the participants of the presence of the guard, it made us wonder what other impulses from virtual characters can have an impact on the user.

I was intrigued by the question if haptic feedback is limited to altering the user's self-perception or if it also can be applied to others. Can haptics be a way of improving the "feeling" of others being there or is it limited to visual, sound, and behaviour animations? Characters in VR usually take the form of agents (computer-controlled characters) or avatars (human-controlled characters). Computer-controlled characters are easy to spot after a short exposure or interaction period. Even if these agents are well implemented, including voice recordings, behaviour scripts, animation, high-resolution 3D modeling, etc., they are easily identified by users. Interactions with agents quickly break the illusion of a "real" person. Even in traditional desktop games, players can do unexpected things, where agents will not react accordingly. Even more so in VR.

We found that simple haptic impulses, such as a tap on the shoulder, can influence the user's perception of other characters and blur the line between computer-controlled agents and human-controlled avatars [P18]. Therefore, it opens up future researchers and designers to a new tool to improve and design social VR experiences, which hold immense potential for future communication and social life.

4.5 Exploration of Unique VR Experiences: Perspective Continuum

Are we quite certain we're here anyway?

Terminal Show - Ian Fraser Kilmister

While working on the previous project I realised that in VR things do not work as one might expect and the perception of the user can be stretched. Research and development are so focused on improving VR by recreating reality that we forget and ignore the immense potential that VR holds. To unlock this potential we however first need to understand how VR works, we therefore can foster knowledge on how to design and build better and unique VR experiences. An understanding of the uniqueness of VR as a medium is needed before we can build an often expected and demanded "killer app".

This curiosity and my previous experience in seeing how VR can transform the self-perception and perception of others led to the exploration of the perspective continuum.

Traditional games that are played on a flat-screen are presented in a variety of perspectives (side-scrolling, top-down, isometric, etc). The two most common perspectives in 3D games are the first-person and third-person perspective. In VR however, the first-person perspective is used almost exclusively, as the technology is based on the user exploring the virtual world by moving their head, walking, and interacting with their virtual hands.This potential to "teleport" somebody in a virtual scene is immense, the obvious choice for developers, and awestriking to users. Therefore, developers who implement a third-person perspective are rather rare. However, implementing a third-person perspective in VR does not reflect the typical third-person perspective on desktop games.

In desktop games, the player "remote-controls" the character while looking at it from the outside. In VR however, the player can take the role of two bodies at the same time – the character that is controlled and the observer in the form of the camera position. I therefore wanted to explore this potential of VR to go beyond the recreation of reality and create an out-of-body experience that is only possible with the medium of VR. We therefore explored and ran a study on how such an out-of-body experience is perceived.

We found that instead of two distinct perspectives (first- and third-person) in VR perspectives should be rather described as a perspective continuum [P9]. However, how the experience is perceived heavily depends on the user. While some perceive the scene from an observer position that remotely controls the character, others feel as seeing and controlling their own body from the outside, while others describe the experience as being multiple entities. This dependency on the user's perception of the scene leads to the need of a new terminology. Therefore, we further suggested the use of terminology that is design-dependent and perception-independent [P9]. Currently, it is unclear what design elements influence the individual's perception along the continuum. Future research about the perspective continuum needs to investigate how to actively move the user's perception along the continuum by the use of haptics [P8], visual representation of the character or control schemes.

This is our first step to use the new medium of VR in ways that go beyond the replication of reality and offer unique experiences only possible in the virtual world. By this, I demonstrate the potential to open up a new design space for a new medium that has barely been explored as of yet.

4.6 Discussion

My research journey started with an approach to improve the haptics of VR experiences. Current VR systems are capable of telepresence and creating the feeling of being in a distant world. However, haptic feedback is needed to give a more substantial physicality to the virtual world, therefore strengthening the acceptance and perceived realness of the virtual world. A lack of adequate haptic feedback can break the illusion when interacting with the virtual world. Having full control over every aspect of what is presented to the user is essential to create comprehensive virtual experiences. All these aspects such as haptic feedback should be considered as tools that are available for the people creating the experiences. In scenarios where an accurate and lifelike response and behaviour are needed, having the tools to create realistic environments, be it visual, auditory, or haptic, is essential. In training scenarios, the user can practice and train without being in danger while still perceiving an urgency and threat of danger. This needed so that the practiced procedures can be transported and applied in real-life scenarios. Currently, it is unclear how much realism is necessary to achieve the same behaviour and user reactions as in real-life scenarios. Future research needs to explore what level of realism is real enough and in what ways the level affects the users perception and behaviour.

However, I especially am interested in what comes after we reach a fully replicated reality in VR (simulation). What are experiences that are not possible in real life and are unique to VR (simulacra)? While formulating the RQ1 - "How can VR evolve from simulation to simulacra?" it was clear that answering this open question is beyond the scope of a single PhD thesis and is a mere gaze into the far future of a new medium. To explore RQ1 I formulated RQ2 - "How can we formalise operationalise the understanding of the theoretical design of perception in VR". I presented examples where haptic and auditive elements are not only used to increase the level of replication itself but can be used to intentionally alter the perception and behaviour of the user. This bridges the gap between mere replication and creates tools to further explore VR as a combination of simulation and simulacrum. A step further towards a simulacrum is presented in the form of the Perspective Continuum, which is an experience only possible in VR and not in any other medium or real life.

To reach the next level of VR HCI and engineers need to understand the possibilities offered by VR as a simulacrum. To reach the true spheres of beyond reality it is essential to further develop the tools and understanding to create such experiences. While this bridges the gap artists might be needed to explore the medium itself and see what is beyond.

4.7 A Note on Responsibility and Ethical Implications

> *"Thou art strong human, surely thine kind are more than pure Dark."*
>
> Dark Souls - Hidetaka Miyazaki

The basis for VR is an illusion, a world that is commonly not created by the user itself. Therefore, the perception of the world and oneself is controlled by a creator or designer of the medium. Like with every other medium, this can influence the person exposed to the medium on many levels.

It is important to note that VR might offer a higher potential to affect users in the long term or in more intensive ways. Therefore, designers should consider the ethics of changing or manipulating the perception, be it self-perception or any other form. From my personal experience with current setups, users mentally quickly return to the real world when taking off the HMD, and the illusions disappear instantly.

On the other hand, it is important to note that often people consider VR a step toward a dystopian world, at the same time frowning upon the idea that our reality already is a *matrix*. While the simulation hypothesis might not be proveable, the insights discussed in this thesis might give new interesting discussion points about our perception.

Simulation vs. simulacra is one of my main points of discussion. I want to note that it is currently unclear to me if being exposed to a simulacrum makes it clearer to distinguish the virtual world from real life or if the users could get "lost" in what they experience. Ideally, the knowledge gathered through this thesis can help understand perception and human interpretation of reality. Yet, given the implications of VR on perception, the role of VR designers is crucial. Not only must they consider aesthetics and usability, but they also need to be aware of VR's potential psychological effects. The boundary between virtual and real can become blurred, placing designers in a unique position to influence an individual's understanding of reality. Thus, it is our responsibility as designers and researchers to create VR experiences that are ethical and mindful of a user's well-being.

V

Publications

Chapter 5

Publications

5.1 Selected Publications and Contribution Statements

In the paper *"There Is No First- or Third-Person View in Virtual Reality: Understanding the Perspective Continuum"* [P9], we show the existence of a perspective continuum in VR. Instead of the classification of perspectives in traditional desktop games (first-person perspective and third-person perspective). We further propose how this perspective continuum can be used to design experiences based on shifts of self-perception. The paper is a research example of going beyond replicating reality in VR, but rather offering something unique to and only possible in VR. **My contribution to this paper is the concept development and conceptualisation of the theory and prototype implementation. Further, I was responsible for the planning and organisation of the project, review of related work, and contributed to the implementation of the system. As the main author I took over publication duties and coordinated the manuscript, the critical review, and the preparation of the final manuscript. This included the design of the experiment, data collection, data analysis, and analysis interpretation and discussion.**

A Human Touch: Social Touch Increases the Perceived Human-likeness of Agents in Virtual Reality [P18] explores how the perceived "human-likeness" of a computer-controlled character (agent) can be manipulated to appear more like a human-controlled character (avatar) by inducing a simple haptic stimulation. The illusion of an agent being accepted as a human being is an integral part of most virtual environments. The appearance of others often lies within oneself and the interpretation of elements such as visuals, movement, and reactive behaviour of others. While overall, the "human-likeness" of virtual characters improves, agents are still easily identified after interacting with them for a short period. Closing this gap towards agents that are perceived as human is complex and expensive as it involves motion and voice capturing and the creation of routines for all possible scenarios. However, pointedly placed simple touch events can help to blur the boundary between agent and avatar by making use of the theoretical concept of social touch. **My contributions to this paper are the concept development and conceptualisation of the theory and prototype implementation. Further, I was responsible for the planning and organisation of the project, review of related work, and contributed to the implementation of the system. As the main author I took over publication duties and coordinated the manuscript, the critical review, and the preparation of the final manuscript. This included the design of the experiment, data collection, and analysis interpretation and discussion.**

VRsneaky: Increasing Presence in VR Through Gait-Aware Auditory Feedback shows how multimodal feedback can improve and change the user's experience in virtual worlds. With a shoe-based system that detects the user's footsteps, gait, and pressure, we presented the user with different forms of stepping sounds based on their gait and movement. While stepping sounds increase the user's sense of presence, VRsneaky also changes the user's walking behaviour in the form of gait, stride length, and number of steps taken. Therefore, allowing the creator of virtual reality experiences to impact the user's behaviour via simple elements such as stepping sounds and giving the user a better impression of their impact on the virtual world. **My contribution to this paper is the concept development and conceptualisation of the theory and prototype implementation. Further, I was responsible for the planning and organisation of the project, review of related work, and contributed to the implementation of the system. As the main author I took over publication duties and coordinated the manuscript, the critical review, and the preparation of the final manuscript. This included the design of the experiment, data collection, and analysis interpretation and discussion.**

In the paper *Odin's Helmet: A Head-Worn Haptic Feedback Device to Simulate G-Forces on the Human Body in Virtual Reality* [P17] we presented a prototype to actuate the user's head with a propeller driven helmet. This actuation allows to control the user's head tilt and, e.g., represent virtual forces such as acceleration or haptic feedback. **My contribution to this paper is the concept development and conceptualisation of the theory and prototype implementation. Further, I was responsible for the planing and organisation of the project, review of related work, and contributed to the implementation of the system. As the main author I took over publication duties and coordinated the manuscript, the critical review, and the preparation of the final manuscript. This included the design of the data recording, and data interpretation and discussion.**

In the paper *VRHapticDrones: Providing Haptics in Virtual Reality through Quadcopters* [P15], we presented a novel concept of using quadcopters (commonly referred to as drones) to provide hands-free haptic feedback in virtual reality. We developed a concept and implemented a unique and complex system of off-the-shelf components. The system automatically places the touchable surface of a drone at the location of a virtual object the user wants to touch. Combined with 3D hand tracking, this allows for a hands-free interaction and tactile exploration of virtual objects. **My contribution to this paper is the concept development and conceptualisation of the theory and prototype implementation. Further, I was responsible for the planning and organisation of the project, review of related work, and contributed to the implementation of the system. As the main author I took**

over publication duties and coordinated the manuscript, the critical review, and the preparation of the final manuscript. This included the design of the experiment, data collection, data analysis, and analysis interpretation and discussion.

DronOS: A Flexible Open-Source Prototyping Framework for Interactive Drone Routines [P11] is a framework consisting of multiple components that enable researchers to create drone routines and utilise DIY-drones in research projects. While this framework was built as a basis for our own research projects, we published the framework and components such as 3D files for drone elements. As a community-driven drone framework, DronOS can help to kickstart researchers with building and automating their own drones with indoor tracking systems. **My contribution to this paper is the concept development and conceptualisation of the theory and prototype implementation. Further, I was responsible for the planning and organisation of the project, review of related work, and contributed to the implementation of the system. As the main author I took over publication duties and coordinated the manuscript, the critical review, and the preparation of the final manuscript. This included the design of the experiment, data collection, and analysis interpretation and discussion.**

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VII

APPENDIX

Table 5.1: Overview of examples given for comparing VR to the medium of games. In order of mentioning. Release Year refers to first global release.

Game Title	Year of Release	Reference
Tennis for Two	1958	https://en.wikipedia.org/wiki/Tennis_for_Two
Pong	1972	https://en.wikipedia.org/wiki/Pong
Space Invaders	1978	https://en.wikipedia.org/wiki/Space_Invaders
Asteroids	1979	https://en.wikipedia.org/wiki/Asteroids_(video_game)
Super Mario Bros.	1985	https://en.wikipedia.org/wiki/Super_Mario_Bros.
Commander Keen	1990	https://en.wikipedia.org/wiki/Commander_Keen
The Secret of Monkey Island	1990	https://en.wikipedia.org/wiki/The_Secret_of_Monkey_Island
Doom	1993	https://en.wikipedia.org/wiki/Doom_(1993_video_game)
Final Fantasy 7	1997	https://en.wikipedia.org/wiki/Final_Fantasy_VII
Metal Gear Solid	1998	https://en.wikipedia.org/wiki/Metal_Gear_Solid_(1998_video_game)
Braid	2008	https://en.wikipedia.org/wiki/Braid_(video_game)
Dark Souls	2011	https://en.wikipedia.org/wiki/Dark_Souls_(video_game)
Journey	2012	https://en.wikipedia.org/wiki/Journey_(2012_video_game)
The Stanley Parable	2013	https://en.wikipedia.org/wiki/The_Stanley_Parable
Dactyl Nightmare (VR)	1991	https://en.wikipedia.org/wiki/Virtuality_(product)

Eidesstattliche Versicherung

(Siehe Promotionsordnung vom 12.07.11, § 8, Abs. 2 Pkt. 5)

Hiermit erkläre ich an Eides statt, dass die Dissertation von mir selbstständig und ohne unerlaubte Beihilfe angefertigt wurde.

München, den 31.10.2023

Matthias Hoppe