OVERCOMING CHALLENGES OF CONTROLLER-BASED AND FREE-HANDED INTERACTION IN CROSS-REALITY

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During my pursuit of an academic title,
I realized that only one “title” truly matters
- being a *father*.

Dedicated to my beloved wife Nacera and daughter Alica Nailah.

ABSTRACT

With the new technology of cross reality (XR or extended reality), an umbrella term for virtual, augmented, and mixed reality, countless new forms of interaction arise, which seemed impossible in the past. To manipulate virtual content and transfer actions from the physical to the virtual world, we apply sensors that observe these actions and interfaces that interpret them into input commands. Since our hands are evolutionary our most powerful and versatile tools, it is no surprise that analog to the establishment of mice and joysticks for personal computers, hand-held controllers have become the state-of-the-art input device of commercial virtual reality (VR) systems.
With increasing tracking precision and the integration of haptic feedback, XR controllers are constantly growing in their interaction fidelity. However, as with any hand-held device, XR controllers have limitations such as additional weight and a static form-factor. Specifically, in virtual reality, where scenarios involve empty-handed interaction or holding different tools that do not necessarily fit the form factor of the current controller, the mismatch between visual representation and haptic feedback can break the feeling of presence, i.e., reduce the feeling of being there. Furthermore, some users are physically or cognitively unable to use state-of-the-art VR controllers and have no or very limited alternative forms of interaction.

With increasing technical possibilities of tracking, free-handed interaction also finds its way into modern XR systems. This change presents developers with the challenge of choosing between the two types of interaction or integrating both as options, as is the case with the Oculus Quest 2. When deciding between the interaction types, it is important to weigh the respective drawbacks, such as technical or human limitations.

This dissertation explores the open questions of both interaction types, focusing on three essential interactions: selection, travel, and haptic feedback.
The dissertation consists of seven case studies, each addressing one of these three interactions.
To address the inaccuracy and fatigue of gesture-based mid-air selection, indirect selection on a smartwatch was investigated. The resulting contact surface increased selection accuracy even for small targets. The spatial disturbance of a controller caused by a button press, also called the Heisenberg effect, was investigated in detail in another case study. It exposed characteristics of the Heisenberg effect

and evaluated compensation strategies that offset its influence on selection accuracy.
To combine free-handed teleportation with the immersion of physical motion, physical jumps were investigated as a travel technique in *JumpVR*. The virtually scaled jumps increased the sense of presence and, due to their hyper-realistic nature, may be a valuable extension of existing travel techniques as a special component, e.g., a special ability. Another case study examined discrete rotations at fixed intervals to prevent simulator sickness and disorientation during controller-based rotation and teleportation. This was the first time the influence of the concrete angle during discrete rotation on simulator sickness and disorientation was measured.
To provide haptic feedback in the form of inertial forces, flywheels were attached to an HMD in *GyroVR* and rotated at high speeds. The resulting drag force could be used in combination with visual effects to increase user presence successfully. To leverage the contact area between an HMD and users' faces for haptic feedback, *Face/On* embedded actuators in the face cushion of a head-mounted display (HMD). Through complex feedback patterns and synergies between different types of actuators, user presence could be increased.

The goal of this dissertation is to assist in the decision processes between controller-based and free-handed interaction in XR, and to offer a basis for subsequent research by providing own solutions to the open questions in these areas.

ZUSAMMENFASSUNG

Mit der neuen Technologie der Cross Reality (XR oder Extended Reality), einem Überbegriff für virtuelle, erweiterte und gemischte Realität, entstehen unzählige neue Formen der Interaktion, die in der Vergangenheit unmöglich schienen. Um virtuelle Inhalte zu manipulieren und Handlungen von der physischen in die virtuelle Welt zu übertragen, setzen wir Sensoren ein, die diese Handlungen beobachten, und Schnittstellen, die sie in Eingabebefehle interpretieren. Da unsere Hände evolutionär gesehen unsere mächtigsten und vielseitigsten Werkzeuge sind, ist es nicht verwunderlich, dass analog zur Etablierung von Mäusen und Joysticks für Personal Computer, Handcontroller zum State-of-the-Art-Eingabegerät kommerzieller Systeme für virtuelle Realität (VR) geworden sind.
Mit zunehmender Tracking-Präzision und der Integration von haptischem Feedback werden XR-Controller in ihrer Interaktionstreue immer besser. Wie bei jedem handgehaltenen Gerät gibt es jedoch auch bei XR-Controllern Einschränkungen wie zusätzliches Gewicht und einen statischen Formfaktor. Insbesondere in der virtuellen Realität,

wo Szenarien freihändige Interaktion oder das Halten verschiedener Werkzeuge beinhalten, die nicht unbedingt in den Formfaktor des aktuellen Controllers passen, kann die Nichtübereinstimmung zwischen visueller Darstellung und haptischem Feedback das Gefühl der Präsenz brechen, d.h. das Gefühl des Vor-Ort-Seins reduzieren. Darüber hinaus sind einige Nutzer physisch oder kognitiv nicht in der Lage, moderne VR-Controller zu nutzen und haben keine oder nur sehr eingeschränkte alternative Interaktionsmöglichkeiten.

Mit zunehmenden technischen Möglichkeiten des Trackings hält auch die freihändige Interaktion Einzug in moderne XR-Systeme. Dieser Wandel stellt Entwickler vor die Herausforderung, sich zwischen den beiden Interaktionsarten zu entscheiden oder beide als Option zu integrieren, wie es bei der Oculus Quest 2 der Fall ist. Bei der Entscheidung zwischen den Interaktionsarten ist es wichtig, die jeweiligen Nachteile, wie technische oder menschliche Einschränkungen, abzuwägen.

Diese Dissertation untersucht die offenen Fragen beider Interaktionsarten und konzentriert sich dabei auf drei wesentliche Interaktionen: Selektion, Fortbewegung und haptisches Feedback.
Die Dissertation besteht aus sieben Fallstudien, die sich jeweils mit einer dieser drei Interaktionen befassen.
Um die Ungenauigkeit und Ermüdung der gestenbasierten Mid-Air-Selektion zu adressieren, wurde die indirekte Selektion auf einer Smartwatch untersucht. Die resultierende Kontaktfläche erhöhte die Genauigkeit auch bei kleinen Zielen. Die räumliche Störung eines Controllers durch einen Tastendruck, auch Heisenberg Effekt genannt, wurde in einer weiteren Fallstudie detailliert untersucht. Dabei wurden Charakteristika des Heisenberg Effekts aufgedeckt und Kompensationsstrategien bewertet, die dessen Einfluss auf die Selektionsgenauigkeit ausgleichen.
Um die freihändige Teleportation mit der Immersion der physischen Bewegung zu kombinieren, wurden physische Sprünge als Fortbewegungstechnik in *JumpVR* untersucht. Die virtuell skalierten Sprünge steigerten das Gefühl der Präsenz und können aufgrund ihrer hyperrealistischen Beschaffenheit eine wertvolle Erweiterung bestehender Fortbewegungstechniken sein, z.B. als Spezialfähigkeit. Eine weitere Fallstudie untersuchte diskrete Rotationen in festen Intervallen, um Simulatorkrankheit und Desorientierung während der controllerbasierten Rotation und Teleportation zu verhindern. Hier wurde zum ersten Mal der Einfluss des konkreten Winkels während einer diskreten Rotation auf Simulatorkrankheit und Desorientierung gemessen.
Um haptisches Feedback in Form von Trägheitskräften zu erzeugen, wurden Schwungräder an einem HMD in *GyroVR* angebracht und mit hohen Geschwindigkeiten gedreht. Die daraus resultierende Wi-

derstandskraft konnte in Kombination mit visuellen Effekten genutzt werden, um die Benutzerpräsenz erfolgreich zu erhöhen. Um die Kontaktfläche zwischen einem HMD und den Gesichtern der Benutzer für haptisches Feedback zu nutzen, bettete *Face/On* Aktuatoren in das Gesichtspolster eines HMDs ein. Durch komplexe Feedback-Muster und Synergien zwischen verschiedenen Arten von Aktuatoren konnte die Benutzerpräsenz erhöht werden.

Das Ziel dieser Dissertation ist es, eine Hilfestellung bei den Entscheidungsprozessen zwischen controllerbasierter und freihändiger Interaktion in XR zu liefern und durch eigene Lösungen zu den offenen Fragen in diesen Bereichen eine Grundlage für nachfolgende Forschung zu schaffen.

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ACRONYMS

VR Virtual Reality

AR Augmented Reality

VE Virtual Environment

XR Cross Reality

HMD Head-Mounted Display

DOF Degrees of Freedom

FOV Field of View

IADL Instrumental Activity of Daily Living

LIST OF PUBLICATIONS

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

[W1] J. Gugenheimer, D. Wolf, E. R. Eiriksson, P. Maes, and E. Rukzio. "GyroVR: Simulating Inertia in Virtual Reality Using Head Worn Flywheels." In: *Proceedings of the 29th Annual Symposium on User Interface Software and Technology*. UIST '16. Tokyo, Japan: Association for Computing Machinery, 2016, 227–232. ISBN: 978-1-4503-4189-9. DOI: 10.1145/2984511.2984535.

[W2] D. Wolf, D. Besserer, K. Sejunaite, A. Schuler, M. Riepe, and E. Rukzio. "CARe: An Augmented Reality Support System for Geriatric Inpatients with Mild Cognitive Impairment." In: *Proceedings of the 18th International Conference on Mobile and Ubiquitous Multimedia*. MUM '19. Pisa, Italy: Association for Computing Machinery, 2019. ISBN: 978-1-4503-7624-2. DOI: 10.1145/3365610.3365612.

[W3] D. Wolf, J. J. Dudley, and P. O. Kristensson. "Performance Envelopes of in-Air Direct and Smartwatch Indirect Control for Head-Mounted Augmented Reality." In: *2018 IEEE Conference on Virtual Reality and 3D User Interfaces*. IEEE VR '18. Reutlingen, Germany: IEEE, 2018, pp. 347–354. DOI: 10.1109/VR.2018.8448289.

[W4] D. Wolf, J. Gugenheimer, M. Combosch, and E. Rukzio. "Understanding the Heisenberg Effect of Spatial Interaction: A Selection Induced Error for Spatially Tracked Input Devices." In: *Proceedings of the 2020 CHI Conference on Human Factors in Computing Systems*. CHI '20. Honolulu, HI, USA: Association for Computing Machinery, 2020, 1–10. ISBN: 978-1-4503-6708-0. DOI: 10.1145/3313831.3376876.

[W5] D. Wolf, M. Rietzler, L. Bottner, and E. Rukzio. *Augmenting Teleportation in Virtual Reality With Discrete Rotation Angles*. 2021. arXiv: 2106.04257 [cs.HC].

[W6] D. Wolf, M. Rietzler, L. Hnatek, and E. Rukzio. "Face/On: Multi-Modal Haptic Feedback for Head-Mounted Displays in Virtual Reality." In: *IEEE Transactions on Visualization and Computer Graphics*. TVCG 25.11 (2019), pp. 3169–3177. DOI: 10.1109/TVCG.2019.2932215.

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[W8] A. Colley, D. Wolf, K. Kammerer, E. Rukzio, and J. Häkkilä. "Exploring the Performance of Graphically Designed AR Markers." In: *19th International Conference on Mobile and Ubiquitous Multimedia*. MUM 2020. Essen, Germany: Association for Computing Machinery, 2020, 317–319. ISBN: 978-1-4503-8870-2. DOI: 10.1145/3428361.3432076. URL: https://doi.org/10.1145/3428361.3432076.

[W9] J. Gugenheimer, F. Honold, D. Wolf, F. Schüssel, J. Seifert, M. Weber, and E. Rukzio. "How companion-technology can enhance a multi-screen television experience: a test bed for adaptive multimodal interaction in domestic environments." In: *KI-Künstliche Intelligenz* 30.1 (2016), pp. 37–44. DOI: 10.1007/s13218-015-0395-7.

[W10] J. Gugenheimer, C. Winkler, D. Wolf, and E. Rukzio. "Interaction with Adaptive and Ubiquitous User Interfaces." In: *Companion Technology*. Springer, 2017, pp. 209–229. DOI: 10.1007/978-3-319-43665-4_11.

[W11] S. Karaosmanoglu, K. Rogers, D. Wolf, E. Rukzio, F. Steinicke, and L. E. Nacke. "Feels like Team Spirit: Biometric and Strategic Interdependence in Asymmetric Multiplayer VR Games." In: *Proceedings of the 2021 CHI Conference on Human Factors in Computing Systems*. CHI '21. Yokohama, Japan: Association for Computing Machinery, 2021. DOI: 10.1145/3411764.3445492.

[W12] D. Wolf, D. Besserer, K. Sejunaite, M. Riepe, and E. Rukzio. "CARe: An Augmented Reality Support System for Dementia Patients." In: *The 31st Annual ACM Symposium on User Interface Software and Technology Adjunct Proceedings*. UIST '18 Adjunct. Berlin, Germany: Association for Computing Machinery, 2018, 42–44. ISBN: 978-1-4503-5949-8. DOI: 10.1145/3266037.3266095.

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[W15] D. Wolf, T. Wagner, and E. Rukzio. “Low-Cost Real-Time Mental Load Adaptation for Augmented Reality Instructions - A Feasibility Study.” In: *2019 IEEE International Symposium on Mixed and Augmented Reality Adjunct (ISMAR-Adjunct)*. 2019, pp. 1–3. DOI: 10.1109/ISMAR-Adjunct.2019.00015.

Part I

INTERACTION IN CROSS REALITY

1 INTRODUCTION

1.1 THE EVOLUTION OF XR HMDS

The form factor of computers changed drastically from large mainframe computers in the late '50s to the first laptops in the '80s. Apart from the weight and size, one key change was integrating input and output capabilities that were initially only available via peripheral devices such as external monitors and keyboards. Even today, where tablets and laptops vastly outperform their mainframe predecessors, there is still a *raison d'être* for peripheral devices. Sometimes users are willing to compromise the compact form factor and portability of their laptop or tablet to benefit from a peripheral device's capabilities. Touchpads, for instance, are versatile input devices for everyday tasks but are inferior to a computer mouse in most 2D interactions [142]. However, a stylus can outperform a mouse for radial dragging [40] and path tracing [189]. Similarly, special use cases such as gaming might require better-suited special-purpose input/output devices, e.g., joysticks or game-controllers. In addition to a form factor that matches in-game objects (e.g., the airplane stick in a flying simulator), most of these devices incorporate haptic feedback, which increases enjoyment during gameplay [154].

XR HMDs went through a similar development. Ivan Sutherland's "Sword of Damocles", the first VR HMD developed in 1968 [163], evolved from a static and experimental VR setup to a more portable and consumer-ready Oculus Rift VR HMD in 2016 [1]. This HMD setup included external optical sensors for spatial tracking and two handheld controllers that incorporated buttons and vibrotactile feedback. In the same year, Playstation [2] and HTC Vive [3] followed with their VR HMDs that had a similar tracking and interaction design. User studies could show that user enjoyment increased in VR compared to traditional monitor-based gaming [143] and VR controllers offer superior locomotion techniques compared to traditional game controllers [56]. Despite the rich input and output capabilities of the above mentioned VR setups, Samsung and Google released controllerless smartphone-powered VR HMDs in 2015 controlled via a button [4] or a touchpad [5] on the HMD's side, allowing free-handed interac-

1 https://www.oculus.com/rift
2 https://www.playstation.com/de-de/explore/playstation-vr/
3 https://www.vive.com/de/product/vive/
4 https://arvr.google.com/cardboard/
5 https://www.samsung.com/de/wearables/gear-vr-r323/

tion while saving the costs for controller hardware. Although both HMDs were thereby limited in their input and output capabilities, they inspired a wide range of controller-less HMDs with their own user base. This development raises the question of why users would give up controllers in the first place.

1.2 REASONS FOR FREE-HANDED INTERACTION

1.2.1 *Comfort and Mismatch of Feedback*

In some cases, the decision not to use a controller is a question of user preference. While some VR applications feature a gun that needs to be hand-held by the user, holstering a weapon is only possible in the virtual world since the controller does not leave the user's hand. This conflicting haptic sensation could disrupt the feeling of "being there," a standard definition for presence in VEs [185]. Furthermore, the haptic sensation of grabbing an object does not vary due to the static form factor of a controller, requiring a simulation via vibrotactile feedback. This mismatch of feedback and the desire to have a free-handed experience could have inspired a new generation of VR systems such as the Valve Index [6]. These systems feature controllers with a strap that users can attach to their hands. Although the fingers can now be released to let go of an object virtually, the controller's weight is still limiting the free-handed experience. In contrast, there is an effort to integrate a hand-tracking feature into XR HMDs (e.g., Oculus Quest 2 [7]) to enable a fully free-handed interaction. While this approach solves the issue of feeling constant haptic feedback and weight, it cannot provide any haptic feedback relying solely on the visual and auditive channel.

1.2.2 *Health-Related Issues*

Sometimes using a controller in combination with an HMD is not possible due to physical or cognitive impairments of the target group. To support geriatric patients with cognitive impairment with the task of cooking, we developed a framework for the Microsoft Hololens augmented reality (AR) HMD. The framework guided patients between cooking instructions and their respective locations via smart visual indicators [W2]. The framework required a manual confirmation of each completed instruction step by the patient. The state-of-the-art confirmation technique for the Hololens is the air tap gesture, a gesture where the thumb and index finger have to touch within the HMD's optical tracking space. We applied this gesture for the framework setup performed by the caregiver, but the physical exer-

6 https://store.steampowered.com/valveindex/
7 https://www.oculus.com/quest-2/

tion and cognitive load were considered not befitting the vulnerable target group. Holding the Hololens clicker, a wireless hand-held controller with a button and gyroscope was impractical since patients required both hands for the cooking task. Picking it up for each confirmation was cognitively demanding since most patients had impairments affecting spatial and temporal memory.

Our instructions' sequential nature allowed us to realize simple navigation back and forth between instructions with speech input. A more complex framework would require a more extensive dictionary of commands, which would not have been feasible with this target group. This example shows that free-handed interaction can be necessary in some cases, but meaningful alternative interaction forms are missing.

The apparent need for free-handed alternatives for controller-based interaction is the main inspiration for this dissertation. It attempts to answer where the drawbacks of controller-based and free-handed interaction lie and how these drawbacks can be balanced.

2 BASICS OF INTERACTION IN CROSS REALITY

2.1 CROSS REALITY AND ITS APPLICATION

With the introduction of virtual, augmented, and mixed reality, the boundaries between physical reality and virtual worlds seem to blend. Even Milgram and Kishino, authors of the well-known taxonomy of mixed reality, admit that "an attempt to distinguish these classes [...] leads to quite different groupings among [them]" [109, p. 2]. However, whether the virtual content overlays the real-world (augmented reality), integrates it partially into the virtual experience (augmented virtuality), or shuts off the user from the real world altogether (virtual environment), there is always a need to interact with the virtual content. The form of interaction can be highly context- and technology-specific. An assembly worker or surgeon that is supported by augmented reality during a bimanual task might require free-handed interaction via head gestures or speech to continue working, while players in an immersive VR environment want to feel the controller's weight as a substitute for a virtual object in their hands. Since the focus of this dissertation is on interaction with all realities, it will not discriminate between augmented reality (AR), augmented virtuality (AV), and virtual reality (VR) unless necessary and refer to them as cross reality (XR) according to the definition of Paradiso and Landay [115]. In the following, we will discuss how the interaction in XR can be classified and implemented for controller-based and free-handed interaction.

2.2 BASIC INTERACTIONS IN XR INTERFACES

Since XR presents users with virtual content, some characteristics of interaction in virtual environments (VEs) can be transferred to the interaction in XR. Following the definition by Bowman and Hodges, most interactions in VEs fall into the three categories *selection*, *manipulation*, and *travel* [6]. Given that the research area for each of these categories is vast and discussing all of them would overextend this dissertation's scope, the focus had to be limited. As "[m]anipulation requires a selection technique, but the converse is not always true" [6, p. 46], manipulation was not considered in this dissertation but should definitely be examined in future work. Thus, the following section will discuss the remaining interaction categories *selection* and *travel*. Since interaction always includes an output component, *haptic feedback* is discussed as a third category.

2.2.1 *Selection*

According to Bowman and Hodges's taxonomy, the task of selection is composed of the building blocks *feedback*, *indication of object*, and *indication to select* [6].

Feedback is required before, during, and after the selection process. It includes the presentation of the target, the current pointing position (e.g., during a virtual ray-cast [124]) and a confirmation of the selection via visual, auditive, or haptic output [6].

Indication of Object is important to indicate which object or target is to be selected. From the physical world, we are used to manipulating things directly with our hands. Techniques that emulate this behavior in XR, i.e., apply a 1-to-1 mapping of the user's movement into the virtual world, are called isomorphic. Since isomorphic mapping would limit the user's reach to an arm's length, Stoakley et al. suggest inventing tailored interaction techniques for VEs, so called nonisomorphic techniques [161]. While nonisomorphic techniques are very distinct from real-world interaction metaphors (e.g., extending the user's hand [124]), they achieve a similar or even higher performance and usability than isomorphic techniques and make up the majority of interaction techniques for VEs [6].

Indication to select refers to the act of confirming a selection via voice, button, gesture, or no explicit command [6]. Gesture and voice commands are the state-of-the-art interaction techniques of the Microsoft AR HMD Hololens. Here, targets are indicated via gaze cursor and selected via a spoken command or an air tap gesture. Additionally, a Bluetooth-connected clicker can confirm selections via button press, which is also the most common confirmation technique for VR systems.

According to Bowman and Hodges, selection techniques should aim to optimize speed, accuracy and user comfort [6].

2.2.2 *Travel*

Travel is the movement component of the navigation task and is considered the "most ubiquitous VE interaction" [6, p. 44]. The importance of travel for virtual environments is beautifully summarized by Bowman et al. [24, p. 45]:

> "Travel, by which we mean the control of user viewpoint motion through a VE, is an important and universal user interface task which needs to be better understood and implemented in order to maximize users' comfort and productivity in VE systems."

In their taxonomy, Bowman and Hodges decompose travel into the task of *direction/target selection*, *velocity/acceleration selection*, and *input conditions* [6]. Next to the selection metrics speed, accuracy, and user comfort described above, all travel techniques should focus on increasing subjective measures such as the feeling of presence and spatial awareness [6], while keeping simulator sickness low. In order to explain their taxonomy, it will be applied to teleportation, which is an example for state-of-the-art VR travel techniques (e.g., [27]).

Direction/target selection is the act of indicating a travel target (e.g., an object or position in the VE) or the travel direction (e.g., via gaze, 2D or 3D pointing). Depending on the implementation, teleportation targets are either restricted via predefined positions (i.e., fixpoint teleportation [56]) or free to choose by pointing at any valid position within the VE.

Velocity/acceleration selection describes how the speed and acceleration of a travel technique is selected. The naming is unfortunate, since velocity consists of a speed and direction component by definition, although the latter has already been defined by the previous task. Acceleration is most relevant for travel techniques with continuous movement since it can impact the sense of self-movement (vection) and therefore induce simulator sickness [133]. Most implementations of teleportation have a predefined speed or transport the user instantaneously, avoiding the effect mentioned above but introducing potential disorientation due to the loss of reference frames [112].

Input conditions describe how travel is initiated and include constant travel where no input is required, continuous input, e.g., holding a button to travel, explicit start and stop, and automatic start and stop. Teleportation requires an explicit start and stop. The usual implementation consists of three stages: a button-press to initiate the technique, ray-casting to select a target, and confirmation of the teleportation by releasing the button.

2.2.3 *Haptic Feedback*

Feedback is required to close the interaction loop between a user and a system [174]. In XR interfaces, literature generally distinguishes between selection feedback, which includes feedback during the indication of an object or after the indication to select (e.g., a button press) [6] and ambient feedback of the environment (e.g., [129]). Current VR systems are mostly limited to haptic selection feedback via vibrotactile actuators in handheld controllers. This state-of-the-art is not surprising since the sense of touch is "an ideal channel of interaction with handheld devices" [123, p. 52]. Several user experiments confirmed the importance of haptic feedback for VEs [29, 30]. A possible division of tactual sensory information into classes is tactile and kinesthetic information [152]. Tactile information describes the surface properties such as geometry, temperature, slippage, and smoothness, while kinesthetic or force-feedback includes object hardness, weight, and inertia [30].

2.3 CONTROLLER-BASED INTERACTION

Controller-based interaction requires a hand-held input device, which can optionally offer output capabilities. According to Laviola et al., input devices can be categorized by various characteristics, such as their hardware components or the interaction required to perform an input [93]. To demonstrate the various characteristics that can be applied to categorize an input device, some of them will be applied to the HTC Vive controller, which is a representative example of state-of-the-art XR controllers.

Control dimensions or degrees-of-freedom (DOF) for input devices describe the number of manipulable positional (i.e., x, y, and z) and rotational (i.e., pitch, roll, and yaw) directions. The amount of dimensions that can be manipulated simultaneously in one movement is the integration of control dimensions. By this definition, the Vive controller is a 6-DOF integrated controller [145].

The input type and the frequency of the values generated can classify the individual components of an input device, i.e., whether the data is continuous (i.e., real-value) or discrete (e.g., a Boolean). The spatial tracking data generated by the optical and inertial sensors of the Vive controller is continuous [1]. The Vive controller buttons are discrete except for the trigger button, which generates continuous values for the press value up to the click moment, which is a discrete value. Similarly, the touchpad generates continuous values upon touch and

1 It is to be mentioned here that the combination of both tracking types is classified as a hybrid-tracker [93].

discrete values upon click.

Furthermore, the generated values can be absolute or relative, i.e., calculating the difference to a previous input. Both the touch positions on the touchpad and the spatial data within the Vive coordinate system are absolute.

Another characteristic is the physical interaction required. Active components always require user input to generate data, while passive components generate data without any user input. The latter are also referred to as monitoring devices [144]. The Vive controller buttons are purely active, while the spatial tracking component is purely passive.

The intended use of an input device can be an additional characteristic, including locators (i.e., position and orientation), valuators (i.e., real number values) and choice (i.e., selecting an element from a set). While the Vive controller is a locator and valuator in hardware, a common usage of the touchpad in many VR applications is the visualization of a pie menu directly on the touchpad, converting its intended use to 'choice.'

Lastly, input devices can be broken down into position control (e.g., a tracker) and force control (e.g., a joystick). The trigger button of a Vive controller is a force control element, since it generates trigger press values while force is being applied to it until the final click is generated. The Vive controller itself offers position control.

Due to their combination of a tracker and buttons, Laviola et al. classify VR controllers such as the Vive controller as a hand-held 3D mouse.

The numerous characteristics should illustrate how extensive and rich the input possibilities of a controller can be. These possibilities must be provided similarly for free-handed interaction in order to maintain the input capabilities. The output from most controllers, on the other hand, is limited to vibrotactile feedback. Therefore, more output options are needed for both controller-based and free-handed interaction.

2.4 FREE-HANDED INTERACTION

Due to a missing hand-held device, free-handed interaction requires alternative means for both input and output. A common implementation of free-handed input is external or bodyworn sensing. External sensing can include camera-based tracking, such as RGB cameras (e.g., [113]) or motion-capture setups (e.g., [176]). Since the interaction is not limited to hands only, all body parts can be tracked and used for input with this approach (e.g., feet [174], head [145], or whole-body [72]). Many modern HMDs such as the HTC Vive Pro include cameras that allow out-of-the-box hand tracking so that users can choose between controller-based and free-handed interaction. Other kinds of bodyworn sensors can include accelerometers (e.g., [174]), touch-enabled surfaces for on-device or on-body interaction [96] or electromyography, i.e., measuring muscle activity (e.g., [137]). Since the aim of this dissertation is to weigh up the strengths and shortcomings of controller-based and free-handed techniques, interaction modalities not represented in both categories (e.g., speech input [120] or gaze input [7]) are out of scope and will not be discussed in detail. Output generators can be grounded, e.g., robotic arms [140], or ungrounded/wearable actuators, e.g., HMD-mounted devices [119, 128]. Although there are approaches that suggest hand-held props for interaction that are technically no controllers (e.g., passive haptics [5]), these solutions do not comply with the goal of exploring unencumbered free-handed interaction and will therefore not be included. More examples of free-handed approaches and their performance compared to controller-based solutions will be discussed throughout this dissertation.

3 METHODOLOGY

Human-centered or user-centered design (UCD) is an ISO standardized process and a common approach in HCI [156]. With ideation techniques such as brainstorming and expert interviews, UCD methods were at the core of each artifact created in this dissertation's scope. These artifacts were either the main contribution or served as a platform to answer a research question by collecting user data.

As the term "user-centered" implies, the user is highly involved in the process. The main components of the iterative workflow are specifying the user context, specifying user requirements, producing design solutions to meet user requirements, and evaluating against the requirements. While research artifacts rarely achieve a consumer-ready stage, the iterative prototyping approach of UCD with its multiple evaluation cycles results in artifacts with high usability.

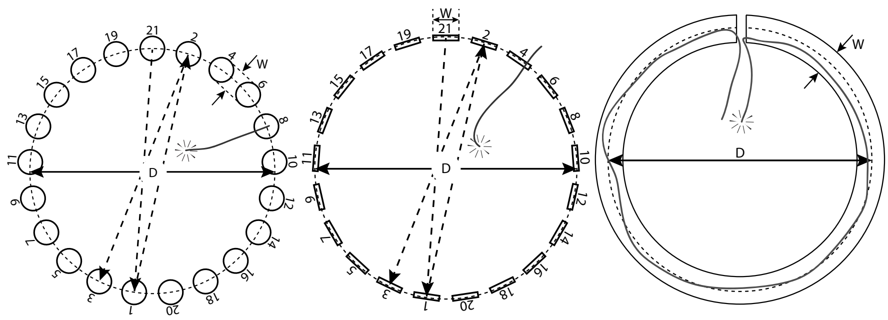
SPECIFYING USER CONTEXT [156] As a first step, the context of usage was analyzed and specified, e.g., whether the user will be in a mobile or stationary context or how many users will be interacting with the intended artifact.

SPECIFYING USER REQUIREMENTS [156] Next, gaps and challenges in existing research were identified via extensive literature research. The problem fields were afterwards discussed with experts and user groups to collect the first user and software or hardware artifact requirements. Early prototypes were then evaluated with experts and users to gather quantitative and qualitative data to further refine each cycle's requirements.

PRODUCING DESIGN SOLUTIONS [156] The collection of requirements was followed by an iterative development process of software and hardware prototypes. While all prototypes collected quantitative user data to refine the design after each evaluation cycle, the visual fidelity depended on the current research question. Task and performance-driven prototypes were visually minimalistic, providing only the necessary environment (e.g., targets for a pointing task). Prototypes evaluating user presence and immersion, two standard subjective measures for user experience in VEs [185], must be visually appealing to the user while keeping the implementation workload of VEs reasonable. Therefore, VEs either provided restricted movement (e.g., following a predefined path) or a restricted area (e.g., surrounded by a fence).

EVALUATING AGAINST REQUIREMENTS [156] The interactions in VEs explored in this dissertation fall into the categories: selection, travel, and haptic feedback. Each category has a different focus, resulting in varying evaluation methods for the respective artifacts. All artifacts were evaluated against the collected requirements in user studies, a standard approach of the UCD process.

Selection has a strong focus on usability metrics such as input precision and speed, which were quantified via error rate (i.e., percentage of missed targets) and throughput ($\frac{\text{bits}}{\text{minute}}$), two common measurements to compare input techniques and interfaces in HCI [102]. Depending on the selection task, throughput was calculated following the ISO 9241-9 standardized tapping task [155], which is derived from the well-known Fitts' Law [102] and its extensions the steering task [1] and goal crossing task [2] (see figure 1).



(a) Tapping task. (b) Goal crossing task. (c) Steering task.

Figure 1: User interface selection tasks are applied to measure an input technique or interface throughput. In general, it is calculated from the movement time while selecting targets with a range of widths (W) and distances to each other (D). (Image taken from [W3], © 2018 IEEE)

Directly measuring a haptic feedback interface's quality is difficult due to missing appropriate assessment tools for participants' subjective feelings. Therefore, it is a common approach of HCI to measure it indirectly via its impact on user presence and immersion, i.e., whether presence and immersion can be further increased when haptic feedback is present. There are various definitions for immersion ranging from purely technical [149] to the subjective feeling of "being there," which is a standard definition of presence in VEs [185], leading to an interchangeable usage of both terms in literature. Presence and immersion were measured with the well-established post-task questionnaires by Witmer and Singer (PQ) [185], Slater, Usoh, and

Steed (SUS) [147] and Lin et al. (E^2I) [98]. Additional feedback on perceived realism of the haptic feedback and general comfort was assessed via custom Likert scale items.

Travel in VEs, as discussed in chapter 2.2, should aim to increase the feeling of presence and spatial awareness. Otherwise, it can lead to user disorientation and thus to a break of immersion. Efficiency was measured as the time taken to complete a task or the score achieved within a given time frame. User comfort and immersion were measured with integrated questionnaires (i.e., questionnaires presented within the VE to maintain presence [55]), post-task questionnaires, and custom items. The general mood can be described by the affective state, measured with the self-assessment manikin (SAM) [28], a questionnaire with three pictorial items that integrates well into a VE due to the short amount of time it requires to finish. As an additional measure for user comfort and disorientation, simulator sickness was assessed via the simulator sickness questionnaire by Kennedy et al. [81]. In general, simulator sickness is a "byproduct of modern simulation technology" [81, p. 203] with symptoms such as eye strain, nausea, and disorientation. A widely-accepted theory for its origin is the sensory conflict between the visual and the vestibular system [94]. Since simulator sickness can affect the user experience, all works of this dissertation focused on keeping a low simulator sickness level or reducing it compared to the baseline.

Statistical analysis was performed with parametric and nonparametric tests depending on the data and its distribution. Questionnaire scores and parametric data were compared with Analysis of Variance (ANOVA). The Friedman ANOVA, a nonparametric alternative, was applied to Likert scale items and nonparametric data with p-value adjusted post-hoc tests such as Wilcoxon Signed Rank test or Dunn's pairwise test. Ranking scores were analyzed for concordance with Kendall's W test and correlations were tested with Pearson's r and Spearman's ρ for parametric and nonparametric data, respectively.

Part II

RELATED WORK

4 DEFICIENCIES OF CONTROLLER-BASED INTERACTION

Although controllers offer a limited possibility of haptic feedback, their current main function is user input. As already mentioned in chapter 2, this consists of selecting targets (e.g., objects) and target locations/directions. Since the controller's position and rotation are largely responsible for the accuracy of the selection of targets, a disturbance of the controller is a potential source of error that has to be taken into consideration. The selection of target locations/directions is a component of travel in VR and poses a major challenge, as this involves moving the user's field-of-view (FOV) and potentially causing simulator sickness and disorientation.

4.1 DISTURBANCE OF THE CONTROLLER

As discussed in section 2.3, a hand-held controller can have up to six degrees-of-freedom (three axes of position and three axes of rotation). A disturbance of any of these degrees can lead to selection errors. Especially with cursor-based selection techniques that rely on distal pointing at remote targets (e.g., virtual ray-casting [124]) a disturbance of the controller can lead to an even greater disturbance of the cursor. Several sources of disturbance have been identified by previous work, including jitter [14, 166] and selection-induced spatial disturbance [26].

4.1.1 *Jitter*

According to Pavlovych and Stuerzlinger, the latency and jitter of input devices are related and have a "detrimental effect on pointing performance" [117, p. 195]. Latency or lag is defined as the delay between user input and visual output [46] and can vary over time [117]. For three-dimensional pointing, even "relatively small lags can cause considerable degradation in performance if the targets are small" [179, p. 331].

Jitter is a result of hand tremor and noise in the tracking signal [117] and can affect all six degrees-of-freedom [14, 166]. When jitter values are low, latency has a "stronger effect on human performance" [166, p. 43]. However, when jitter values are high, the trade-off of introducing a small amount of latency to filter spatial jitter improves selection precision and speed [117].

Instead of filtering jitter to increase the selection precision, i.e., stabilize the controller or cursor position (e.g., [52]), improving the selection technique itself could reduce the error rate even for small targets [8, 88]. Proposed techniques include pointers that bend towards targets [159, 160], selection via a spotlight metaphor [51, 97], i.e., using a cone rather than a ray for selection, multistep selection via iterative refinement [8, 88], and direct manipulation instead of pointing [122, 161].

4.1.2 *Selection Induced Spatial Disturbance*

Following Bowman and Hodges' taxonomy for interactions in virtual environments, the task of selection requires an "indication to select" [6, p. 48], i.e., a confirmation of the selection. As discussed in chapter 2.3, XR controllers such as the HTC Vive controller offer discrete input components, i.e. components with on-off states such as buttons for selection confirmation. According to Bowman et al., discrete input on spatially tracked input devices leads to a disturbance of the controller position and rotation, the so-called "Heisenberg effect of spatial interaction" [26, p. 2]. Taking the HTC Vive controller as an example, pressing the trigger button would cause the controller to move, which in turn would offset the cursor from its intended position. While Bowman et al. suggested confirming selections with the non-pointing hand to avoid this phenomenon and the resulting displacement of the controller [26], to our best knowledge, no formal evaluation of this effect has been performed so far. Strategies found in related work for dealing with this effect are: Robust selection techniques and avoidance strategies.

Robust selection techniques have been introduced above and include improved ray-cast techniques that stick to targets [160], cone-selection [65], and direct manipulation instead of pointing [161]. While these techniques improve selection accuracy, they still need to be implemented in commercial XR experiences. The predominant selection technique, however, remains ray-casting which is highly affected by the Heisenberg effect [26].

Avoidance strategies typically involve time-shifting, i.e., going back to a cursor position before the displacement occured (e.g. [31, 86, 188]), and, as mentioned above, assigning the task of pointing and confirming to separate hands (e.g. [26, 106]).

4.2 TRAVEL IN VIRTUAL REALITY

Since augmented reality only overlays the physical world with virtual content, navigation is typically realized via physical walking. In virtual reality, however, the user is shut off from the physical world and needs techniques for navigation/locomotion. As discussed in section 2.2.2, travel is a component of navigation through virtual environments. As it involves a virtual motion and rotation of the user perspective while the corresponding physical stimulus might be absent [16], a strong focus of locomotion techniques is a low simulator sickness and disorientation and a high presence [6, 24].

Although previous work has shown the superiority of physical walking in VR over controller-based locomotion in terms of presence [148] and orientation [35], some scenarios limit or prevent physical movements such as a limited tracking space [158], a sitting body posture [12] or physical impairment [91]. Out of a wide range of available controller-based locomotion techniques, steering, i.e., a continuous movement of the user perspective (e.g., [148]) and teleportation (e.g., [27]) have emerged as the most popular techniques that are included in most interactive state-of-the-art VR experiences [21]. While each has its strength, both techniques come with limitations that users and developers have to consider.

4.2.1 *Steering*

Controller-based steering is considered easy-to-use [21] but can induce simulator sickness due to the illusion of forward-movement (i.e., vection) resulting from continuous movement [133]. To combat the resulting simulator sickness, Lin et al. explored continuous movement with varying FOV parameters [98]. They found a significant decrease in simulator sickness for reduced FOV settings. However, the downside is that a low FOV harms user presence, thereby calling for a considerate application of this approach.

Particularly controller-based rotation has been shown to cause simulator sickness [125] and disorientation [24]. While Lin et al. focused on the translation aspect of locomotion [98], Sargunam and Ragan explored the impact of VR rotation techniques on orientation and simulator sickness [141]. They compared traditional continuous rotation, continuous rotation with FOV reduction, and discrete rotation at fixed intervals, i.e., rotating the user's view by a predefined angle. No significant difference in orientation could be found, "but the results of sickness ratings found discrete rotations to be significantly better than field-of-view reduction" [141, p. 74]. Similarly, Rahimi et al. found no increase in disorientation for discrete rotations of up to 145°, while animated transitions (i.e., automated continuous rotation) led to an increase in simulator sickness [126]. However, the differences between varying rotation angles remain unclear, and no design recommendations are given.

4.2.2 *Teleportation*

Teleportation is considered "effective due to its fast navigation" [21, p. 1], but can be immersion breaking due to visual jumps and the resulting disorientation [10, 24] and loss of reference frames, i.e., visual cues of the environment [112]. Due to the selection-based nature of teleportation [93], the process of selecting a destination point is furthermore prone to be affected by the selection issues jitter and spatial disturbance described above in chapter 4.1. To remedy the effects of disorientation, commercial games such as Raw Data implement teleportation as a "dash" forward instead of instant translation in a blink [19]. In this version of teleportation, the users are presented with a blurred and distorted view of the environment, which simulates a very fast movement forward. Bhandari et al. formally explored these visual cues against state-of-the-art teleportation and found a positive impact on path integration, i.e., the estimation of the path traveled, while simulator sickness remained unchanged [19].

5 DEFICIENCIES OF FREE-HANDED INTERACTION

Without an input device, selection, travel, and haptic feedback must be implemented in an alternative way. Existing solutions and open challenges for these interactions are discussed in the following.

5.1 FATIGUE AND IMPRECISION OF MID-AIR SELECTION

In addition to technical limitations such as jitter and latency discussed in section 4.1, free-handed selection can be affected by fatigue effects [48] and the inherent imprecision of human pointing [105, 121].

5.1.1 *Fatigue*

Prolonged mid-air pointing can lead to arm fatigue or the so-called "gorilla arm" effect [59], which can impair a user's motor performance [47]. Selection techniques should therefore balance its impact on hand tremor and selection errors [17]. Reacting to high levels of fatigue would require a real-time measurement of a declining muscle force, which can be a complicated task [48] and is performed via expensive sensors [74, 194] or immersion-breaking subjective reports [22, 55]. Alternatively, fatigue can be reduced by providing a resting surface for the selecting hand. Benko and Feiner proposed a helium balloon metaphor to prevent fatigue during selection in an MR environment above a tabletop [17]. Using multi-touch gestures on the tabletop provided a resting surface for the user's hands, thereby avoiding hand jitter and fatigue. Similarly, Gugenheimer et al. proposed attaching a touchpad to the back of a VR HMD, leveraging proprioception, i.e., locating a body part in relation to the body, for increased selection precision and reducing arm fatigue due to a resting finger posture [62].

5.1.2 *Pointing Imprecision*

Indicating a target via pointing gestures is a common free-handed interaction technique that usually requires the assistance of a visual pointer due to imprecision in the underlying pointing model [121] and missing haptic feedback [34]. According to Mayer et al., human pointing inaccuracy decreases performance in virtual environments due to a systematic offset between intended pointing position and cursor [105]. This inaccuracy could be partially explained by human limitations such as hand tremors and fatigue effects [74] and techni-

cal limitations such as system jitter [117] (see chapter 4.1).
Mayer et al. propose correcting the cursor's visual representation to compensate for the inaccuracy of human pointing [105]. Their results suggest that offset correction increases accuracy for both cursor-less and cursor-based pointing. Besides, Plaumann et al. argue that cursor-less "pointing accuracy could be significantly improved by acknowledging users' handedness and ocular dominance" [121, p. 633], thereby improving the underlying pointing model.

As an alternative to distal pointing, directly touching the virtual content is advised (e.g. [44, 45]). Dudley et al. evaluated a free-handed direct interaction technique for the Microsoft HoloLens AR HMD that allowed 10-finger typing on a virtual keyboard that was presented in front of the user [45]. It was compared against the state-of-the-art selection technique for the HoloLens, which is pointing at targets with a head-cursor and confirming the selection with a finger gesture. Although typing speed was significantly increased compared to the baseline, missing haptic feedback led to difficulties in judging the cursor depth, i.e., how far the fingers are penetrating the virtual plane, an accuracy-speed tradeoff, and arm fatigue.
This finding is not surprising since haptic feedback is important to close the interaction loop [174] and due to the "lack of tactile feedback, direct-touch interaction on an intangible display may show poor performance even on the simplest of target acquisition tasks" [34, p. 2625]. Especially in AR scenarios where virtual content is not explicitly occluded by the user's hand [165], important depth cues such as shadows are missing for direct interaction with the content, requiring a visual representation of the user's hand position. However, visualizations of this kind are against the goal of AR "to minimise or eliminate the distinction between physical and virtual content from the perspective of the user" [45, p. 2].

5.2 FREE-HANDED LOCOMOTION IN VIRTUAL REALITY

As mentioned in chapter 4.2, physical walking offers numerous advantages for a feeling of presence in virtual environments but encounters spatial and technical limitations. On the other hand, teleportation has become the standard locomotion technique despite its drawbacks in presence and orientation. These two techniques are discussed below for free-handed interaction.

5.2.1 *Physical Walking*

As discussed in section 4.2, physical walking is a free-handed locomotion technique that is superior to controller-based steering in terms of presence [148, 173] and spatial awareness [35]. Its high spatial re-

quirements, however, render this technique impractical for daily usage [158]. Naive redirection techniques with curvature gain, i.e., subtly rotating the user FOV, attempt to trick users on a curved path without ever reaching the tracking space's boundaries, which allows continuous walking (e.g., [130, 158]). To keep this manipulation of the user FOV beneath the detection threshold, however, the required circular path would still exceed a typical tracking space [134]. Previous work proposed walking-in-place [148, 167, 169] and arm swinging [107] as a physical walking alternative that is not limited by a small tracking space. However, a comparison against physical walking revealed a lower spatial awareness for walk-in-place and arm-swinging [183].
Rietzler et al. propose *TeleWalk*, a redirected walking technique that applies high translational gains (i.e., virtually scaling the walked distance) to reduce the user's walking pace, while high curvature gains force users on a perfectly circular path [135]. The direction is selected via head rotation, thus preventing users from leaving the predefined path. While simulator sickness values were high, participants perceived *TeleWalk* as being more natural than teleportation. Alternatively, Williams et al. propose to freeze the users' position within the VE when they reach the boundaries, while users reorient themselves towards the center of the tracking space and still maintain their spatial awareness [182].
Similarly, Liu et al. present physical reorientation by walking through portals that appear next to the user [100]. Since users get a preview of the new orientation through the portal, their reference frame remains intact and they become less disoriented [112]. Their results show that reorientation via portals leads to fewer teleportations and more physical walking, which increases presence [173].

5.2.2 *Free-Handed Teleportation*

Although teleportation can lead to disorientation due to visual jumps, i.e., a sudden change of location [10, 112], its robustness towards simulator sickness [27] and efficiency has made it the de facto state-of-the-art locomotion technique for VR [21]. To explore a free-handed version of teleportation, Bozgeyikli et al. explored finger-pointing for selecting a teleportation destination via dwell time [27]. LaViola et al. presented a foot-controlled version of teleportation, where users could summon a world-in-miniature map at their feet by using a foot gesture and step onto the desired destination to execute teleportation [95]. While no evaluation of this approach exists yet, there is evidence from other experiments that world-in-miniature locomotion can be superior to teleportation and steering in spatial knowledge and simulator sickness [18]. Another form of controller-less teleportation is stepping through portals, as proposed by Liu et al. [100] and

Freitag et al. [53]. Both approaches apply portals to reorient users towards the center of the tracking space, reducing the number of required teleportations while increasing the distance walked physically, which increases presence [173].

A limitation of the aforementioned teleportation approaches and teleportation in general is a missing physical movement, which generates vestibular and proprioceptive feedback [16]. A lack of these essential components impedes path integration, "i.e., estimating the distance traveled, which can lead to spatial disorientation" [19, p. 153]. To substitute this missing feedback of self-movement (vection), Rietzler et al. explored the potential of providing short bursts of rotation feedback to the user while visually presenting only forward acceleration [138]. Their results suggest that substituting motion cues by rotational feedback can lead to a lower simulator sickness and higher presence. Not strictly teleporting, but jumping small distances was proposed by Ioannou et al. [72]. In a similar fashion to Rietzler et al., Ioannou et al. proposed to substitute the sensation of running with running-in-place and the sensation of forward-jumping with jumping-in-place. While motivation and immersion of participants increased, the continuous forward movement induced additional simulator sickness.

5.3 HAPTIC FEEDBACK

While tactile feedback is crucial for selection performance [34], its importance for immersion in VR has been shown in several studies [29, 127]. Due to a missing hand-held device, tactile information in free-handed interaction has to be presented by external actuators (e.g., robotic arms [140]) or to other body parts than the hands (e.g., the face [79]). Although these approaches enable free-handed haptic feedback, they introduce limitations such as a limited user mobility and a low dimensional haptic feedback.

5.3.1 *Limited Mobility*

Grounded feedback devices such as robotic arms [140] have the advantage of a high resisting force generated, albeit it severely limits the user's mobility due to a stationary design [140]. Similarly, wearable solutions are often tethered limiting the walking distance [129] and can reach a high weight encumbering the user [139, 172]. To circumvent the limitation of grounded feedback, previous work suggested grounding the prototype on the user's body [49, 90, 103]. This approach can lead to restrictions of the direction of force that can be generated (e.g., only perpendicular to the body [49]) and the maximum force resistance that can be created [90]. Using lightweight passive designs such as breaking mechanisms in exoskeletons can significantly reduce the prototype weight [38, 146], but also reduce the range of objects that can be simulated (e.g., due to breaks that can only be locked or unlocked [38]). Applying drones to provide mobile haptic feedback that is weightless to the user, on the other hand, can significantly reduce the force resistance, which is necessary to simulate static objects [71].

5.3.2 *Low Dimensional Haptic Feedback*

Especially head- or HMD-mounted haptic feedback prototypes can lead to physical discomfort due to pressure [119] or propagating vibrations [118]. To keep the prototype weight low, some free-handed solutions focus on only one actuator type or a low actuator resolution, thereby limiting the dimensions of feedback [119]. Increasing the actuator resolution is challenging as users are less capable of localizing individual actuators when actuator resolution is too high (e.g., vibrations [43, 78]). In an extreme form, a high actuator density can lead to the so-called "funneling illusion — experiencing one stimulus when two tactors [are] activated" [82, p. 55].
An alternative to increase the dimensions of haptic feedback is multimodal haptic feedback, i.e., combining actuator types such as vibration and thermal feedback [118], thermal and olfactory feedback [129] or thermal feedback and wind [128]. All these approaches could show an increase in user presence when actuator types were combined, although the individual actuator resolution was low.

Part III

RESEARCH QUESTIONS AND CONTRIBUTIONS

6 CHALLENGES OF INTERACTION IN XR

As discussed in chapter 1, there is always a need to manipulate virtual content, irrelevant of the technology applied. Since the trend in XR is towards both controller-based and free-handed interaction, gaps in the literature need to be identified for both types of interaction if interaction techniques are to be improved. Since the research body covering the problem fields is large, a structured viewpoint is necessary to narrow down the relevant previous works and classify own contributions. In chapter ii, we saw that the problem areas that emerge could be roughly divided into input and output, which is the basis for all interactions with computer systems. A more detailed examination reveals that the input can be further subdivided into selecting targets and selecting a target location or direction of movement (travel). This subdivision is in line with Bowman and Hodges's classification, who see selection and travel as important interactions in virtual environments [6]. Output can be presented through different channels, such as the visual, auditory, and haptic channels. Since the haptic output of commercial XR systems is minimal and haptic feedback is essential for selection precision [34] and the sense of presence in virtual environments [29, 30], many open challenges can be found in this research area.
To this end, this dissertation limited its focus to the three essential interaction categories *selection*, *travel*, and *haptic feedback* that will be discussed in the following and addressed in own works. An overview of own contributions to the respective categories and interaction types can be found in table 1.

	CONTROLLER-BASED	FREE-HANDED
Selection	[W4] Heisenberg	[W2] cARe [W3] Smartwatch AR
Travel	[W5] Discrete Rotation	[W7] JumpVR
Haptic Feedback		[W1] GyroVR [W6] Face/On

Table 1: Overview of own works in the interaction categories selection, travel, and haptic feedback for controller-based and free-handed interaction

7 SELECTION

As discussed in chapter 2.2.1, selection can be decomposed into the building blocks *feedback*, *indication of object*, and *indication to select* [6]. Feedback is necessary to display a target, indicate the current cursor position during selection [87, 105], and to confirm a successful selection. However, before a selection can even occur, users must first perceive their surroundings and localize potential targets. A particular challenge here can be technical limitations of the HMD and human factors, such as cognitive impairment. To address all components of selection, this chapter is divided into *Target Localization*, *Indication of Object*, and *Indication to Select*, which will be discussed and addressed in the following.

TARGET LOCALIZATION Especially when using AR HMDs, which offer only a very narrow FOV, the localization of virtual objects around the user is a great challenge since only targets within the FOV can be displayed [131]. Experimental approaches attempted to extend the users' FOV via peripheral [61, 104] and 360°-vision [60, 114], which introduced an additional mental load of understanding this novel mapping for the users. Alternatively, the locations of objects outside of the FOV can be presented as visualizations within the FOV. Among others, these off-screen visualizations have been proposed in form of 3D arrows [37], paths [131], and "attention funnels" [20] that lead towards the target or concentric waves that are emitted from the target [132]. Since most of the proposed visualizations point directly towards the target instead of calculating a sophisticated walking path, they could lead to intersections with the users. For example, a 3D arrow would point towards the users when a target is behind them, increasing the task load of localizing the target. Non-visual directional cues were proposed using spatial sound [150] and vibrotactile feedback on the head [80] to get a user's attention. Considering that AR technology is increasingly being applied to support users with cognitive impairment [58], this form of guidance could be too technical and cognitively demanding, since this user group requires additional assistance [57].

The challenge of creating a framework that can support users with cognitive impairment with localizing and selecting targets inspired the following case study. It aims to support geriatric patients with cognitive impairment with a cooking task via AR instructions.

Research Question 1: *How can users with cognitive impairment locate objects in an AR HMD with a narrow FOV?*

7.1 CARE

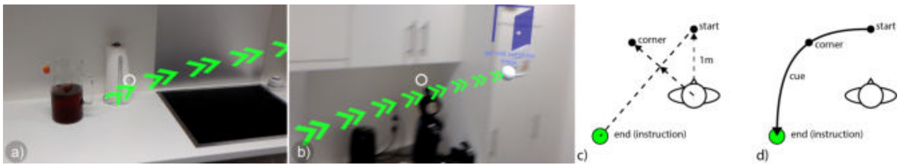


Figure 2: A visual cue guides patients from their current FOV (a) towards the next instruction (b). By calculating an additional position between the user's FOV and the next instruction (c), a guidance cue can be presented that does not intersect with the user (d). (Images taken from [W2])

In this case study, we proposed *cARe*, an AR framework to assist geriatric patients with cognitive impairment in performing instrumental activities of daily living (IADL) such as cooking via step-by-step instructions. Experts, caregivers, and patients were involved in the development process to address all requirements that an assistance system designed to preserve a patient's autonomy should meet. Since all AR instructions were placed in the physical space in the form of images and text (e.g., on the refrigerator, see Figure 2 b), one of the main requirements was to make the guidance between instructions as self-explanatory and comprehensible as possible. Visual cues were introduced since spatial audio cues had proven difficult to find in the initial tests with patients. These visual cues originate from the users' FOV to gain their attention and lead directly to the next instruction in an arc without intersecting with the user (see Figure 2 a-d). A feasibility study (n=6) compared cooking with our framework against recipe-based cooking, showing the feasibility of our guidance concept.

The contributions of *cARe* are:

- the design, concept, and implementation of an AR framework to support geriatric patients with cognitive impairment in retaining their autonomy of performing IADLs
- insights from a case study with geriatric inpatients (n=6) showing the feasibility of our *cARe* guidance concept
- insights into patients' acceptance of the technology and its impact on patient behavior such as risk assessment, autonomy, and self-confidence

INDICATION OF OBJECT To achieve a high selection accuracy, a precise indication of the target is necessary [6]. As discussed in chapter ii, in addition to technical factors such as system jitter, human factors can also negatively affect the accuracy of free-handed pointing. These include fatigue [59], hand tremor [17], and limited depth perception of one's own hand when interacting directly with the virtual content [45].
Possible solutions for free-handed interaction include input on touchscreens, which provide a resting surface for hand and fingers, thus preventing fatigue and hand tremor [17, 62]. However, to date, only static and portable solutions such as input on a tabletop [17] or a touchscreen on the back of a VR HMD [62] have been investigated. As AR applications are increasingly being used in a mobile context, the question arises whether touchscreens also provide reliable input in this scenario.
Depth perception for AR HMDs can be improved by introducing occlusion between the virtual content and the user's hand, i.e., drawing the content in front or behind the user's hand depending on its position [165]. However, this approach is only available for HMDs that can reliably track all 10 fingers [186]. For low-fidelity HMDs with coarser hand tracking there is no sensible alternative.

Therefore, the following case study investigated input on a smartwatch touchscreen to provide a low-fatigue solution for the mobile context. Furthermore, a novel concept of depth visualization for direct hand input in AR was investigated.

Research Question 2: *How can fatigue and hand jitter be prevented for free-handed selection and how can depth perception between user hand and AR content be improved for coarse hand-tracking?*

7.2 SMARTWATCH AR

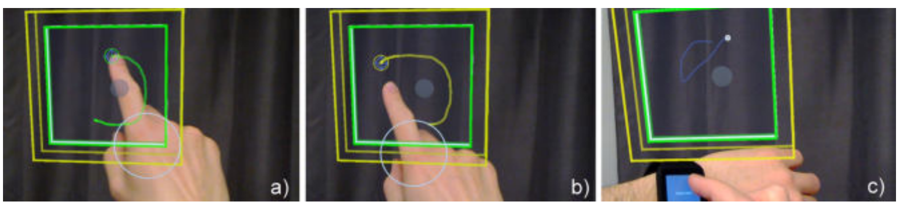


Figure 3: a) A green line trail of the cursor represents proximity to the selection plane. b) The line trail turns yellow if depth adjustments are necessary. c) Recent touch positions on the touchscreen are represented as a cursor with a line trail. (Image taken from [W3], © 2018 IEEE)

In this case study, we compared the selection performance of direct in-air selection [45] with indirect cursor-based selection on a smart-

watch. Depth estimation of the user's hand in relation to the AR content was improved compared to in-air selection proposed by Dudley et al. [45] by introducing a three-dimensional selection pane that supports continuous gestures. We implemented a color-coded 3D cursor that leaves a line trail and changes its color according to the current selection volume, i.e., the prism-shaped space around the selection plane. The cursor appears green while it stays within the inner selection volume close to the central selection plane (i.e., the 2D interface containing the targets, see Figure 3 a) and turns yellow when it enters the outer selection volume (see Figure 3 b). This way, users can adjust their depth position to stay close to the selection plane.
We included indirect control via a smartwatch in our experiment to evaluate an unobtrusive technique with low fatigue and resistance to hand jitter. A cursor with a line trail of fixed length represents the smartwatch's last touch position (see Figure 3 c) with a 1-to-1 mapping between smartwatch screen and selection plane. Due to missing visual feedback when there is no touch, we applied lift-off to indicate a selection and improve accuracy. Since the selecting finger can rest during target selection, hand jitter and fatigue were low, leading to higher accuracy for smaller targets than the in-air condition. The in-air selection was more efficient than the indirect cursor, supporting our depth cueing approach, albeit it may lead to higher fatigue. We concluded from our results that both techniques could complement each other.

The contributions of this work are:

- the design, concept, and implementation of indirect smartwatch control and direct in-air control with depth cueing
- insights from a case study (n=20), showing the feasibility and speed-accuracy tradeoff of both techniques, suggesting a complementary usage
- design implications for AR interfaces, including a practical example of performance prediction

INDICATION TO SELECT After indicating the target, a selection has to be confirmed via voice, gesture, a button, or no explicit command [6]. As discussed in section 4.1, spatial disturbance due to button selection on a spatially tracked input device, i.e., the Heisenberg effect, is a well-known yet not well-explored phenomenon [26]. Strategies found in related work for dealing with this effect are: *robust selection techniques* and *avoidance strategies*.

Robust selection techniques, i.e., techniques that prevent or tolerate inaccuracy, include ray-cast techniques that stick to targets [160], cone-selection that select via a volume instead of a ray [65], and direct selection techniques that are less prone to disturbance [161]. While these techniques improve selection accuracy, they still need to be implemented in commercial XR experiences. The predominant selection technique remains absolute ray-casting which is highly affected by the Heisenberg effect [26].

Avoidance strategies typically involve time-shifting, i.e., going back to a cursor position before the displacement occurred (e.g. [31, 86, 188]), and assigning the *indication of object* and *indication to select* to separate hands (e.g. [26, 106]).

Since no work could be found on understanding the Heisenberg effect in-depth and dealing with its consequences, i.e., compensate for its impact on selection performance, we elaborated on this in the following case study.

Research Question 3: *What are the characteristics of the Heisenberg effect and how can it be compensated for ray-casting in VR?*

7.3 HEISENBERG

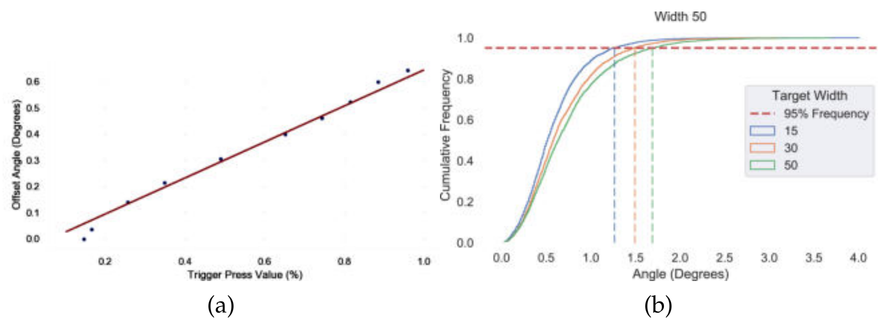


Figure 4: a) The angular controller offset in relation to how far the trigger button has been pressed (from 0 to 1.0). b) Cumulative histogram of the angular offsets observed by target width. (Images taken from [W4])

In this case study, we explored the impact of the Heisenberg effect on selection performance in VR and evaluated compensation strategies. To evaluate the effect for a range of common input scenarios, we tested varying body postures, arm postures, and degrees-of-freedom. We found a systematic offset between the cursor position before and after the button press and, thus, a detrimental effect on both effective throughput and error rate, irrelevant in which condition. To deal with this effect, we evaluated and discussed several avoidance and compensation strategies: time-shifting, increasing target width, and a correction function based on the collected selection data.
Time shifting to the beginning of the selection process, i.e., when the

trigger button is pressed first, resulted in a high error rate even for the largest targets due to selections that started outside of the target. More than half of the selections began outside of the target when performed in a ballistic movement. Only stationary selection, i.e., resting within the target before the trigger press, showed an improvement in the error rate.
Regular time shifting to a cursor position before the click (e.g., [31, 86]) requires fine-tuning since the trigger press value (i.e., how far the trigger is pressed from 0% to 100%) showed a nearly linear relationship with the cursor offset (see Figure 4 a), i.e., the controller disturbance increases with the trigger press value. Time shifting to a trigger press value close to 0% would mean accepting unfinished selections, i.e., unintended finger movements where the trigger was pressed slightly but not fully clicked. According to our data, there were 0.87 unintended trigger presses for every valid selection. To reduce the number of these false positives, the time shift should be close to a trigger press value of 100%, leading to a high cursor offset. We suggest a value of 83% to avoid 95% of false trigger presses and reduce the angular offset by 19.7%.
We calculated the minimum target width necessary to compensate for approximately 95% of displacements due to the Heisenberg effect. As shown in Figure 4 b, in 95% of the cases, angular offsets between the controller rotation at the beginning of a selection and its end achieved a value of 1.7° for our experiment's largest targets. The resulting minimum target width (which depends on the target-to-controller distance) would be too large for practical application, calling for alternative compensation strategies.
As a novel compensation approach, we computed the cursor offset of the recorded selections globally and grouped by conditions (i.e., considering body posture, arm posture, and DOF) to create a correction function for selections. Recalculating the effective throughput and error rate post hoc with our correction function, we could show a significant improvement for both correction functions, with condition-wise correction performing best. Therefore, we introduced a compensation mechanism that can be easily integrated into existing VR environments to reduce the impact of a phenomenon that is inherent to spatially tracked input devices.

The contributions of this work are:

- insights from a case study (n=16), analyzing the impact of the Heisenberg effect on effective throughput and error rate
- insights into the characteristics of the Heisenberg effect
- compensation strategies for the Heisenberg effect

8 TRAVEL

As discussed in chapter 2.2.2, travel is the movement component of navigation and consists of a translational and a rotational component. Some travel techniques have no rotational component by default, e.g., teleportation [27], while others combine translation and rotation, e.g., during physical walking [173]. To give both components a separate consideration, this chapter is divided into *Translation* and *Rotation*.

TRANSLATION As discussed earlier in chapter 4.2, spatial awareness and low simulator sickness are important for travel techniques in VEs so that users can move efficiently and their sense of presence is not disturbed [6]. For spatial awareness, an understanding of the path traveled is essential (path integration) [16]. This awareness is created, among other things, by vestibular feedback, i.e., actual physical locomotion. Since physical walking is primarily subject to spatial constraints and can also lead to fatigue in the long run, teleportation has become an efficient alternative in commercial applications [21]. However, this technique leads to reduced spatial awareness and even disorientation due to the abrupt locomotion and lack of vestibular feedback [10]. Since vestibular feedback for forward motion has already been successfully substituted by rotation [138] and jumping-in-place [72], the question arises whether the missing vestibular feedback can also be substituted for teleportation to neither sacrifice efficiency nor incur simulator sickness. This question was addressed in the following case study.

Research Question 4: *How can the vestibular feedback of physical jumps be combined with the efficiency of teleportation to realize a free-handed locomotion alternative with low simulator sickness?*

8.1 JUMPVR

Not strictly teleporting, but jumping small distances was proposed by Ioannou et al. [72]. Combining physical jumps with walk-in-place locomotion allowed users to make scaled virtual jumps while presenting the continuous forward motion of fast running. While their work focused on increasing intrinsic motivation for physical activity, the lack of evaluation of the isolated jumping component and its performance compared to teleportation inspired this case study. By virtually scaling a user's physical jump and adding a forward movement, we allow users to perform hyper-realistic jumps of up to 30m (see

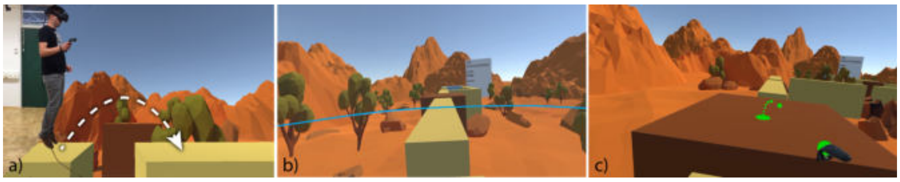


Figure 5: a) Physical upwards jumps were scaled virtually to create hyper-realistic forward jumps. b) A range indicator helps with estimating the landing position of the next jump. c) Teleportation was one of two baselines. (Image taken from [W7])

Figure 5 a). Surprisingly, participants perceived some of the scaled jumps as natural without experiencing additional simulator sickness. We identified two possible explanations.
First, the physical sensation of jumping and landing could have substituted the missing cues of self-movement, leading to a feeling of vection as described by Rietzler et al. [138].
Second, instead of being teleported between locations, which causes disorientation, users maintain their frame of reference, i.e., visual cues of their environment, during the virtual jump, leading to a better path integration, i.e., estimating the distance traveled [19].
To further assist with path integration, we added a jump range indicator that visualizes the next jump's approximate landing position, calculated from the jump height of the previous physical jump (see Figure 5 b). We compared scaled jumping-in-place to state-of-the-art teleportation (see Figure 5 c) and physical forward jumping and found a significant increase in user presence and immersion. Qualitative feedback suggests that physical jumping is engaging yet tiring, making it a viable extension of less demanding locomotion techniques such as walk-in-place or steering to cross large distances or add a hyper-realistic component.

The contributions of this work are:

- evaluation (n=28) of the feasibility of physical jumping in VR as a stand-alone locomotion technique
- insights into the scaling parameters of hyper-realistic jumps
- implications for the design of hyper-realistic jumping and its inclusion in VR experiences

ROTATION In addition to teleportation, controller-based steering has also become a popular travel technique [21]. Due to the continuous movement in virtual space without the corresponding vestibular feedback, a sensory conflict occurs, leading to simulator sickness [133]. Continuous rotation, in particular, is severely affected by simulator sickness and a loss of orientation, among other things [24]. Applying discrete rotation, i.e., rotation in predefined intervals, can reduce simulator sickness compared to continuous rotation [141]. However, the intervals required for this rotation approach and their impact on usability and user experience have not yet been sufficiently explored. An alternative approach is adding a rotation component to teleportation to perform rotation and translation simultaneously [27]. Although previous results argue against this approach, since it can increase the interaction time and disorientation, this type of rotation is increasingly found in commercial VR applications. Given that only a continuous variant of this rotation has been investigated so far (i.e., users can select an arbitrary rotation interval via a continuous gesture) [27], the following case study deals with the potential of discrete rotations as a teleportation component and as a stand-alone rotation technique.

Research Question 5: *Can discrete rotation as a stand-alone technique and as an extension of teleportation reduce simulator sickness and increase user presence, and what is the effect of varying rotation intervals?*

8.2 DISCRETE ROTATION

We introduced two rotation concepts in our case study, a rotation centered around the user's position (InPlace) and a rotation component for teleportation (TeleTurn). Using two rotation intervals (22.5° and 45°), we compared the discrete variants of both concepts with their respective state-of-the-art. Although the discrete version of TeleTurn could largely outperform its continuous state-of-the-art in terms of disorientation and user preference, the interaction time was still significantly higher than for regular teleportation without rotation, which is consistent with previous work [27]. Discrete InPlace rotation expressed no increase in simulator sickness and disorientation, with the highest discrete rotation angle being more efficient and more preferred by participants than physical rotation. Therefore, we could show that discrete InPlace rotation can avoid physical rotation-induced vection and the resulting simulator sickness, while both concepts induced no significant disorientation even at high rotation angles. Thus, discrete rotation presents a viable alternative to physical rotation for scenarios where physical movement is unwanted or restricted (e.g., while sitting or lying).

The contributions of this work are:

- concept, design, and implementation of two discrete rotation variants
- insights from our case study (n=12) regarding the impact of rotation parameters on usability and user experience

- implications for the integration of discrete rotation in VR experiences

9 HAPTIC FEEDBACK

As already mentioned, haptic feedback is essential for precise selection, which is especially challenging for free-handed interaction [34]. A rather underrepresented but important form of haptic feedback represents ambient environmental effects to the user, such as acceleration forces [138] or weather [119]. In general, haptic feedback is divided into kinesthetic feedback and tactile feedback [152], which will be discussed in light of ambient environmental effects in the following chapter.

KINESTHETIC FEEDBACK Kinesthetic feedback is also referred to as force feedback in the literature and includes the representation of hardness, weight, and inertia [30]. The main challenge of force feedback is the counter force or grounding necessary to generate sufficient force to represent, for example, a static object convincingly [71]. While grounded prototypes can limit user mobility [140], mobile prototypes can either become very heavy [103, 139, 172] or generate limited or unilateral force [49, 71, 90]. Although approaches for object-based kinesthetic feedback such as impact to the head [170] or the body [101] already exist in a mobile form factor, the representation of inertia, which is important to generate environmental effects such as gravity, has not been adequately explored. Therefore, the following case study investigates the use of the gyroscopic effect to generate inertial forces on the HMD.

Research Question 6: *How can inertia forces for HMDs be generated in an ungrounded and mobile design?*

9.1 GYROVR

This case study was inspired by the gyroscopic effect of resistance to simulate inertia, which has already been explored for hand-held prototypes (e.g., GyroTab [9]). For this purpose, we attached flywheels to the front and back of an HMD and set them in motion using motors (see Figure 6). If the flywheels are now brought out of their axis of rotation, a resisting force perpendicular to the rotation axis is generated. By combining this force with visual effects in VR, we created the sensation of inertia. This sensation was evaluated in three scenarios with different mapping. In a flying scenario, the force was controlled by the flying speed. Simulating a wounded player state, the resistance was increased in a shooter scenario for every shot the player

Figure 6: To simulate inertia, flywheels were attached to the front of an Oculus Rift DK2 HMD and the back of a bicycle helmet. (Image taken from [W1])

suffered. Lastly, a constant high resistance was applied to simulate an increased gravity in a scenario on a foreign planet.
The prototype was entirely mobile, ungrounded, and self-contained. Since a minimum weight of 96g per motor was necessary to create enough spinning mass, the motor was continually spinning at a low speed to reduce the ramp-up time while being beneath the users' detection threshold. The prototype's total weight (390g) led to fatigue effects and propagating vibrations during our experiment. The total weight and latency could be reduced in a future prototype using less spinning mass and a more powerful motor. Nevertheless, immersion and presence could be increased compared to the conditions without haptic feedback. This finding supports our approach of creating the sensation of inertia in a mobile form factor.

The contributions of this work are:

- the concept, design, and implementation of mobile kinesthetic feedback that simulates inertia in VR
- insights from our user study (n=12), evaluating the impact of the mounting position and haptic feedback of GyroVR on immersion, enjoyment, and simulator sickness
- three distinct virtual scenarios that demonstrate the design space of inertia feedback in VR

TACTILE FEEDBACK To simulate environmental effects using tactile feedback, approaches such as thermal [119], olfactory [129], and wind feedback [128, 139] have already been proposed. Although it has already been shown that different types of actuators could form synergies and thus further increase the range of feedback [118], only a few of these approaches exist so far. Furthermore, most solutions use only a small set of actuators, which leads to a correspondingly low resolution or richness of the feedback [118, 119]. On the other hand, high-resolution feedback has not yet been sufficiently explored, which is the motivation for the following case study, which focuses

on high-resolution haptic feedback in the facial area.
Most solutions for feedback in the face or head area have the disadvantage that they attract the user's attention due to their weight [W1], lack of comfort [119] or size [139], which can lead to a break in immersion. Since HMDs have contact with the user's facial skin by design, this contact area is an ideal opportunity for haptic feedback. The following case study therefore investigates how actuators can be embedded unobtrusively in an HMD.

Research Question 7: *How can high-resolution haptic feedback and thermal feedback be embedded inside an HMD to increase user presence and immersion?*

9.2 FACE/ON

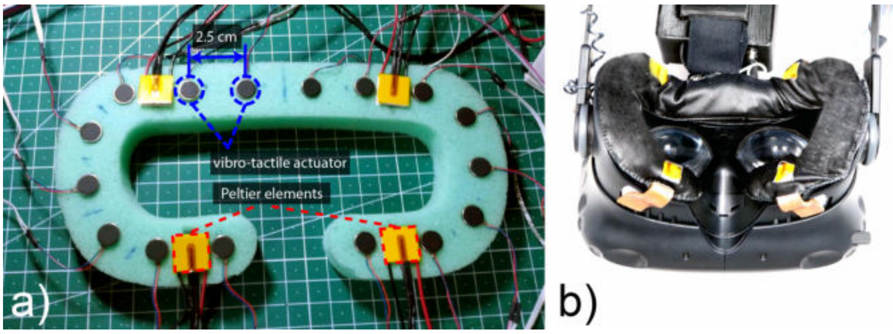


Figure 7: a) All 16 vibrotactile and four thermal actuators are embedded inside a VR HMD face cushion. b) To improve skin contact with the thermal actuators, openings in the cover material were created. (Image taken from [W6], © 2019 IEEE)

Like Peiris et al. [118], we combined vibrotactile and thermal feedback presented to the facial area but focused on environmental and object-based feedback. Leveraging the effect of a "funneling illusion" due to tightly arranged actuators [82], we applied 16 coin-type vibration motors to create continuous haptic patterns rather than punctual vibrotactile feedback of previous work that focused on directional cues rather than user presence (e.g. [80]). The distribution of our four thermal actuators was adapted from Peiris et al. [119] with the exclusion of the fifth actuator on the central forehead, which had the lowest effect. Learning from the limitations of previous work regarding comfort [119], we embedded all actuators inside the face cushion of a VR HMD (see Figure 7 a) except for small openings in the cover material for better skin contact with the Peltier elements (see Figure 7 b). This way, the typical feeling of intrusiveness and encumbrance of wearable prototypes should be minimized. Although the thermal actuators' power consumption required a tethered power supply, the remaining components were contained inside a controller case, which was mounted on top of the user's head for optimal weight distribution. With a battery of sufficient power, the prototype could be completely mobile, albeit the weight would increase. We created feedback patterns for frequently used effects that were hard-coded in the microcontroller to create rich haptic feedback with low latency. This way, all actuators could be controlled by a single command of the VE software, rather than toggling each actuator individually. Further avoiding latency of thermal feedback reported by Peiris et al. [119], we explored scripted events that allowed synchronizing thermal actuation and visual effects. We investigated comfortable actuation ranges for both actuator types in a preliminary study (n=8). In our user experiment (n=16), comparing no actuation with each actuation type and a combination thereof, the multimodal condition led to the highest user presence and immersion, supporting our high-resolution design.

The contributions of this work are:

- concept, design, and implementation of high-resolution vibrotactile and thermal feedback embedded inside a VR HMD cushion
- insights from a preliminary study (n=8) regarding optimal parameters for both actuator types
- insights from a user study (n=16), evaluating the complex feedback patterns that use Face/On's high-resolution design
- guidelines for multi-actuator haptic feedback in the facial area

Part IV

CONCLUSION

10 CONCLUSION

Interaction with virtual content in cross reality is mainly achieved by means of a controller or free-handed. This dissertation explored reasons supporting one or the other type of interaction and critically addressed the respective limitations and open questions. The problem areas were reduced to three essential interactions with virtual content: content selection, travel within virtual environments, and haptic feedback generated by the environment. For each identified challenge, solution approaches were designed, implemented and evaluated, and presented as case studies.
For selection, indirect selection using a smartwatch was investigated, which enables precise input with low fatigue and thus complements gesture-based free-handed input. In another case study, the disturbance of the controller position when pressing a button was explored in depth, and compensation strategies were presented and evaluated to minimize its impact on selection precision.
To make free-handed travel efficient and immersive without inducing additional simulator sickness, a jump-based technique was presented. This technique virtually scales physical jumps to create hyper-realistic jumps that allow fast travel similar to teleportation. Rotation in controller-based travel can cause simulator sickness and disorientation when performed in a continuous motion. This limitation has been addressed in our case study applying discrete rotations at predefined angles and evaluating the effect of the rotation angle on simulator sickness and disorientation, with the largest angle achieving the best results.
Haptic feedback via inertial forces, which could not previously be represented in VR, was implemented using flywheels attached to an HMD that generate a counterforce when deflected from their rotation axis. This force was leveraged to create effects in different scenarios that resulted in a higher user presence. In another case study, the contact area between the users' faces and the HMD was used to embed haptic feedback. The prototype uses a novel and high-resolution design to generate complex feedback patterns and take advantage of synergies between different actuator types to increase user presence.

Overall, this dissertation identified and addressed several open challenges in the field of interaction in XR. Although the solutions presented throughout this dissertation each represent only one of many approaches to a specific problem, they provide evidence and insight for subsequent research to make interaction in XR more accessible, user-friendly, and diverse.

11 DISCUSSION

To weigh up controller-based and free-handed interactions, we have seen that some limitations, such as tracking jitter or prototype weight, can affect both interaction types, implying a conceptual rather than a technical nature. Most of the discussed solutions, including own works, succeeded in addressing one or several of the identified drawbacks while suffering from others. This finding leads to the conclusion that there is no best modality or technique for a given task but rather best practices that depend on the context of the application and the target group. In the following, these practices and the limitations thereof will be discussed, abstracting from the type of interaction where possible.

11.1 INTEGRATION OF TARGET GROUP

As mentioned earlier, few useful alternative interaction techniques for vulnerable target groups such as the elderly or patients with cognitive impairment exist. When designing novel interaction concepts, these potential users should be involved in the development more intensively than already specified by the UCD process anyway, since many of the existing best-practices for users without limitations are not applicable in this case. Our project *cARe: An Augmented Reality Support System for Geriatric Inpatients with Mild Cognitive Impairment* found that for object localization, patients with cognitive impairment could not correctly recognize spatial audio cues nor detect static visual guides. Thanks to early testing, we were able to identify and address these insights in time, which led to the successful development of dynamic visual cues that made an important contribution to the whole concept's success.

11.2 COMPLEMENTARY USAGE OF TECHNIQUES

As discussed, direct pointing techniques such as ray-casting are very efficient yet prone to errors due to hand or controller displacement. Robust techniques that improve selection accuracy in real-time (e.g., via refinement or touchscreen), on the other hand, almost inevitably increase the selection time, reducing the overall performance. I suggest a complementary usage of techniques that offer both efficiency and accuracy, as presented in our work *Performance Envelopes of In-Air Direct and Smartwatch Indirect Control for Head-Mounted Augmented Reality* [W3]. Here, the speed of direct in-air selection for large targets could be complemented with the high precision of an indirect cursor to select small targets. If target size is not an issue, "the optimal selection technique is a user choice and depends on personal preference, current fatigue level, and task complexity" [W3, p. 352].

11.3 DATA-DRIVEN TECHNIQUES

Post-hoc or automatic correction unnoticed by the user can avoid an increase in selection time; however, it requires a per-user or per-system calibration. For instance, the correction functions presented in our work *Understanding the Heisenberg Effect of Spatial Interaction: A Selection Induced Error for Spatially Tracked Input Devices* [W4] used the data collected during the experiment with an HTC Vive controller. The correction vectors calculated from this data would not apply to HMDs with a different controller since the selecting button's characteristics might vary. Developers that would want to integrate these approaches without introducing an explicit calibration could apply an iterative correction mechanism that improves its parameters as the user generates data. Alternatively, the correction could be enabled as soon as sufficient data is available.

11.4 USER PREFERENCE

Traveling is an important task to explore VEs and exists as a variety of locomotion techniques. While previous research focused on improving side effects such as simulator sickness and disorientation during teleportation or walking-in-place, users have got accustomed to these seemingly unrealistic locomotion techniques. As a result, they are sometimes not willing to give up on their efficiency. In our project *Augmenting Teleportation in Virtual Reality With Discrete Rotation Angles* [W5], we explored a rotation component for teleportation that could potentially reduce disorientation. By letting users choose between this novel rotation technique and rotation centered at the user position, we observed that participants strictly avoided the novel technique whenever possible. Our results indicate that users were unwilling to accept a longer teleportation time to reduce disorientation and opted for the state-of-the-art instead. This finding is just one example that illustrates the challenge of optimizing a well-established interaction technique, especially when efficiency and comfort are affected.

11.5 HYPER-REALISTIC EXPERIENCES

On the other hand, whole-body movements have the potential to increase user motivation to the extent that they are willing to sacrifice efficiency and comfort for enjoyment and user presence. We observed this effect in our project *JumpVR: Jump-Based Locomotion Augmentation* *for Virtual Reality* [W7]. By virtually scaling users' physical jumps, we enabled super-human leaps over large distances. The fun experience let users forget about their fatigue and was suggested as a unique game element by some. Interestingly, only the larger scaling factors were well accepted, while low factors led to simulator sickness and were less preferred, probably due to the shorter jumping distance and, thus, a higher number of required jumps. This example shows that although realism and comfort is the goal of many interaction techniques and a mismatch between visual and vestibular input is considered to induce simulator sickness, the element of hyper-realism can be perceived by users "as its own technique, rather than interpreting it as noise in their perceived visual and vestibular input" [W7, p. 8].

11.6 CONSIDERING HARDWARE LIMITATIONS OF PROTOTYPES

Research prototypes are usually several times heavier than industrially manufactured hardware. Therefore, it is not surprising that a high weight was an often mentioned limitation of haptic feedback devices in previous work and during own experiments. Although approaches to reduce the overall weight exist, they can introduce new limitations. Pulley systems with counterweights, for instance, limit the users' walking range. Using light-weight materials and passive designs, on the other hand, can affect the durability of the prototype and the richness of haptic feedback. Entirely weightless solutions, such as grounded devices or drones, limit the user's mobility while providing a high resistance force or are fully mobile yet hardly withstand a user's touch, respectively. As discussed, the best-suited solution is case-sensitive. If mobility is not relevant due to a sitting position or a walk-in-place locomotion technique, pulleys or grounded feedback devices are viable. If the interaction targets user interfaces rather than static objects, drone-based haptic feedback could be preferred.

Approaches that cannot avoid limitations, such as weight, vibrations, and noise, could include these sensations as a component of the experience to increase rather than impede user presence. In our work, *GyroVR: Simulating Inertia in Virtual Reality using Head Worn Flywheels* [W1], for example, users perceived the noise and vibration of the prototype as part of the experience in a flying scenario, since a higher flying speed led to a faster spin of the flywheels.

11.7 EMBEDDING HAPTIC FEEDBACK

Another contributor to a high prototype weight can be additional actuators meant to increase the richness of haptic feedback. These additional components are usually mounted on the user's body or the HMD, encumbering the user and drawing the user's attention from the VE, thus disrupting the feeling of presence. We argue that embedding actuators inside existing hardware is less intrusive and reduces the impact on user presence. In our work *Face/On: Multi-Modal Haptic Feedback for Head-Mounted Displays in Virtual Reality* [W6], all actuators were embedded in such a way that establishing the contact with the user's face was part of the natural act of putting on the HMD. Although the prototype included a visible controller box on top of the user's head, we argue that an industrially manufactured version of this approach could be completely integrated into the HMD, reducing the additional weight and the need for a tethered power supply.

12 FUTURE WORK

12.1 EVALUATE LEARNING EFFECTS

Most of our works aimed to increase user presence and enjoyment by improving existing or introducing a novel technique. Since the population sample was mainly academical, which is a highly debated HCI issue [99], participants' technical affinity might have skewed the presence and enjoyment results towards novel techniques. Performance, on the other hand, might have suffered due to missing experience. Therefore, we suggest performing long-term studies to balance novelty effects and gain insights on a technique's performance closer to real-life. Alternatively, techniques could be deployed at users' homes with data collected over a more extended period. This way, even XR novices will have the opportunity to get accustomed to both the hardware and the novel techniques.

12.2 VALIDATION OF CONCEPTS IN OTHER REALITIES

At the moment, all concepts in own works were designed and evaluated for a specific use case, i.e., a distinct reality. We argue that most techniques could be applied to other realities as well. Compensation strategies for the Heisenberg effect, for instance, could be applied for all forms of distal-pointing that involve a hand-held pointing device with discrete selection buttons, e.g., the Microsoft HoloLens clicker. The smartwatch-based indirect selection evaluated for AR, on the other hand, could be realized for VR to provide a precise selection technique since the interaction is eyes-free and visual cues appear in front of the user and not on the smartwatch screen. HMD-embedded actuators presented in Face/On are so small and light-weight that they could be implemented in AR HMDs to provide more convincing holograms, e.g., a sun that radiates heat in a planet simulation. The guidance concept of cARe addressed the small FoV of current AR HMDs. Although the FoV of VR HMDs is larger in general, it does not cover human peripheral vision. Therefore, users could benefit from guidance towards targets outside of the FoV, e.g., in training environments or large VEs.

12.3 STANDARDIZE EVALUATION OF HAPTIC FEEDBACK

As discussed, an open HCI challenge is measuring the subjective feeling of haptic feedback. Instead, it is measured indirectly via its impact on user presence and immersion. Besides, we collected qualitative feedback and applied custom items in questionnaires to gain additional insights. The lack of standardization for this process impedes comparability between works. Therefore, we suggest creating a custom questionnaire with a specific focus on haptic feedback. As an alternative or extension, a data-driven approach could collect biometric data and provide an objective measure of the participants' reaction to haptic feedback stimuli. This way, we could integrate a fast and automatic calibration mechanism for our research prototypes.

12.4 DIRECT COMPARISON OF CONTROLLER-BASED AND FREE-HANDED CONCEPTS

This dissertation does not claim that controller-based or free-handed interaction is superior to one another; instead, its usefulness depends on the context. However, a direct comparison between both modes of interaction could aid designers' and developers' informed decisions. As presented in JumpVR, where we compared free-handed jumping locomotion to controller-based teleportation, there is value in comparing other techniques as well. We compared smartwatch-based indirect selection against direct in-air selection, another free-handed technique. Future work should compare both against a controller-based alternative, such as the gaze-and-clicker interaction of the Microsoft HoloLens.

Part V

APPENDIX

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DECLARATION

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

Ich bin damit einverstanden, dass die Dissertation auch zum Zweck der Überprüfung der Einhaltung allgemein geltender wissenschaftlicher Standards benutzt wird, insbesondere auch unter Verwendung elektronischer Datenverarbeitungsprogramme (§ 8 Abs. 1 Nr. 8 Rahmenpromotionsordnung).

Ulm, März 2021

Dennis Wolf

GyroVR: Simulating Inertia in Virtual Reality Using Head Worn Flywheels

Jan Gugenheimer, Dennis Wolf, Eythor R. Eiriksson, Pattie Maes, and Enrico Rukzio. 2016. GyroVR: Simulating Inertia in Virtual Reality using Head Worn Flywheels. In Proceedings of the 29th Annual Symposium on User Interface Software and Technology (UIST '16). Association for Computing Machinery, New York, NY, USA, 227–232.
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ABSTRACT
We present GyroVR, head worn flywheels designed to render inertia in Virtual Reality (VR). Motions such as flying, diving or floating in outer space generate kinesthetic forces onto our body which impede movement and are currently not represented in VR. We simulate those kinesthetic forces by attaching flywheels to the users head, leveraging the gyroscopic effect of resistance when changing the spinning axis of rotation. GyroVR is an ungrounded, wireless and self contained device allowing the user to freely move inside the virtual environment. The generic shape allows to attach it to different positions on the users body. We evaluated the impact of GyroVR onto different mounting positions on the head (back and front) in terms of immersion, enjoyment and simulator sickness. Our results show, that attaching GyroVR onto the users head (front of the Head Mounted Display (HMD)) resulted in the highest level of immersion and enjoyment and therefore can be built into future VR HMDs, enabling kinesthetic forces in VR.

Author Keywords
gyroVR; haptics; virtual reality; mobile VR, nomadic VR

ACM Classification Keywords
H.5.2. Information Interfaces and Presentation (e.g. HCI): User Interfaces

INTRODUCTION
Virtual Reality HMDs strive to immerse the user inside a virtual environment and are currently mainly targeting the visual sense. Several research projects showed that including the haptic sense inside a virtual environment leads to an increased level of immersion [17].

GyroVR focuses on the kinesthetic part of the haptic perception and mainly on inertia, which occurs when being in fast motion (e.g. flying) or in an altered environment (e.g. underwater). The resistance of the wind, when flying in a wingsuit acts upon the human body as a kinesthetic force, which impedes the movements of the head or limbs similar to when people try to move underwater. This concept of motion is currently one of the most used for Oculus Rift experiences.

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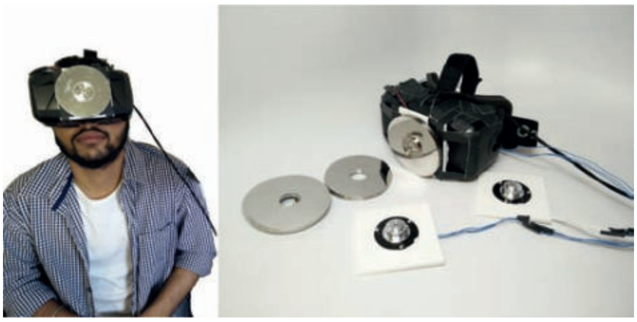

Figure 1. Left: A user wearing a VR HMD with GyroVR attached. Right: A prototype implementation of GyroVR attaching flywheels on the front of an Oculus Rift DK2.

We enable this sensation by attaching flywheels to the human head. These flywheels leverage the gyroscopic effect which occurs when the user tries to rotate his head against the rotational axis of the spinning flywheel. The gyroscopic effect will affect the motion of the users to the perpendicular axis of the motion which is mainly perceived as a resistance [19]. In combination with the visuals of the virtual scene the sensation of inertia is created. We conducted a user study (n=12) to explore how mounting GyroVR to different positions on the human head (back and front) impacts the level of immersion, enjoyment and simulator sickness inside a virtual environment.

Contributions
The main contributions of this work are: (1) the concept of simulating kinesthetic motion forces using head worn flywheels,(2) the implementation of GyroVR, a small, self containing and generic device capable of being attached to the human body, (3) the insights from our study on human perception and the impact of

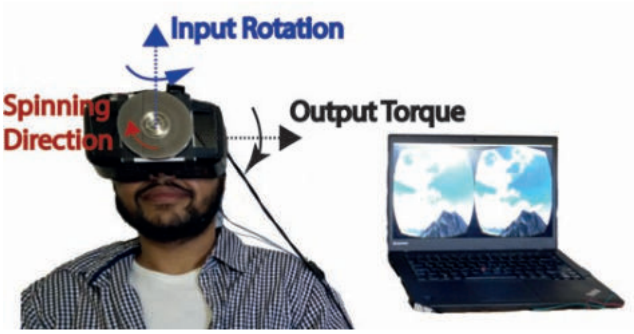

Figure 2. GyroVR is designed to render the simulated force of inertia occurring during movements. The key idea is that the flywheel mounted on the VR HMD impedes the motion of the users. Here the user is experiencing a flying simulation and tries to steer his direction using his head motion (Users' Motion). The rotation speed of GyroVR is correlated with the speed the user has in the virtual environment. GyroVR impedes this motion by generating a perpendicular force creating an experience for the user where it is more difficult to move his head when he is in high motion.

kinesthetic forces by head worn flywheels attached to different locations in terms of immersion, enjoyment and simulator sickness.

GYROVR

GyroVR is designed as an ungrounded haptic feedback device to simulate the kinesthetic force of inertia which fits to different VR experiences (e.g. flying). Ungrounded means that GyroVR has no grounding to counterbalance the output force such as Phantom or HapticMaster [13]. Figure 2 illustrates a setup where the user flies through an environment and depending on his speed perceives a higher or lower level of resistance during his head movements. The concept of GyroVR leverages the effect that the directional force is not perceived precisely enough and more like a general resistance [18]. One important concept of GyroVR is that the force generated does not necessarily have to be realistic (e.g. actual wind resistance). In informal pre-evaluation with colleagues we found that users mostly do not know the exact force which should be acting upon them in most situations but only expect some kind of force which is comprehensible.

Implementation

Similar to [3] we built GyroVR out of desktop computer hard drive components (Western Digital WD 2500). We removed the motor (7200 rpm overclocked to ≈12.000 rpm) and discs from the HDD. For our implementation we used three discs on each motor resulting in a total weight of 96g. We experimented with a different number of discs and found a balance between weight and performance using three. Furthermore, a higher number of discs resulted in the motors to struggle at start-up since they are not used to spin a higher number of discs. To control the three phase HDD motor we used a Hobbyking 30A ESC which receives a PWM signal from an Arduino Nano. After our initial tethered prototype with three motors on the HMD (Figure 6) we built a mobile version (Figure 3) by adding the Bluetooth HC-06 module for the communication between computer and Arduino and adding a 1500mAh Lipo-Battery (from an AR Drone 2.0). The use of off the shelf hardware allows researchers to easily rebuild our implementation.

To experiment with the force on different locations of the human body we built a mobile version (Figure 3 right) where we

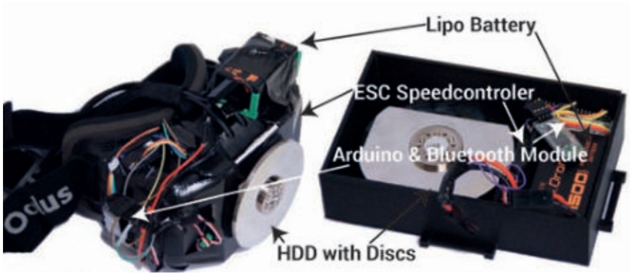

Figure 3. Two implementations of GyroVR. Left: The GyroVR prototype directly attached onto an Oculus Rift DK2. Right: A mobile implementation of GyroVR, built in a generic form factor to be mounted onto the human body.

assembled all components inside a 3D printed case (overall weight 390g). This prototype can be mounted onto the human body using straps (Figure 5). To reduce some of the weight we built a second prototype where we assembled all the components directly onto an Oculus Rift DK2 (Figure 3 left).

Gyroscopic Precession

The force generated by GyroVR is based on Newton's first law of motion which states that objects in motion try to stay in motion. The rotational pendant to this is the gyro effect which states that spinning masses will continue spinning in the same direction around the same axis. Once the user rotates his/her head at a desired angular velocity ω_{in}, a gyroscopic torque τ_out is experienced perpendicular to the head rotation axis. (Figure 4). The relationship is as follows

$$\tau_{out} = \omega_{in} \times L_s = \omega_{in} \times I\omega_s \quad (1)$$

where L_s is the spin angular momentum, I is the moment of inertia and ω_s is the angular velocity of the spinning mass.

By having a double gyroscope setup, sharing the same rotational axis and spinning in the same direction, the angular momentum contribution becomes additive. Effectively doubling the perceived effect and output torque τ_{out}. Figure 4 depicts such a double gyroscope setup where the gyroscopes have been mounted in such a way that they provide a counter balance of weight. Additionally, it illustrates the relationship between head rotation velocity ω_{in} and the gyroscopic torque τ_{out} experienced by the user around the yaw axis.

Mounting Positions

We experimented with several mounting position on the users body using the GyroVR mobile prototype (Figure 5). Our goal was to find mounting positions where users would perceive the force strong enough so it could be used in a user study. Since the force of GyroVR is a reactive force (only perceived if an input force is generated e.g. rotating the head) we experimented with mountings on the human body which are used frequently in motion when inside a virtual environment. The evaluation of the different mounting positions we report here are based on informal pre-evaluations the authors conducted on themselves to pre-select relevant mounting positions for the follow up user study. We evaluated the mounting positions based on *ease of attachment and level of perception*.

Hands: Mounting the device onto the palm (or holding it in the hand) resulted in the strongest perception of the force. This is

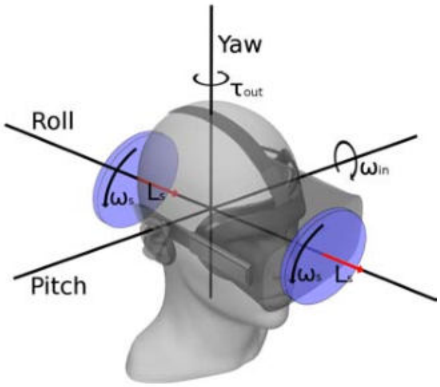

Figure 4. When disks are spun with angular velocity ω_s and the head is rotated around an input axis at angular velocity ω_{in}, the gyroscopic output torque τ_{out} around the yaw axis is experienced by the user.

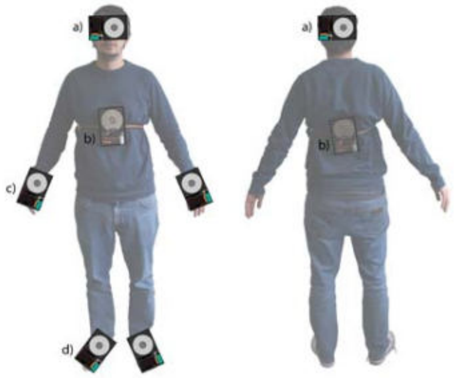

Figure 5. The different mounting positions on the human body which were explored with the mobile implementation of GyroVR.

probably because of the high density of muscle spindles which are responsible for perceiving the kinesthetic force [8]. The mounting onto the hand turned out to be more difficult since the prototype must be rigidly attached and thereby restricted motions of the hand. Furthermore, the size of the prototype lead to occlusion of the fingers which excluded simple hand tracking using the Leap Motion. The best result occurred from holding the prototype in the hand. We excluded that option of holding, since similar results were already reported in prior work [3, 21].

Torso: The least force was perceived when GyroVR was mounted on the torso. We experimented with different mounting locations but did not find a position which resulted in a force which could actually be perceived. As the torsos freedom of motion is by rotating around a vertical axis, the GyroVR must exert an output torque by twisting around the horizontal axis, essentially leveraging the entire body.

Legs/Feet: Attaching GyroVR to the legs resulted similar to the torso location in an easy mounting but low perception of the output force. We also experimented with mounting GyroVR to the feet (similar to a shoe). The force is only perceived when tilting the foot and is only of relevance for room scale VR such as HTC Vive.

Head: Mounting GyroVR onto the head resulted in a high perception of the force since the neck consists of most muscle spindles

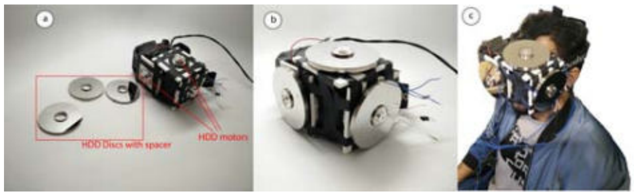

Figure 6. An early prototype of GyroVR on an Oculus Rift DK2 (a) which had a flywheel mounted onto each axis (b). We conducted informal evaluations to asses the output force (c)

[8]. We built one initial prototype (Figure 6) with flywheels on each rotational axis (yaw, pitch and roll). We then experimented with each individual flywheel and its possible combination and ended up with mounting the flywheel to the roll axis as the best result. The reason is that when mounted on the roll axis the gyroscopic effect is perceived when applying a force on the yaw and pitch axis (basically turning the head left/right or up/down). This position benefits from the fact that users explore the virtual environment by rotating the head. Even if the realistic case would be to perceive the force on the whole body, by bundling this haptic feedback with the main source of input (head rotation) the user gets an immediate feedback for an action and accepts the force as part of the immersive experience (see section user study).

APPLICATION EXAMPLES

To explore the design space for GyroVR we implemented three example applications which each create a different mapping of the force and the environment (Figure 7). We used those applications for the user study. For some applications we needed to let the participants generate input (e.g. press button to fly). We used a wireless bluetooth gamepad for this interaction. Applications which depend on virtual forward motion tend to induce simulator sickness (sensory conflict theory). Due to the nature of inertia which mostly appears during motion we took some precautions (e.g. Oculus Guidelines) during the application design to lower simulator sickness. In every scenario we used a different mapping between the virtual environment and the physical rotation to dynamically control the rpm. To generally shorten the ramp up time the flywheels are kept constantly spinning on low rpm (which did not generate enough torque for the participants to feel). All applications were implemented using Unity 3D.

Simulating Forces of Motion - Flying

In the flying game (Figure 7 a) the user can fly over a city. By holding down one button on the gamepad the user can speed up and control his direction by rotating the head. The rotational speed of the flywheel is mapped onto the virtual speed inside the game. For the flying game we used a linear mapping between virtual movement and rotation speed. This allows the user to perceive a higher resistance in turning his head when flying in higher speed. To encourage head rotation we placed stars inside the environment which the user has to collect. The placement is done in such a way that after collecting one star the users has to quickly rotate towards the next target.

Impeded Motion - 3D Shooter

Figure 7 b shows the implementation of the 3D shooter game. The user is located inside a warehouse and has to find two

Figure 7. Screenshots of the applications which users experienced in the user study. (a) The flying application showing a star in the distance. (b) A first person view of the warehouse from the 3D Shooter game. (c) The surface of the foreign planet showing the location of several parts which the user has to collect

weapons hidden in random locations. The controls work by having one button to run and a second one to jump. The direction of the running is controlled via head rotation. During the search the users get constantly shot by hidden enemies which they can't find. The more damage the user takes the faster the flywheel spins and the more difficult it becomes to move. At the start of the scene no rotation was used. Every time a user gets hit, the rpm are increased rapidly by a 6th of the maximum rpm. After seven hits the game ends. This allows the user to experience an impeded motion as if he is wounded.

Simulating new Environments - Space Jumper

The last game (Figure 7 c) locates the user on a new planet with new physical forces. The flywheel is constantly spinning at full speed thereby highly restricting head motion and simulating a new form of gravitation. The get off the planet the user has to collect three parts which he needs to repair his spaceship. To move on the planet users are encouraged to jump. To encourage a high head movement, users only have a certain "boost" which they can use to jump that has to be regenerated by shaking their head. The gravitation on the planet is set to almost zero. The user has visually the impression as if he moves in lower gravity, the flywheels generate a force as if he would actually be in an environment with a higher gravitation as earth (since moving the head is difficult). This application beautifully demonstrates the concept of non-realistic forces. Even if that scenario is physically impossible, participants inside our user study ignored this fact and perceived the forces as appropriate, some even calling it "realistic".

RELATED WORK

Our work builds upon the work in the field of ungrounded kinesthetic feedback and virtual reality.

The gyroscopic effect was often used to create an ungrounded kinesthetic force such as the GyroCube [19] which is a handheld gyroscope generating forces along each rotational axis. Sakai et al. evaluated the levels of perception inside the users palm using GyroCube [18]. Badshah et al. applied this concept into the field of HCI by attaching flywheels onto the back of a tablet to generate kinesthetic forces for the user [3]. Several authors presented a concept to make the gyroscopic effect proactive by attaching a flywheel onto a gimbal and control that gimbal [21, 2, 22] to give the user directional cues. Murer et al. presented this concept attached onto a tablet called "TorqueScreen" [16]. By rotating the gimbal with a flywheel attached, the authors could generate kinesthetic feedback allowing the user to feel a virtual ball on the tablet bounce of the edges. The main difference to

Figure 8. The study apparatus of GyroVR consisting of a Oculus Rift DK2 with GyroVR attached and a bicycle helmet having a mobile GyroVR prototype attached to the back.

GyroVR is that all those prototypes were designed to be handheld and not mounted onto the human body.

A different direction in the field of ungrounded kinesthetic feedback is work which tries to mount those flywheels onto the human body. Mostly the motivation is to assist human balance [1, 4, 14]. Those prototypes are often quite large to generate a strong enough force and too heavy for casual use. Ando et al. presented a concept for a body worn prototype based on brake change in angular momentum to create a directional force [1]. The prototype built, however, was not wearable but users had to hold it in their hand.

In the field of Virtual Reality, there is a big direction of work focusing on novel input concepts [5] and generating haptic feedback [11, 7, 12, 17, 6]. Early prototypes were used in CAVE environment and were attached to the users limbs using exoskeletons [20] or pulley systems [15]. Both systems are considered to use a grounded force. Recently, Lopes et al. presented a concept for simulating impact in VR using electrical muscular stimulation and a solenoid [11].

To our best knowledge, GyroVR is the first to use head-worn flywheels to simulate kinesthetic feedback in VR.

USER STUDY

To measure the impact of GyroVR onto immersion, engagement, enjoyment and simulator sickness we conducted a user study (n=12). We also evaluated the best position of GyroVR on the users head.

Study Design and Procedure

The study had one independent variable *motor location* with four levels (front, back, both and none). In the *both* condition both flywheels rotated in the same direction along the roll axis to sum up the force. For the user study we used a different apparatus (Figure 8) which consisted of a bicycle helmet which had a GyroVR prototype mounted on it. We used the helmet to ensure

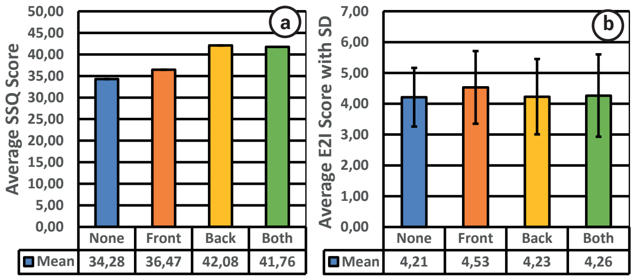

Figure 9. A distribution of the simulator sickness (a) and immersion, engagement and enjoyment questionnaire (b) of the user study.

a sturdy attachment of GyroVR onto the back of the participants' head. To ensure that the force was created equally, both flywheels were equidistant to the users head (≈ 8cm). The *none* condition was used as the baseline. The study took on average 30 minutes and participants received 5 currency. The flywheels generate a small rotation noise which was not heard by the participants due to the use of headphones. To avoid vibration we used hand moldable plastic to press fit a perfectly fitting layer of plastic between the HMD case and the flywheel mount. The battery lasted for at least 2 studies (1h) before charging.

Participants were introduced to the concept of GyroVR and could experience the force. Afterwards they put on the Oculus DK2 and the bicycle helmet and played all three applications (section *Application Examples*) with each of the four conditions of the motor (front, back, both and none). After each motor condition participants were asked to fill out the SSQ (Simulator Sickness Questionnaire) [9] and E^2I questionnaire (immersion, engagement and enjoyment) [10]. At the end participants rated all four conditions as what they perceived as the best experience. Applications and motor conditions were counterbalanced using a Latin-square.

Participants
We randomly recruited 12 participants (3 female) with an average age of 28.5 (range: 25 to 36) from our institution. Six participants had already experience with VR HMDs and all had an academic background.

Results
Quantitative: Figure 9 a shows the distribution of the simulator sickness of all levels of the motor condition. A repeated measures ANOVA revealed no significant differences (F(3,33)=.639, n.s.). Even if not significant, the trend shows that the front mount resulted in the lowest level of simulator sickness compared to the other motor levels. Participants in general mentioned that the applications induced a higher level of simulator sickness since they all dependent on virtual movement. The overall ranking of immersion, engagement and enjoyment over all motor levels can be found in Figure 9 b. A repeated measures ANOVA revealed no significant differences (F(3,33)=.745, n.s.) between the levels. Nevertheless, the front condition received a slightly higher ranking. This again correlates with the user feedback we received during the study.

Qualitative: In the final feedback after the user study participants comments can be categorized in three topics (*immersion*, *sickness*, *fatigue*): Rapid increase of RPM resulted in a little nudge in a direction and was partially perceived as 'unpleasant' and therefore fitting to increase the level of *immersion* of the 3D Shooter, where a hit from a bullet was simulated by a rapid increase of rpm. Participants said they perceived the front condition as being the strongest in terms of output force. In the final rating of the overall best experience participants preferred having a motor (7) vs having no motor (5). The participants which ranked the "no motor" condition the best mostly experienced an overall high level of *simulator sickness*, which they then correlated with the motor running. In a final ranking participants (6) reported that during the motor conditions, using both motors induced the most level of sickness. Participant 7 mentioned that if GyroVR was not tightly fixed to the head this potentially increased the sickness. High rpm were reported to potentially lead to less head movement due to *fatigue*. Participant 9 suggested to use this effect as a 'punishment' in an attention guidance scenarios. The overall weight of the study apparatus resulted in a certain level of fatigue over the duration of the whole study. However, removing one of the gyros would result in an unbalanced setup (and create an unfair comparison between conditions). Therefore, we decided the leave both gyros on the participants during the whole study. A possible solution to keep the same output force but reducing the weight would be by increasing the rpm. A future prototype which is based around a custom motor with higher rpm would be able to generate the same output force but avoid the high weight and resulting fatigue effects.

DISCUSSION
Our study showed that GyroVR creates an "immersive and realistic" (P3, P5) kinesthetic force which "enhances the experience" (P9). After experiencing a condition with either of the motors and afterwards the *none* condition, participants reported the experience to be "boring without the force" (P10). Overall participants reported they enjoyed the concept despite a certain base level of simulator sickness. Even though the user study did not quantitative show a clear benefit for immersion, engagement and enjoyment when using GyroVR, a possible trend does exist, which warrants further testing with a larger sample size to determine if the trend truly indicates significance.

CONCLUSION
We presented GyroVR, head worn flywheels designed to render inertia in Virtual Reality. These flywheels leverage the gyroscopic effect which impedes users head movement and thereby is perceived as inertia. We presented several implementations and initially explored the mounting positions on the human body. In three example applications we explore the design space and different concept of mapping the force inside of the virtual environment. In a user study we explored the effect of GyroVR attached to the users head on immersion, engagement, enjoyment and simulator sickness. Our results give a first understanding of the implications of attaching a flywheel to the front of a HMD to enable kinesthetic forces of inertia in virtual reality.

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cARe: An Augmented Reality Support System for Geriatric Inpatients with Mild Cognitive Impairment

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cARe: An Augmented Reality Support System for Geriatric Inpatients with Mild Cognitive Impairment

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Figure 1: Locations for in-situ instructions are positioned in the room via gaze pointer (i.e., the current location to be positioned is following the current gaze direction) and AirTap gesture (a). This way, virtual locations can be attached to their real-world counterpart (b) to present instructions at their corresponding position (c).

ABSTRACT

Cognitive impairment such as memory loss, an impaired executive function and decreasing motivation can gradually undermine instrumental activities of daily living (IADL). With an older growing population, previous works have explored assistive technologies (ATs) to automate repetitive components of therapy and thereby increase patients' autonomy and reduce dependence on carers. While most ATs were built around screens and projection-based augmented reality (AR), the potential of head-mounted displays (HMDs) for therapeutic assistance is still under-explored. As a contribution to this effort we present *cARe*, an HMD-based AR framework that uses in-situ instructions and a guidance mechanism to assist patients with manual tasks. In a case study with six geriatric patients, we investigated the prototype's feasibility during a cooking task in comparison to a regular paper-based recipe. Qualitative and quantitative results indicate that *cARe* has potential to offer assistance to older individuals with declining cognitive function in their day-to-day tasks and increase their independence in an enjoyable way.

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CCS CONCEPTS

• **Human-centered computing** → **Accessibility technologies**; *Mixed / augmented reality*; • **Applied computing** → Computer-assisted instruction.

KEYWORDS

assistive technology, dementia, augmented reality, mixed reality, IADL, in-situ

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1 INTRODUCTION

As to this day, dementia is a not fully explored condition that affected about 47 million people worldwide in 2015 and is expected to reach 75 millions by 2030 [59]. With a worldwide lack of caregivers, researchers are looking for ways to alleviate the burden on both, patients and caregivers via interventions [3] and assistive technologies [55]. This way, the independence of patients can be increased while the immense treatment costs for dementia can be reduced [60].

With the development of stand-alone AR HMDs such as the Microsoft Hololens, AR became a promising platform for assistive technology [55]. AR support of manual tasks such as maintenance [26], assembly [1] or surgery [23] has been widely researched over the course of the last five decades. These setups usually consist of four key features: registration of objects and spaces via maker-based or marker-less tracking [1], object-fixed or world-fixed virtual content [45], step-by-step instructions [34], and guidance between points of interest [4]. With the development of the inside-out-tracking approach, AR applications for HMDs have found their way into non-instrumented environments such as private homes. The ability to augment every-day objects with visual and acoustic information opened a new path to assist occupational therapists and geriatric patients. However, while related work focused on target groups such as surgeons and industrial workers, usability requirements for cognitively impaired users are still being explored [38].

As a contribution to this effort, we developed a generic AR framework that can be set up by caregivers without any programming knowledge to assist patients with cognitive impairment such as dementia in various manual tasks. The framework's architecture allows it to support any sequence of manual tasks to be a flexible tool for both patients and caregivers. While the framework could theoretically support many tasks, cooking is one of the first IADLs that is affected by dementia and was therefore chosen as an example use-case for the case study [11, 58]. While preparing meals has been the focus of previous work targeting cognitively impaired individuals, to our best knowledge this is the first HMD-based approach [2, 42].

This work describes the design and implementation of an AR support system for cognitively impaired patients and presents insights into challenges during the iterative development process. A case study with six geriatric patients displaying mild cognitive impairment has shown that AR devices might offer assistance to older individuals with declining cognitive function in their day-to-day tasks. The main contributions of this work are therefore:

- Design and implementation of an AR framework for patients with declining cognitive function
- An application for therapists to quickly set up cARe with a new set of instructions without any programming knowledge
- Design guidelines for developing AR assistive technologies for cognitively impaired users
- A case study with 6 geriatric patients showing mild cognitive impairment

2 RELATED WORK

This work is grounded in the field of AR task support and draws from findings in the medical and industrial research which will be discussed in the following. Since *cARe* combines insights from different fields, this chapter is divided into four sections, namely suitability for the target group, guidance, in-situ instructions, and input modalities for AR.

2.1 Suitability of AR for a Cognitively Impaired Target Group

According to a survey of Madjaroff and Mentis, older adults with mild cognitive impairment see technology in their home as an "opportunity for autonomy and safety" [41] . This expresses a general openness of this target group towards assistive technology and motivates us to evaluate head-mounted augmented reality as a means of providing cognitively impaired patients with more independence in their daily life.

Augmented reality has been previously explored with a cognitively impaired target group with promising results. In 2015, Tartanas et al. evaluated a mobile phone based AR serious game as an objective tool to detect amnestic mild cognitive impairment (aMCI) [62]. Their results indicate that motor performance during everyday activities and dual-task walking could be a good marker for early diagnosis of aMCI. Similarly, Boletsis and McCallum proposed an AR serious game for cognitive screening to support early diagnosis of cognitive impairment [5]. They found that "Augmented Reality can be utilized in a meaningful way" and "help bridging the technology gap between ICTs and the elderly users". While not using augmented but virtual reality, Eisapour et al. demonstrated that head-mounted displays are well accepted by older adults with cognitive impairment [12].

2.2 Guidance in AR

To guide a user's attention between points of interest or provide general directional cues in augmented or virtual reality, previous work has explored different modalities. Sodnik et al. propose to register spatial sound with virtual objects [57], while Kaul and Rohs argue that directional cues generated by a head-worn vibrotactile grid are superior to spatial sound [32]. They admit, however, that visual cues are still superior in localization precision and speed. Early pilot tests of the *cARe* framework with geriatric patients wearing the Hololens proved that spatial audio cues could not be localized reliably by the patients. Head-worn feedback generators such as the vibrotactile grid by Kaul and Rohs could be encumbering the user and increase cognitive load. Therefore, no additional hardware was added to the Hololens and only visual navigation concepts were considered for the *cARe* framework.

Off-screen visualization techniques have been well explored for mobile devices but were mostly limited to 2D screens [6, 22]. To avoid visual clutter in HMDs peripheral vision was evaluated to get a user's attention via movement [44] or additional LEDs [21]. Similarly, a miniature map metaphor was suggested to display targets in a physical environment but was found to have a high cognitive load on the users [10]. Similarly, techniques that allow 360 degree vision via distorted vision [47] or visualizations [19] were considered too mentally demanding for the target group.

Since targets in a 3-dimensional environment have 3-dimensional coordinates, Chittaro and Burigat propose 3D arrows to guide users [9]. Their results showed that 3D arrows performed as well as 2D arrows in a walking scenario and even outperformed them in a flying scenario. While 2D arrows have been shown to be well accepted by cognitively impaired individuals for hand-held AR [40], Gruenefeld et al. compared a 3D arrow-based technique with comparable visualizations in AR and reached a lower mental load for the

3D arrow condition [20]. Bocca et al. proposed a funnel metaphor where 3-dimensional segments were placed in approx. 0.2 m distance from each other to create a visual navigation path [4]. Due to the limited space inside a kitchen room, straight guidance cues between instructions could lead to intersections with the user and therefore be more difficult to follow. A novel approach to create curved navigation paths between instructions was designed and implemented in the *cARe* framework (see subsubsection 3.2.1).

2.3 In-Situ Instructions in AR

Since digital and real-world objects are easily distinguishable in an AR HMD [49], the concept of localized instructions in AR has been explored since over two decades [8, 50]. The transition from printed manuals to AR instructions is usually either an adaptation of the printed text to an AR representation [13] or a set of purely graphical instructions via pictures and animations [43]. The advantage of AR instructions over paper-based and screen-based instructions in accuracy and speed has been shown by previous work [26]. This advantage was confirmed for a cognitively impaired user group by Funk et al. where in-situ instructions were compared to traditional pictorial instructions [16]. The benefit, however, seems to depend on the users' cognitive potential [37] and expertise [15]. Experts were found to achieve a lower benefit from AR in-situ instructions than novices and cognitively impaired users that require constant assistance [17].

While AR instructions are not yet well received in industrial settings [54] their benefit in a geriatric facility or private home is not yet fully explored. Although video-based instructions have been found to be superior to AR instructions regarding completion time [18], we argue that therapeutic activities are not a time-critical task and can still benefit from AR-specific advantages such as positioning instructions in an optimal position of the users' field-of-view (FoV) [67].

2.4 Input Modalities for AR

Since this framework is aiming to support a manual task, controllers and other hand-held devices for interaction were not considered in the design process. Wearable devices such as smartwatches have been explored for pointing and selection in previous work by using inertial sensors to control a ray cast from the users' perspective [27, 33]. Pointing tasks, however, are very susceptible to hand jitter [48]. This is a significant limitation considering that geriatric patients can also suffer from tremor that can affect mid-air pointing as well as touch input [51]. Wolf et al. compared gesture-based interaction in AR with an indirect cursor on a smartwatch [63]. Their results indicate that both approaches are feasible but suffer from delays and heavy fatigue effects. Although direct manipulation was fast and efficient, the maximum distance of AR content has to be at arm's length. Considering the cooking use-case and the limited mobility of geriatric patients, this limitation was too restrictive to be considered for the *cARe* framework.

All the aforementioned approaches focus on explicit input by the user. In an implicit interaction a tracking system could recognize the progress of the current manual task automatically. This can be realized via markers on the corresponding items [29] or via model-based recognition [36]. While this approach is promising for industrial use cases where tools and work pieces are standardized, cooking ingredients can be more difficult to track [66].

Speech interaction is considered to be the most natural way of interacting with machines for some people [61] considering that a sophisticated language model is available for the given language [7]. Since older adults often have difficulties using a desktop computer due to little knowledge of computing or impairments such as memory loss, Zajicek et al. explored a voice-based interface to provide internet access via a standard telephone [65]. An online survey by Pradhan et al. uncovered that voice-assistants such as Amazon Alexa are actively being used by users with impairments including cognitive impairment with improvement of independence and ease of use being the most mentioned benefits [52]. Wolters at al. evaluated the specific requirements of spoken dialogue interfaces for people with dementia and suggest an interface that acts like a 'patient, encouraging guide' [64]. This finding is supported by the caregivers that were interviewed during the development of the *cARe* framework. One goal of this work was to mimic this behavior in *cARe*'s voice interface.

3 *CARE* CONCEPT

The ability to perform tasks of daily living independently is a key aspect of an individual's quality of life [58]. Especially older people and patients with cognitive impairment are at risk of functional loss and require regular therapy to retain their independence. With a growing older population and a lack of personnel, caregivers will not be able to provide the same quality and quantity of therapy in the future [35, 53]. To alleviate the burden on caregivers and patients, we propose to outsource repetitive components of therapy sessions to assistive technology. Our vision is that a sophisticated AR system can lead patients through their day-to-day tasks in a caring way while giving them the feeling of independence. The system could be extended by real-time support from therapists or relatives to guide patients through potentially critical tasks such as sorting their pills for the week by providing visual cues in their field-of-view without giving them a feeling of "surveillance" [28]. To test the feasibility of this concept the *cARe* framework was implemented with a user-centered design approach that included repeated pilot studies with cognitively impaired patients and discussions with their caregivers to meet the requirements of both user groups. During discussions, caregivers acted as intermediators as proposed by Johansson et al. [30]. The insights gained during pilot tests and the final framework consisting of a caregiver and a patient application are described in the following.

3.1 Caregiver Application

The input required by caregivers to set up *cARe* for a patient can be seen as two steps: Content generation and room set-up.

3.1.1 Content Generation. Instructions for cognitively impaired patients are in general more detailed than those for users without cognitive impairment (e.g. due to limited memory retention) meaning that a simple cooking recipe can result in many individual instructions, e.g. 'Take a spoon from the drawer'. To facilitate the creation of these instructions a recipe editor was implemented in

WPF with a graphical user interface. Creating a new set of instructions from a given recipe consists of the following steps: First, key-locations required for the recipe are defined, e.g. ‘fridge’, ‘drawer’ and ‘stove’. Then, individual instructions are created and each is assigned to its key-location, e.g. ‘Take a spoon from the drawer’ to ‘drawer’. Pilot tests revealed that complex instructions that include the usage of a scale or measuring cup require additional assistance. To this end, each instruction can be assigned an image file to clarify complex tasks such as using a specific tool or to present a picture of the desired result (see Figure 1 c). Finally, the instructions are exported as an XML-file and copied to the HMD. This step has to be completed only once for each new recipe and concludes the content generation process.

3.1.2 Room Set-Up. Having completed the content generation and, thus, copied the instructions to the HMD, caregivers can now set up a new room for *cARe* support by assigning all key-locations from the list of instructions to their real-world positions. To this end, a Hololens application written in Unity3D displays a mesh of the environment and visualizes the intersection point of the user’s current gaze direction with the mesh. Using the Hololens AirTap gesture, key-locations can be positioned in the room (see Figure 1 a). The application iterates over all key-locations until each has been assigned to a position (see Figure 1 b). Key-locations can be re-positioned using the same technique, namely gaze-cursor for pointing and AirTap for selection. Depending on the current recipe, the room set-up takes only a few seconds to complete and could be also performed by caregivers and relatives in the user’s home in the future.

3.2 Patient Application

In consideration of the specific requirements of cognitively impaired patients reported by related work and experts interviewed during the development of this framework, several mechanisms were integrated into the patient application that was written in Unity3D: an intuitive guidance mechanism, a natural interaction concept, and a motivation mechanism to encourage patients.

3.2.1 Guidance. To provide location information and reduce mental load on the patients, *cARe* uses in-situ instructions, i.e. instructions are displayed at the location they should be executed at. To assist patients in discovering these locations a guidance mechanism was developed in an iterative process. Depending on the kitchen floor plan key-locations can be far from each other or on opposite sides of the room which is challenging considering that the FoV of the Hololens is limited to 30°. Pilot tests of spatial audio cues against visual cues resulted in lower error rates for the visual cues which is consistent with related work [32]. To prevent the visual cue from intersecting with the patient its shape is defined as a Bezier-curve around the patient and updated dynamically (see Figure 2). The curve is calculated via a quadratic Bezier-function that is described by the points P_0, P_1 and P_2:

$$\mathbf{B}(t) = (1-t)[(1-t)\mathbf{P}_0 + t\mathbf{P}_1] + t[(1-t)\mathbf{P}_1 + t\mathbf{P}_2]\ , 0 \le t \le 1 \quad (1)$$

In early prototypes the cue was drawn statically between two consecutive instructions which occasionally resulted in patients losing sight of the cue due to the small FoV. Recovering from this situation proved as challenging since patients were not familiar with the concept of a FoV. For the final prototype, the cue was re-designed to start at the patients’ center-of-view and end at the new instruction position (see Figure 3 a-b). The cue is hidden as soon as the gaze cursor enters the next instruction (see Figure 3 c) and reappears if the patient finishes the current instruction, asks for help or is idle for too long (see Figure 3 d).

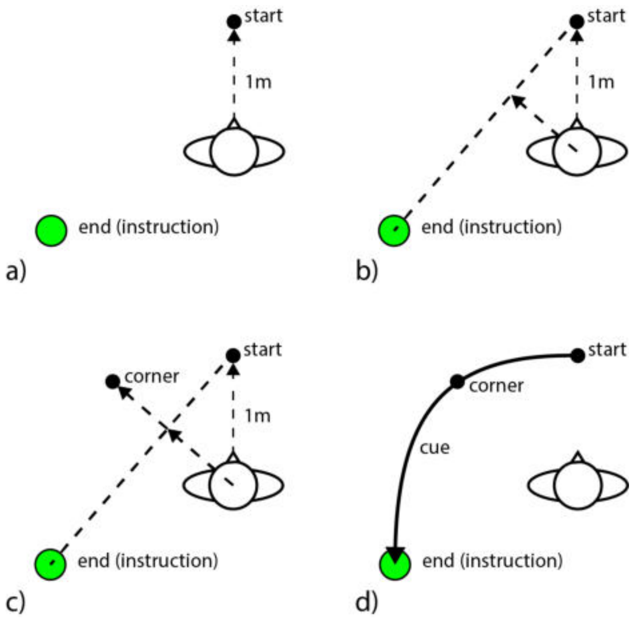

Figure 2: Guidance cues update their shape dynamically. The quadratic Bezier-function used to draw the shape expects three positions: a starting point, a corner point, and an end-point. In each frame, the starting point is defined as a position one meter in front of the patient’s current gaze direction and the end point as the current instruction position (a). To determine a corner point that will curve the shape away from the patient, the HMD’s position is first projected on the vector between start and end point (b). The normalized vector between HMD and the projected point is multiplied by a pre-set factor and added to the projected point (c). The resulting corner point can now be used to calculate a Bezier-curve (d).

3.2.2 Interaction. A low mental demand for the interaction concept was imperative due to the patients’ cognitive impairment. Learning from related work, the interaction via gaze cursor and gestures is physically and mentally too demanding for cognitively impaired patients. Thus, voice input was chosen as the most intuitive and natural interaction modality. Designing an audio interface for cognitively impaired patients is challenging. First, the set of commands has to be kept low due to limited memory retention and be intuitive so that commands can be recalled by logic and instructions repeated if necessary [25]. Second, many cognitive impaired patients suffer from depression and reduced motivation meaning that speech recognition and response time has to be optimized to prevent frustration and confusion. With these requirements in

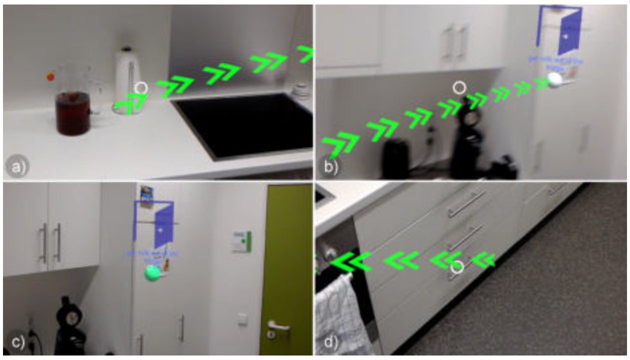

Figure 3: Patient's view of the system: When a new instruction is displayed, patients are guided via cues from their current center-of-view (a) towards the new instruction (b) until the gaze pointer enters the next instruction (c). Saying 'help' or staying idle for a certain amount of time will trigger a cue from the current center-of-view towards the current instruction (d).

mind, a small set of commands was defined in collaboration with patients and caregivers and validated in several pilot tests:

- **'start':** Initiates *cARe* assistance (if the room has been set up beforehand).
- **'next':** Displays the next instruction and draws guidance cues from the current center-of-view. A timeout mechanism prevents triggering this command twice in a row.
- **'back':** Displays the previous instruction and guides towards it.
- **'help':** Draws guidance cues towards the current instruction (if it has been found previously).

The 'back' command was added after some patients ended up skipping instructions while talking to themselves and accidentally saying 'next' in the pilot tests. To prevent frustration during the experiment, a WPF application was implemented as a wizard of Oz mechanism. This way the patient application can be controlled remotely in the case that the speech recognition fails to recognize a command.

3.2.3 Patient Motivation. As cognitively impaired patients often suffer from a feeling of insecurity and a low self-esteem, e.g. due to depression, they require additional motivation. During pilot tests, some patients stopped mid-task and needed additional assistance to continue. In a regular patient-caregiver cooking session caregivers provide regular praise and encourage patients to continue should they get frustrated or get lost in thoughts. Since natural voices are preferred by older adults, this behavior was integrated into the *cARe* framework by recording voice samples of the patients' caregiver containing praising phrases and encouraging words [39]. These voice samples are played back after each completed instruction when the patient triggers the 'next' command. Should patients stay idle for too long, an encouraging phrase is played back to remind them of their task and a visual cue guides them back to the current instruction.

4 CASE STUDY

To our best knowledge, HMD-based AR assistive technology for cognitively impaired geriatric patients has no yet been explored in previous works. To evaluate the potential benefits and risks of this approach we designed a case study with a limited number of subjects. The instruction type was defined as a variable with two levels: *Hololens* and *paper*. Although performance metrics such as cooking time were measured, the goal of this study was to measure the impact of the instruction type on the general ability of the patients to cook individually. The study was approved by the clinic's ethics board and participants were identified by a facility for functional assessment and therapeutic treatment of geriatric conditions. An informed consent was obtained from all patients directly, participants with substitute decision makers were excluded.

4.1 Participants

All participants were selected by a therapist working with the patients and a psychologist assessing cognitive performance. Overall cognitive function was assessed with the Mini-Mental Status Examination (MMSE; [14]). This is a global score with a range from 0 to 30 with 30 indicating no cognitive impairment. Planning capabilities were measured via the "Tower of London" test (ToL; [56]). Six patients (age 73 ± 7.5 years, all female) with mild cognitive impairment (MMSE 27.5 ± 2.1) participated in the case study. It is important to notice that the MMSE is merely a first assessment tool in clinical practice for the beginning of different types of cognitive impairments, which is complemented by others like the consideration of neuropsychiatric symptoms, impairment duration and trajectory as well as different brain functions. All but one participant showed depressive symptoms. One participant was diagnosed with symptoms of dementia. Two of the participants reported to cook on a daily basis, two participants sometimes, and two participants not at all. Only patients showing some impairment of working memory, attention span or planning were included in the study (ToL 14 ± 4). Participants estimated the versatility of using technical instruments on a 5-point Likert-scale with a score of 3.5 ± 1.8 (1: very difficult; 5: very easy). None of the participants had prior experience with HMDs nor AR technology.

4.2 Procedure

To establish a baseline for the case study and measure whether patients were able to cook independently without assistance, patients were instructed to cook with a *paper* recipe from a cooking book at least one day before the *Hololens* condition. Cooking pancakes was selected by therapists as a task being balanced in difficulty and duration. The amount of ingredients was adjusted to suffice for two pancakes. All trials for both conditions were performed in the station's kitchen where therapeutic cooking is usually performed with the patients. Therapists were observing the process via a live video from outside the kitchen. To provide equal conditions therapists were not allowed to intervene even when participants asked for help. If an intervention was necessary (e.g. due to danger or participants being stuck) the trial was aborted to simulate a real scenario. Technical questions and interventions non-related to the recipe (e.g. readjusting the HMD position) were permitted. Aborted trials could not be resumed again and the time of abortion was noted by the therapist. It is important to notice that in case of abortion, participants had no opportunity to practice the subsequent instructions for the next trial, thus reducing the learning bias.

During the *Hololens* condition the following real-time data was recorded: head rotation, head position, instruction position, search time. Both conditions were assessed by an occupational therapist with an experiment protocol that was designed by experts of the local institution. The categories found in Table 1 were created to rate user performance and behavior.

Time	total duration, time until the first question asked, finished with preparing pancake dough, finished first pancake, time of abortion, times looked into paper recipe/asked for help during the prototype condition
Result	a photograph of the end result
Procedure	a list of finished steps, comments regarding initiative, action planning and keeping to the original instructions
Usage of Tools	additional tools used, reasons for deviation from instructions
Hygiene and Safety	handling of tools and stove, additional instructions necessary
Issues	technical issues, reasons for abortion
Behavior	action planning
Self Reflection	post-hoc assessment of performance, comments on usability and issues by the patients
Additional Notes	comments by the therapist, e.g. HMD issues and individual patient background

Table 1: The experiment protocol was created by occupational therapists and was used to document all relevant information during both conditions.

For the *Hololens* condition participants received an extensive introduction by the therapists. First, participants watched a live video transmission from the Hololens perspective while a therapist was interacting with the application and explaining all concepts of the in-situ instruction, voice interaction, and navigation cues. This way, participants could focus on the application itself without coping with the cognitive load of wearing an HMD. After the concept was clear and participants had no more questions they were instructed on how to put on the Hololens. To get used to the interaction and try out all voice commands each participant had to complete a set of instructions to prepare bread and butter. Due to its simplicity the final goal of the recipe was not told in advance. This test recipe gave participants the opportunity to ask questions and therapists to identify mounting issues with the HMD. All voice commands including their functions were printed on a piece of paper and pinned to the kitchen wall.

A trial ended for both conditions upon completion of the meal or abortion by the therapist. After the *Hololens* trial technological competence and acceptance was measured using the TEAG questionnaire [31]. This questionnaire measures the negativity and positivity towards technology and technological enthusiasm and competence with 19 items on a 5-point Likert-scale. On a visual analogue scale participants were asked to rate their overall distress by assigning a score from 0 (no distress) to 100 (significant distress). Subjective workload was measured using the NASA-TLX questionnaire [24]. A custom questionnaire (CQ) was used to assess the general openness towards the prototype. The 7 items in Table 2 were rated on a 5-point Likert-scale (1 - 'strongly disagree', 5 - 'strongly agree').

CQ_Ease	It is easy for me to use technical devices.
CQ_Intro	The introduction to the usage of the Hololens was easy to comprehend.
CQ_Instr	It was easy to follow the instructions presented in the head-mounted display.
CQ_Comfort	The head-mounted display was comfortable.
CQ_Envir	The head-mounted display did not occlude the environment.
CQ_Daily	I would like to use such a head-mounted display in every day life.

Table 2: The general openness towards the prototype was assessed with this custom questionnaire. Items were created in the patients' native language and translated to English for this paper.

4.3 Results - Qualitative

All qualitative data is based on the experiment protocol filled out by an occupational therapist (see Table 1). Items three to seven contain categories created by the therapist to assess patient performance. The number of mentions of theses categories is described below or noted in brackets. Item eight contains patient comments that the therapist considered relevant from a therapeutic point of view. All but one participant were able to successfully prepare the meal using the Hololens, therefore one set of data from the experiment protocol is missing for the *Hololens* condition. We detailed the results in regard to the experiment protocol items.

4.3.1 Hygiene and Safety. The therapist rated the patients according to the categories 'not careful', 'careful', and 'very careful' about hygiene and safety. For the *paper* condition, five of six patients were considered 'careful' and one patient 'very careful'. For the *Hololens* condition, four of five patients were considered 'careful' and one 'very careful'. All six patients in the *paper* condition remembered to close the drawers after usage while one of five patients in the *Hololens* condition forgot to close a drawer. The patient's ability to operate the stove was rated according to the categories 'not able to operate independently' and 'operating confidently'. During the *paper* condition two patients were considered 'not able to operate independently' while four of six patients were rated 'operating confidently'. For the *Hololens* condition, all five patients were rated 'operating confidently'.

4.3.2 Issues. Technical issues appeared only during the *Hololens* conditions and were divided into the categories 'using glasses along with the HMD' (1), a 'slipping HMD' (4), 'loss of tracking (e.g. due to steam)' (2), 'unintentional gesture input' (3), and 'unintentional voice input' (1). Three of the five patients needed an additional explanation of the voice commands and two patients needed an additional explanation of the guidance cues.

4.3.3 Behavior. Patient behavior was rated in the categories 'unstructured', 'structured', and 'very structured'. During the *paper* condition, one out of six patients expressed 'unstructured' behavior, two patients were considered 'structured', and three patients 'very structured'. In the *Hololens* condition, three out of five patients were 'structured' and two patients were 'very structured'. Additionally, the therapist divided patients in the categories 'insecure about cooking independently' and 'cooked without additional help'. Five out of six patients were considered 'insecure about cooking independently' in the *paper* condition and one patient 'cooked without additional help'. All five patients in the *Hololens* condition 'cooked without additional help'.

4.3.4 Self Reflection. This item contains user comments that the therapist considered relevant from a therapeutic point of view. Based on axial coding, these comments were divided into subcategories. The number of mentions of each subcategory was counted and is presented below. In the *paper* condition, some patients were 'disappointed of their performance' (2) and complained about 'unfamiliar kitchen equipment' (2) and 'general insecurity with kitchen tools' (2). Some 'rely on their guts' (1) during cooking or 'use another recipe' (3) when cooking at home. Others considered the paper instruction as 'clear' (2) and cooking in general as 'easy' (1). They had 'no difficulties' (2) and were cooking 'the same way as at home' (2). Only one participant reported to have ceased cooking at home.

In the *Hololens* condition, some patients reported that they 'put themselves under pressure' (2), had 'issues with the arrows (i.e. guidance cues)' (1), perceived an 'uncomfortable weight on the nose' (2) and were 'unfamiliar with voice commands' (1). Some patients praised the concept for not having to 'look at the recipe' (1) and 'seeing the locations of ingredients and tools' (1). Instructions and illustrations were considered 'helpful' (2) and the prototype 'useful to learn how to cook' (3) although some reported to be 'able to cook without the [prototype]' (3). Some patients were 'happy that they tried out the [prototype]' (2) and felt that the '[prototype] took away their anxiety' (2). One patient reported to have enjoyed to 'be in union with the [prototype]'.

4.4 Results - Quantitative

The mean duration of the successful trials was 28 min (SD=15.45 min) for the *paper* and 36 min (SD=9.43 min) for the *Hololens* condition. On average patients asked 6 times (SD=7.6) for help during the *paper* condition and 4 times (SD=3.2) during the *Hololens* condition. One trial was aborted in the *paper* condition and one trial in the *Hololens* condition. The mean subjective workload using the Hololens was 40.83 (SD=12.8) and distress 38.0 (SD=24.0). Results of the custom questionnaire can be found in Figure 4.

Although the limited number of participants allows no reliable significance testing, the recorded quantitative measures were tested for tendencies. The p-values below are reported for the sake of completeness and should be viewed with caution. An analysis of

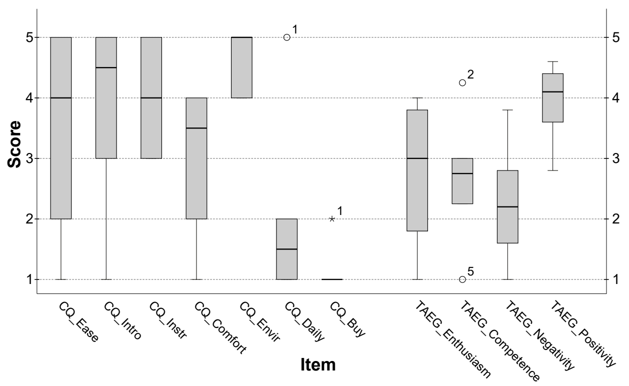

Figure 4: Left: Results of the custom questionnaire (see Table 2). Right: Results of the TAEG questionnaire.

the movement speed during target acquisition revealed no linear relationship between target distance (angle) and movement time. A Spearman's coefficient analysis revealed that the number of meals the participants cooked weekly showed a significant negative correlation with the times participants asked for help ($p = .008, r_s = 0.925$) and required encouragement during the *Hololens* condition ($p = .038, r_s = 0.836$). Furthermore, the self-reported cooking experience of the participants showed a significant negative correlation with the times they needed encouragement in the *Hololens* condition ($p = .034, r_s = 0.845$). The results of the TAEG questionnaire can be found in Figure 4. Overall, participants reached a high positivity score (M=3.93, SD=0.68) and a low negativity score (M=2.27, SD=1.04).

4.5 Limitations

Despite it being a case study the small and only female sample size is a limitation for the generalizability of our results. However, this case study is the very first validation of the prototype and aims to explore tendencies rather than significant results. All patients had no prior experience with HMDs. The impact of the additional workload of using this new technology and the novelty effect that comes with it is unknown. Both effects could cancel each other out or skew user performance in both directions. While all participants were exposed to AR for the first time in their life, this work aims at future generations of geriatric patients that have spent their life getting used to similar technology and interacts freely with it.

Patients had only minor to mild cognitive impairment so that some of the activities needed for cooking (e.g. measuring fluids) were performed independently without reliance on the assistive device. Therefore, a generalized conclusion on the benefit of *cARe* support on patients with more severe cognitive impairment can not be drawn. The benefit of *cARe* for patients with a higher degree of impairment might be larger due to a more affected memory retention.

Participants were performing the task for the second time during the prototype condition and might therefore have gained a certain advantage. It is important to note, however, that the trial was aborted in the baseline condition if the participants asked for help, making it impossible to learn from mistakes and prepare for the next condition. Furthermore, a learning effect would be expected to decrease the cooking time for the second condition, but the opposite was the case.

Although, potentially, *cARe* can support any manual task that can be described by in-situ instruction steps, there is no sophisticated process management system involved that could support parallel processes, e.g. cooking pasta while preparing the sauce at the same time. Furthermore, patients tended to skip instructions or jump several steps ahead to return later to where they left off. This kind of navigation between instructions is not supported yet. Some voice commands were not recognized properly when the environment was too loud, so that a wizard of OZ mechanism was required to trigger the next instruction in these cases and thereby reduce frustration on patient side. Steam seems to be problematic for the spatial tracking cameras of the Hololens which sometimes led to a loss of tracking while hovering over a steaming pot.

Since the focus of this work lies on the patients, the usability of the caregiver application was not considered and requires further optimization to be usable by non-instructed caregivers in the future. An important feature would be the automatic upload of instructions to the patient's application.

4.6 Discussion

Overall, patients expressed a high curiosity towards new technology which is reflected in above average scores for subjective technical versatility (see Figure 4 CQ_Ease) and high positivity scores in the TAEG questionnaire (see Figure 4 TAEG_Positivity). The prototype was well received and the introduction of its features rated as easy to understand (see Figure 4 CQ_Intro). P5 commented that 'cooking with the [prototype] was interesting and fun' and P1 was 'glad of the opportunity to try [...] out [the prototype]'.

Comfort of wearing the HMD was rated below average and could be a result of the 'heavy weight on the nose' (P6) perceived by some patients. Usually, this weight can be reduced by a tight fit of the Hololens head band. In this work, the HMD was adjusted by the therapist and had to be re-adjusted during the experiment on several occasions. With more experience, patients could learn how to readjust the HMD by themselves and thus require less assistance.

Half of the patients required additional explanation of the voice commands and commented that they were 'unfamiliar with voice commands' (P3) in general. Due to the requirement to 'speak louder than usual' (P3), some commands were not recognized properly and had to be triggered via a wizard-of-Oz mechanism. In general, most inquiries for explanations were of technical nature and could be reduced as patients get more familiar with the prototype. Self-reported cooking experience was a good indicator for the amount of help and encouragement needed by a patient. This could be a result of splitting limited resources between the cooking task and coping with a new technology.

While two patients needed an additional explanation for the guidance cues, the instructions were perceived as comfortable and helpful. Patients rated that instructions were easy to follow and did not occlude the environment (see Figure 4 CQ_Instr and C_Envir). P1 specifically liked that she did not have to 'look at a paper but rather get the recipe step-by-step and see the location of the ingredients'.

Although we could not find a statistical decrease of the time required to find an instruction, we believe that more data (e.g. of several cooking sessions per participant) could provide more insights on the changes over time. The higher average cooking time in the *Hololens* condition could be explained by the high granularity of instructions that is aiming at a population with higher cognitive impairment than patients in this sample. This result is consistent with previous work where cognitively non-impaired users were hindered by too much assistance [17].

While consideration for hygiene and safety was rated as similar for both conditions, one patient forgot to close a drawer during the *Hololens* condition which is a safety risk. This lack of caution could be explained by the additional cognitive resources necessary to 'understand the [prototype] and the process' (P5). Additionally, some patients stated that they put themselves under pressure and felt an 'initial nervousness and worry to not be able to comprehend the technology' (P3). This could be an explanation for the increased subjective workload and distress scores. Nevertheless, patients reported that although the '[prototype] felt unfamiliar, [they were] able to understand and execute each instruction' (P3). We expect that more experience with the prototype could reduce the anxiety of making mistakes and further reduce the cognitive workload of operating the prototype.

During the *paper* condition, some patients were rated as unstructured in their planning, insecure about using the stove, and as not able to operate the stove independently by the therapist. On the contrast, all patients were rated as structured, confident, and independent in operating the stove during the *Hololens* condition. An explanation was provided by P1 who reported that she was 'afraid of turning on the stove, but the instructions on how to operate the stove reduced [her] anxiety'.

Half of the patients reported that the prototype could be helpful to acquire or maintain the ability to cook. Since most patients had experience in cooking, half of them reported that they had no need for the prototype. This is also reflected in the low scores for a daily use of the prototype and the willingness to acquire it (see Figure 4 CQ_Daily and CQ_Buy). P6 explained that 'the [prototype] was slowing [her] down due to [her] cooking experience' but it would be 'ideal for people that can not cook'. Due to the mild cognitive impairment of the participants, P5 added that the prototype would be more beneficial for 'people with impairments'.

Overall, the independence of patients could be improved when cooking with the prototype. Most issues that required an intervention were of technical nature and could be reduced with a more advanced HMD. The guidance mechanism and instructions were rated as comprehensive and the concept as promising for a cognitively more limited user group. Further investigation is necessary to explore long-term effects of cooking with the prototype.

5 IMPLICATIONS FOR FUTURE WORK

As discussed above, patients expressed a generally positive attitude towards the concept but were concerned about cognitive load. For the purpose of person-centered care according to the NICE guidelines, it is of importance to know which features were considered helpful and how wearing the prototype made the participants feel. This feedback provides valuable insights for designers of future assistive technologies which might assist cognitively impaired patients in their independence as long as medically possible [46]. To assist future researchers in developing AR assistive technology, the findings of this case study were distilled into design implications.

5.1 Individualized Assistance

Some patients felt restricted by unfamiliar ingredients, recipes, and actions. Since *cARe* is not focusing on teaching patients new skills but rather helping them retain their existing knowledge, future versions could record point-of-view videos of users during their performance in early stages of cognitive degeneration and provide these videos as instructions as the degeneration progresses. This way, each patient would receive individual instructions that could trigger personal memories and help retain individual preferences.

5.2 Comfort

Many geriatric patients rely on glasses to read texts and perform day-to-day tasks. Since most HMDs such as the Hololens can not be used in unison with regular glasses without resulting in an uncomfortable pressure on the nose bridge, researchers should use an insert frame for lenses with individual prescription. Seeing how the HMD had to be re-adjusted on several occasions during the experiment, users should receive a proper training on how to adjust the HMD. Using a more light-weight device could further mitigate this problem.

5.3 Speech Recognition

We observed that memorizing voice commands was cognitively more demanding than using voice input in general. On several occasions, patients used commands that did not match the set of predefined commands but expressed the same semantic. Using a wider set of voice commands or a more natural speech recognition module could reduce the cognitive load on patients and improve the 'dialogue' between patient and assistive technology.

5.4 Illustrations

During the case study, we used illustrations of the actual tools and ingredients that were being used in the recipe. This detail seemed to increase the clarity of complex instructions such as using a scale to measure a certain weight and decrease anxiety of using tools such as the oven. Especially for cognitively impaired patients recognizing familiar objects could trigger memories and make it easier to retrieve the objects displayed on the illustrations. We therefore argue that pictorial instructions should be individualized for each patient. Exchanging media files for instruction steps is already realized as a feature in the therapist application or *cARe*.

6 CONCLUSION

We have presented *cARe*, an AR framework that can support caregivers in treatment of cognitively impaired patients by outsourcing task support and training for IADLs to an AR assistive system. The prototype was carefully designed in collaboration with experts, caregivers, and patients to meet all the necessary requirements for a support system that allows cognitively impaired patients to retain the ability to perform IADLs autonomously. In an iterative approach, we implemented and evaluated a novel guidance mechanism, a voice interface, and a motivation mechanism. Patients were generally positive towards the new technology and were successful in cooking with *cARe* support. From a geriatric point of view this case study clearly demonstrates that augmented reality may support those everyday functions that got lost in older persons with missing day-to-day practice, experience, or due to aging and disease.

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Performance Envelopes of In-Air Direct and Smartwatch Indirect Control for Head-Mounted Augmented Reality

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Performance Envelopes of In-Air Direct and Smartwatch Indirect Control for Head-Mounted Augmented Reality

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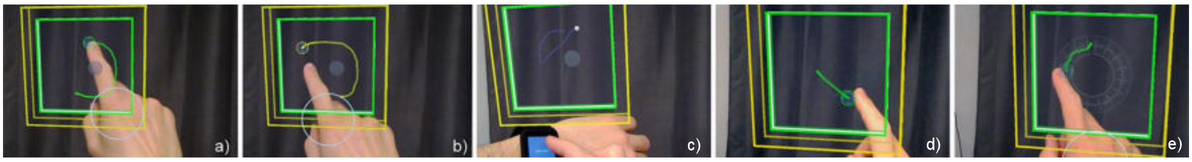

Figure 1: A view of the experiment interface with the two input techniques and three tasks (target acquisition (a-c), goal crossing (d), and circular steering (e)) investigated in the paper. The direct in-air cursor follows the hand position and leaves a green trail to indicate proximity to the ideal selection plane (a) and a yellow trail to prompt the user to adjust the cursor depth (b). The indirect smartwatch cursor is controlled with the smartwatch (c).

Abstract

The scarcity of established input methods for augmented reality (AR) head-mounted displays (HMD) motivates us to investigate the performance envelopes of two easily realisable solutions: indirect cursor control via a smartwatch and direct control by in-air touch. Indirect cursor control via a smartwatch has not been previously investigated for AR HMDs. We evaluate these two techniques for carrying out three fundamental user interface actions: target acquisition, goal crossing, and circular steering. We find that in-air is faster than smartwatch ($p < 0.001$) for target acquisition and circular steering. We observe, however, that in-air selection can lead to discomfort after extended use and suggest that smartwatch control offers a complementary alternative.

Keywords: Fitts' law; steering law; goal crossing; in-air selection; smartwatch; indirect cursor; AR; augmented reality

Index Terms: Human-centered computing—Human computer interaction (HCI)—Interaction paradigms—Mixed / augmented reality

1 Introduction

We envisage a future in which the smartphone is replaced by an interactive near-eye display (NED). The need to preserve mobility and interactivity within the physical world suggests that such devices will deliver augmented reality (AR) experiences rather than purely virtual ones. To enable this vision it is imperative that users are supplied with appropriate techniques for making selections and manipulating interface elements in AR. These techniques must not only be fast and accurate but must also accommodate other usability considerations such as comfort and social acceptability. This future vision motivates research into how both established and novel input techniques perform in the context of head-mounted AR devices. We anticipate that the ideal solution will not be provided by a single input technique but by a suite of complementary alternatives with fluid transitions between techniques.

In this paper we evaluate and compare direct hand-tracking based cursor control and selection with an indirect alternative based on a smartwatch. In the context of this paper we refer to the hand-tracking based technique as *in-air*. The in-air technique is intentionally closely aligned to the physical act of touching, sliding and dragging real world objects. The cursor position is directly controlled by movement of the hand. The smartwatch based technique leverages the familiarity of a touch-screen but at a reduced form factor. Importantly, the smartwatch interaction technique as explored here is indirect in the sense that the touch point on the screen is mapped to a corresponding point in the AR environment.

Among the multitude of possible interaction techniques suited to AR, we examine the smartwatch and in-air techniques for primarily two reasons. First, in both techniques the user's hands remain unencumbered; leaving them free to interact with the environment. Second, we hypothesise that the two techniques are *complementary*: in-air movements are high amplitude but low precision and smartwatch inputs are low amplitude but high precision. In addition to the two reasons listed above, both techniques can be immediately delivered through currently available consumer hardware.

This paper reports on the evaluation of the in-air and smartwatch techniques for three well established fundamental user interface actions: target acquisition, goal crossing and circular steering. These fundamental *actions* combine in designs to form high-level interaction *tasks* (that is, sequences of actions and decisions). Actions provide an experimentally controllable and standardised basis for comparing the two techniques. The evaluation focuses on comparing performance, that is, time (with error controlled), using established mathematical models of human performance for target acquisition, goal crossing, and circular steering. In addition, we report participants' qualitative responses when carrying out the experiment to capture indications of additional factors, such as comfort.

Understanding the performance envelope, that is, the strengths and weaknesses of an interaction technique over typical interface element sizes, provides valuable design insight and can aid both manual design of AR interfaces and be fed into a user interface optimization process, for example by incorporating the human performance model parameters from our experiment into objective functions.

In summary, our contributions are:

1. A validation of smartwatches as indirect control devices for HMD AR.
2. An exploration of the performance envelopes and model parameters for three fundamental user interface actions using in-air direct and smartwatch indirect control.
3. A set of design implications distilled from the experiment.

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2 Related Work

The in-air technique examined in this work represents an extension upon a well established body of research. Historically, most in-air interactions with virtual content have relied on external sensing, requiring markers [7] and/or input devices that encumber the user [25]. Mobile, hand-held devices are nevertheless effective and indeed necessary in certain contexts. Users will naturally prefer a mobile, hand-held input device over tethered cables [4]. We do not argue that hand-held devices have no place with AR HMDs but rather that their use may be precluded in certain use cases, for instance, for a technician who must frequently interact with different physical objects.

Marker-less hand-tracking as supported by the Microsoft HoloLens is a major step forward towards free-hand interaction with mixed virtual-physical environments. The user remains mobile and unencumbered thanks to egocentric sensing. However, in-air interaction based on the physical hand position is not always suitable or preferable. For example, a user may seek to interact with objects that are out of reach or distant. As a consequence, there is potential value in virtual pointer techniques that augment the hand position in some way. For example, a pointer could be presented as a ray extending the user's hand [8] or a virtual hand as defined by Poupyrev et al. [20]. Poupyrev et al. [20] showed that virtual pointers can be efficient to select distant targets, but suffer a loss of accuracy with increasing distance.

An alternative to augmenting the physical hand position through virtual pointers is the use of additional complementary input devices. Ohta et al. [19] proposed smartwatch-based navigation and interaction in a virtual shop to facilitate the shopping process for disadvantaged users, for example senior citizens. AR representations of products could be selected and viewed from various angles via direct selection on the smartwatch touchscreen. To increase selection precision and enable interaction with distant displays, Hartmann et al. [11] proposed to reintroduce mouse-based interaction for tabletops, while Mane et al. [17] argue that precise interactions in a virtual screen should be performed on a two-dimensional touchscreen. Touchscreen controlled cursors have already been applied in the public screen context for multiple users [18], single user [21], and presentation slides [6]. Huo et al. [13] demonstrate the potential value of using a touchscreen to draw projected lines onto physical surfaces. Similarly, we argue that in-air direct selection can be meaningfully complemented by indirect smartwatch-based cursor selection.

Rohs and Oulasvirta [23] explore the performance of "peephole" pointing in the context of magic lens interfaces for large displays. When there is no background context and the peephole content is generated dynamically, they found that Fitts' law does hold. However, when background context is present, they observe that Fitts' law does not accurately model the performance of target selection using a magic lens interface. They hypothesize that this is due to the disruption in the visual feedback loop as the lens is moved over the background scene. In response, they propose a two-part model that separates the physical and virtual stages of the pointing task which improves the movement time prediction model. They subsequently validate that this model holds in a real-world AR task in which the user must target buildings using the "peephole" interface [24]. The investigation of Rohs and Oulasvirta is an interesting example of complex interactions introduced by the human visual and motor control system and highlights the value of examining new and fundamentally different forms of selection control.

3 Interface Actions and Performance Models

We examine three user interface actions: target acquisition, goal crossing, and circular steering. Each of these actions have been extensively investigated in the literature and robust human performance models have been derived for each of them. We also highlight the relevance of these different interface actions from an interaction design perspective.

3.1 Target Acquisition

Target acquisition is the act of moving to and then designating (e.g. selecting) a desired target. Fitts' law predicts that the Movement Time (*MT*) required to make a selection is linearly proportional to the Index of Difficulty (*ID*) of the target. Index of Difficulty is a non-dimensional metric describing the relative difficulty associated with the geometry of the selection interface. The relationship between (*MT*) and (*ID*) can be expressed as

$$MT = a + bID, \tag{1}$$

where a and b are linear regression coefficients. According to the Shannon formulation of Fitts' law [16], ID is defined as

$$ID = \log_2\left(\frac{D}{W} + 1\right), \tag{2}$$

where D is the distance to the target, and W is the width of the target. Throughput (*TP*) is often used as a summative measure representing the efficiency of the target acquisition method, i.e. an efficient method accommodates difficult targets nearly as well as easy targets. Throughput is computed as the inverse of the regression line gradient, that is, $TP = 1/b$.

Target acquisition can be thought of as an abstraction of the basic task of pressing a button. Even typing on a keyboard can be framed as a sequential target acquisition task [5]. Target acquisition thus represents a fundamental interface action.

3.2 Goal Crossing

Goal crossing is the act of intersecting the boundaries of an object, for example entering a button. While acquiring small targets can be time-consuming, crossing targets are only limited in one dimension, that is, the target width perpendicular to cursor movement. Accot and Zhai [2] discovered that the mathematical formulation for the movement time model of target acquisition (Fitts' law), also models goal crossing, that is, crossing targets. If W is target width and D the distance to the target then the movement time to cross the target is modelled by Equations 1 and 2.

Goal crossing as an action can be exploited to support rapid sequential selection of interface elements. However, crossing is not widely used in modern 2D interfaces despite its demonstrated potential. This is in part due to the fact that the majority of crossing research derives from pen-based interaction contexts. For example, Apitz and Guimbretière [3] demonstrate a simple drawing application designed to exploit the fluidity and speed of crossing interactions with a pen on a tablet. Apitz and Guimbretière [3] also motivate the use of the crossing action as a means to accommodate the typically noisy trajectories associated with pen input.

FlowMenu [10] is another example of a feature rich interface element built to exploit crossing actions. FlowMenu supports the fluid navigation of hierarchical menus with minimal motion trajectories. As a consequence, menu elements can remain small and the interactions inherently accommodate small display sizes. This example has particular relevance to the AR scenarios examined in this paper for two reasons. First, the display region of currently available AR NEDs is relatively narrow, limiting the size and placement of visual interface elements. Second, using a smartwatch as an input surface is constrained by the small screen size limiting the shape and size of potential trajectories.

Luo and Vogel [15] evaluate crossing-based selection on a touch input surface. They highlight that the value of a crossing-based interface is only realised when continuous selections can be chained together, and that, "if [there are] many discrete crossing actions, the benefit is lost" [15]. It is thus important to be aware of the influence that usage context may have on the practical benefits of a particular interface action.

3.3 Circular Steering

Circular steering is a trajectory-based interaction where a cursor is navigated through a circular tunnel without leaving its boundaries. Accot and Zhai [1] found that the movement time for steering through a circular tunnel of a given radius R and width W can be predicted by

$$MT = a + bID_C, \quad (3)$$

where circular Index of Difficulty (ID_C) is defined as

$$ID_C = \frac{2\pi R}{W}. \quad (4)$$

Circular steering throughput, TP_C is computed as the inverse of the regression line gradient, $TP_C = 1/b$.

The linear equivalent of circular steering is frequently encountered in the navigation of hierarchical menus. Navigating through a circular tunnel is a reflection of the general ability to follow a curved trajectory. Bounded curved trajectories may be encountered in dial type interface elements or as part of other selection operations such as lassoing [26]. Circular steering is significantly more difficult than an equivalent linear steering configuration due to the additional coordination required [1].

4 TECHNIQUE EVALUATION

This section describes the experimental setup and procedure used to evaluate the in-air and smartwatch input techniques for target acquisition, goal crossing, and circular steering. The experiment was a within-subjects design with 20 participants (10 female) recruited via convenience sampling. Participants were aged between 19 and 60 (mean = 33, sd = 12.3). No participant had prior experience with an AR HMD and only four had previously used a smartwatch.

4.1 Apparatus

The system for the experiment consisted of three components:

- A *Microsoft HoloLens* served as the interactive near-eye display. In addition to providing the interface display environment, the device also provided the coarse hand tracking functionality necessary for the in-air direct cursor control technique. The HoloLens application also acted as a server for receiving and handling the touch events reported by the smartwatch.
- A *Sony Smartwatch 3* running on Android 6.0.1 (API 23) with a screen resolution of 320 × 320 pixels on a 28.7 × 28.7 mm display. The smartwatch ran a client application that registered touch events and reported these to the HoloLens over a TCP connection.
- A dedicated wireless router provided the TCP communication layer between the smartwatch and the HoloLens.

4.2 Interface for Experiment

The interface for the experiment was presented at a distance of approximately 0.5 m from the user and had an apparent real world size of approximately 200 × 200 mm. This size was chosen as it approximately represented the maximum size of an interface that completely fits within the HoloLens' display region when presented at a distance comfortably reachable by the user.

The HoloLens provides coarse hand tracking and the reported position was used to approximate the location of the index finger. It is important to note that the hand tracking does not provide any articulation information and so the index finger location is only approximated. A cursor, referred to subsequently as the *index cursor*, is placed at this location. The user can control the index cursor by moving their hand within view of the headset. Note the feasible tracking region is considerably larger than the display region and so tracking loss was not an issue in this experiment.

A three-dimensional gesture pane was implemented to enable continuous in-air gestures rather than just simple touches. This gesture pane provides feedback to the user on the deviation of the index cursor from the central plane. This feedback helps restrict the user to performing gestures in a fixed plane (within an allowed tolerance). When the index cursor was inside the gesture pane and within the required tolerance of the central plane, the user was presented with a green line trail (see Figure 1a and Figure 2). If the index cursor exceeded an intermediary tolerance threshold, the user was presented with a yellow line trail (see Figure 1b), indicating that they should adjust their depth position to stay within the ideal gesture pane.

All touch events on the smartwatch were sent via a TCP socket to the HoloLens and rendered on the same gesture pane described above. A cursor indicated the most recent touch event and a trailing path of fixed point length was shown (see Figure 3). The average cursor update interval was 30 ms, which allowed users a smooth selection with an average delay between touch event and cursor update of 50 ms.

Every successful selection in both input methods was confirmed by a sound. All selections were calculated by detecting three-dimensional collisions between the index cursor and the target mesh (in-air selection) or by collapsing all three-dimensional pointer coordinates onto a two dimensional interface where a simple boundary check was performed (smartwatch selection).

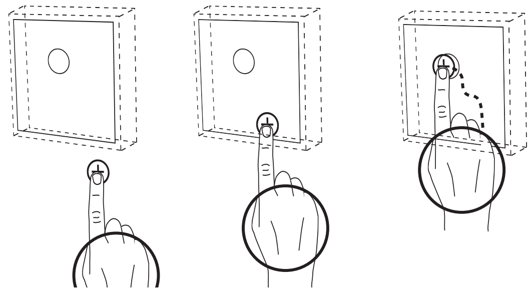


Figure 2: Direct in-air cursor. The current index cursor position is illustrated by a circle and a cross. A trail of fixed length displays the recently traced path. In the experiment interface the color of the cursor trail was used to indicate proximity to the ideal gesture pane and to cue participants to regulate their depth (green trail: within tolerance, yellow trail: adjust depth to meet tolerance).

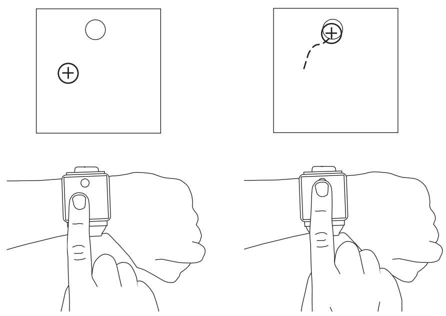


Figure 3: Indirect smartwatch cursor. The most recent touch point is displayed as a cursor. A trail of fixed length indicates the recently traced path.

4.3 Procedure

We conducted a within-subjects experiment, using a factorial design with two conditions:

- **SMARTWATCH**: Indirect cursor control based on smartwatch touch surface.
- **IN-AIR**: Direct cursor control based on coarse hand motion tracking.

All tasks used lift-off to indicate a selection. The reason for a lift-off metaphor lies in the nature of both conditions. Triggering targets in-air based on collision alone would lead to the “Midas touch problem” [14] and select every interface item on the cursor path when used in combination with a rich user interface. Therefore, an explicit selection has to be made by leaving the gesture pane.

Further, the smartwatch condition offers no visual feedback in the interface when there is no touch event. As a consequence, selecting targets on an instantaneous touch alone would render a very low success rate and would not comply with Fitts’ law behaviour. Instead, we allow the user to move the cursor, while contact with the touch surface is maintained, and designate an explicit selection by the lift-off event.

The dependent variable was Movement Time (*MT*). Each condition was tested for user interface actions: target acquisition, goal crossing, and circular steering. The order of the tasks was allocated with a 3×3 Latin square. Target parameters were balanced with a balanced Latin square.

Prior to commencing the experiment, participants were encouraged to familiarise themselves with each selection technique and task. During the familiarisation phase, participants were free to repeat any task until they felt comfortable with their performance. The order of conditions was balanced with the first condition alternating for each consecutive participant. All tasks were completed in one condition before proceeding to the next condition. We encouraged all participants to take off the HMD between each condition to rest their eyes and relax their arms.

Participants performed the experiment while seated and facing a dark flat-colour background. The smartwatch was worn on the non-dominant hand. Selection was performed with the index finger of the dominant hand for both the in-air and smartwatch conditions. Targets were only dismissed upon a correct selection.

4.4 Target Acquisition

The *ID* range and values examined in the target acquisition and goal crossing tasks were chosen from within the bounding constraints of the interface size and minimum feasible target size. The target widths (W = 20, 30, 40, and 50 pixels) and target distances (D = 70, 120, 170, 220, and 270 pixels) are expressed in pixels relative to the smartwatch screen (with a resolution of 320 × 320 pixels) and define 20 unique IDs ranging from 1.26 to 3.86 bits. All 20 W-D conditions were balanced with a balanced Latin square and participants performed 22 trials within each condition.

For a valid selection, participants had to release the cursor within the target (see Figure 4). As releasing the cursor in the in-air condition was a three-dimensional task, early pilot studies showed that selections would often fail due to the cursor leaving the target during a release. Therefore, a distinction between in-air and smartwatch selection was introduced:

- **In-Air selection:** Targets are selected by moving the hand to generate a collision between the index cursor and the target. To select the next target, the hand must first be retracted from the gesture pane before reentering.
- **Smartwatch selection:** Targets are selected by placing the cursor within the target and then lifting the finger from the touch surface. Lifting the finger while the cursor is outside of the target is a selection error even if the target was previously intersected.

We discuss the implications of this distinction in selection behaviour later in Section 6.3.

4.5 Goal Crossing

Goal crossing was identical for both smartwatch and in-air selection. Participants were asked to start their selection in the centre of the interface, cross the target, and release without returning to the centre again (see Figure 5). Missing the target or crossing in the opposite direction (that is, from outside to inside) did not count as a valid selection and had to be repeated again. The index cursor had to remain within the ideal gesture pane during the actual intersection while crossing the goal.

4.6 Circular Steering

The circular steering task is illustrated in Figure 6. The tunnel opening was rotated by 90 degrees between each trial to cover four different starting positions. The necessity of a tolerance at the tunnel opening was determined in early pilot studies. This is a deviation from the original task description in Accot and Zhai [1] due to the uncertainty inherent in in-air and smartwatch-based selection.

For a valid circular steering action, the cursor path must satisfy the following criteria: 1) the first cursor position that lies within the tunnel has to be close to the opening (with a tolerance of 50°); 2) the first cursor position that lies outside of the tunnel after exiting it has to be close to the opening (with a tolerance of 50°); and 3)

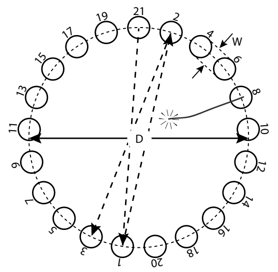


Figure 4: Target acquisition task. Selection can start at any position but must end within the target (smartwatch) or pass through the target (in-air).

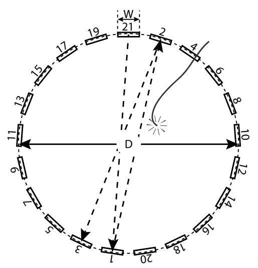


Figure 5: Goal crossing task. Selection has to start within the circle and end after crossing a goal for a valid trial. In-air cursor must stay in the target plane.

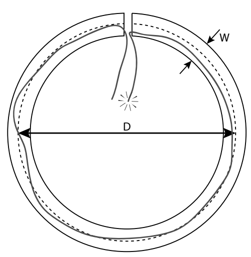


Figure 6: Circular steering task. Selection starts by entering the tunnel opening, steering through the path in a specified direction, then leaving though the same tunnel opening. Entry/exit through the opening has a tolerance of 50°. The circular Index of Difficulty is the quotient of tunnel circumference and tunnel width.

the tunnel has to be steered in the direction indicated by the arrows displayed on the tunnel (clockwise or counter-clockwise).

A different range of index of difficulty values were chosen for the circular steering task due to the different definition of circular index of difficulty, ID_C. According to Equation 4, ID_C is a quotient of tunnel circumference and tunnel width. Therefore, the lowest ID_C that can be defined without the tunnel overlapping with itself is given for $W = 2R$, resulting in an ID_C of π (note that ID_C is not expressed in terms of bits). The tunnel width (W = 30, 40, 50, and 60 pixels) and tunnel circumference (D = 200, 350, 500, 650, and 800 pixels) define 20 unique ID_C values ranging from 3.33 to 26.67. This approximates the range chosen by Accot and Zhai [1] in their original work on circular steering. In our experiment, each *D-W* condition consisted of only four trials due to the time consuming nature of this particular task.

5 Results

This section summarizes the performance of the in-air and smartwatch techniques across the three examined interface actions.

5.1 Target Acquisition

The average movement time across participants in all IDs was 886 ± 87 ms (one standard deviation) for In-Air and 1275 ± 162 ms for Smartwatch. Repeated measures analysis of variance revealed that the difference was statistically significant ($F_{1,19} = 145.01, \eta_p^2 = 0.884, p < 0.001$). Figure 7a shows average movement time (*MT*) as a function of Index of Difficulty (*ID*) across participants. The throughput (*TP*) was 1.75 bit/s for Smartwatch and 4.17 bit/s for In-Air target acquisition.

5.2 Goal Crossing

The average movement time was 1168 ± 452 ms for In-Air and 1269 ± 250 ms for Smartwatch. A repeated measures analysis of variance did not reveal a significant difference ($F_{1,19} = 1.390, \eta_p^2 = 0.068, p = 0.253$). Figure 7b shows average *MT* as a function of *ID*. The throughput was 4.00 bit/s for Smartwatch and 9.09 bit/s for In-Air goal crossing.

5.3 Circular Steering

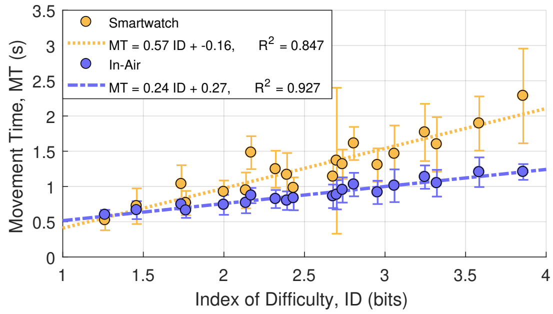
The average movement time was 4276 ± 1217 ms for In-Air and 5575 ± 1088 ms for Smartwatch. A repeated measures analysis of variance revealed that the difference was statistically significant ($F_{1,19} = 44.857, \eta_p^2 = 0.702, p < 0.001$). Figure 7c shows average *MT* as a function of ID_C. The throughput (TP_C) for Smartwatch circular steering and In-Air circular steering was 2.33 s^{-1} and 4.00 s^{-1} respectively.

5.4 Agreement with Performance Models

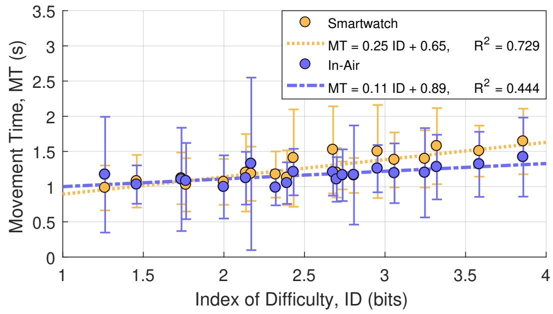
Figure 7 shows the linear regression models for target acquisition, goal crossing, and circular steering. Model fits are calculated using the coefficient of determination (R^2), which is the proportion of the variance in movement time explained by index of difficulty or circular index of difficulty. Overall the model fits are high, in particular for the Fitts' law target acquisition task and the circular steering task. The fit is reasonable for Smartwatch goal crossing ($R^2 = 0.729$) but quite poor for In-Air ($R^2 = 0.444$). We conjecture the poor model fit for In-Air goal crossing is due to the difficulty of adjusting the depth and the position of the hand simultaneously. This conjecture is supported by the high intercept value of 0.89 (see Figure 7b).

6 Discussion

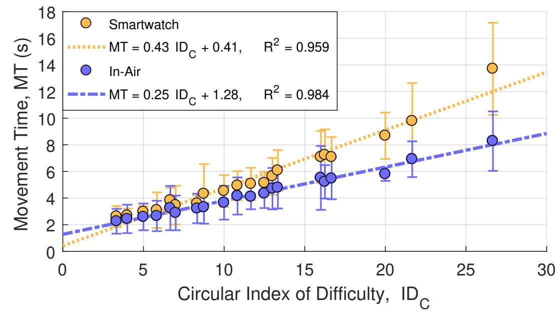
The results suggest that In-Air selection is consistently more efficient than Smartwatch. This is also reflected in the significantly faster movement times for In-Air in target acquisition and circular steering.



(a) Target Acquisition



(b) Goal Crossing



(c) Circular Steering

Figure 7: Across-participants, mean movement time *MT* versus index of difficulty *ID*. Error bars show ±1 standard deviation.

Interpreted in the context of the previously related studies, the throughputs determined in target acquisition for In-Air (4.17 bit/s) and Smartwatch (1.75 bit/s) are approximately consistent with values reported in [9] (8.05 bit/s on a tabletop display with direct-touch and 4.35 bit/s for mouse-based selection). It is reasonable to expect that In-Air performance would be considerably worse than a physical tabletop alternative given the coarse hand tracking provided by the HoloLens in addition to the less ergonomic alignment of the interface selection plane.

The throughput TP_C in the circular steering task (Smartwatch: 2.33 s^{-1}, In-Air: 4.00 s^{-1}) was also in the range reported by Accot and Zhai [1] where the circular steering was performed with several physical devices (mouse (5.5 s^{-1}), tablet (5.4 s^{-1}), trackpoint (3.7 s^{-1}), trackball (3.0 s^{-1}), touchpad (2.5 s^{-1})).

An interesting result was the comparatively similar performance of the two techniques in the goal crossing task. We observed high variance in the measured movement times and no significant overall difference between the two techniques. The throughput for In-Air was approximately double that for Smartwatch, however, the model fit is relatively poor.

An alternative perspective on the results presented in Figure 7, however, is that at low *ID* values the performance of the two techniques converge. If interface elements can be held in these *ID* ranges, other usability considerations might dominate which technique is most suitable. This finding highlights the value of investigating the performance envelope of a diverse range of interaction techniques over a wide range of *ID* values.

A potential factor contributing to the generally worse performance of SMARTWATCH is the additional cognitive demand imposed by the indirect control of the cursor. The user must learn the mapping between the cursor position and the touch location on the smartwatch screen. The fact that the touchscreen is so small means that the scaling required is comparatively large. Although this scaling remains consistent, the scaling up of small movements may significantly exacerbate errors and negatively affect usability. In the context of this study, however, we sought to remove any potential learning affect associated with the control techniques by providing a familiarisation period. Nevertheless, the potential effect of the additional cognitive demand associated with indirect cursor control cannot be eliminated without extensive use. This could mean that the difference in performance observed between the two techniques may decrease with increasing use.

In summary, in-air selection appears to show a definite performance advantage over smartwatch input. However, while conducting the experiment, we received consistent feedback from participants that the in-air technique was fatiguing and uncomfortable after prolonged use, which indicates that actual AR interfaces should limit the frequency of in-air selections to a comfortable value. In contrast, participants generally found smartwatch input comfortable and relaxing to use.

Although untested specifically in this study, participants also expressed their concerns about social acceptance of in-air interactions. By comparison, the social acceptability (at least in the immediate future) of the smartwatch technique is more favourable. The smartwatch technique aligns closely with three of the four key reasons for liking a gesture as proposed by Rico and Brewster [22]: subtle movement, similar to existing technology, and looks or feels similar to everyday actions.

6.1 Integrating Complementary Selection Actions

The performance envelopes of in-air direct and smartwatch indirect control suggest that the two techniques may be complementary. The user can fluidly transition between techniques since each relies on a different control mechanism. The in-air index cursor is always available to manipulate within-reach interface elements while a hand is inside the tracking volume of the NED. The indirect cursor is activated explicitly by placing a finger on the smartwatch touch surface. A minor complication is the fact that indirect cursor control is bound to a designated plane, i.e. cursor movement is restricted to the currently focused interface.

We now describe two hypothetical scenarios in which the techniques deliver complementary functionality supported by fluid mode transitions. In one scenario, the user selects a button on a distant AR menu using the smartwatch-based indirect cursor. A new interface opens in front of the user which is in comfortable reach. The user chooses to switch to in-air direct cursor control for speed. This transition is seamless as the user need only lift their finger off the smartwatch and place their hand inside the NED's field-of-view to activate the index cursor. Alternatively, the user can continue to use the indirect cursor since the focus has been moved to the new interface. At this point, the optimal selection technique is a user choice and depends on personal preference, current fatigue level, and task complexity.

In another scenario, the user is modifying the visual appearance (for example, colour, scale, orientation) of an object placed in the AR scene by interacting with buttons on a context menu. The user initially opts to use the in-air cursor to quickly and approximately adjust the appearance towards desired settings. At some point, however, the user's focus switches to fine adjustment as they seek to accommodate the spatial context and physical scene's background into the visual aesthetics of the object. Consequently, the user prefers to adjust appearance settings using the smartwatch indirect cursor so that their arm is not occluding or otherwise disrupting their view of the mixed-reality scene. The transition from in-air to smartwatch is smooth as the context menu is already active and the user must simply locate the watch on their wrist. The resting finger position facilitates small gestures and the smartwatch cursor occludes only the widget itself.

6.2 An Illustrative Example of Performance Modelling

We now briefly illustrate the process of exploiting knowledge of the performance envelope for each technique to evaluate alternative interface design decisions. Consider an AR application involving creating and/or placing various virtual objects in the space, such as primitive shapes, text boxes, 3D line drawings. The application designer desires to provide a simple context menu that can be displayed depending on the current object in focus. This menu will allow the user to adjust basic object appearance and perform simple actions such as move and delete. The context menu will thus contain four buttons as shown in Figure 8: *Size*, *Colour*, *Move* and *Delete*.

To minimise scene occlusion, the designer wishes to hide the four radial buttons by default but is happy for the single centre *Edit* button to remain visible above the virtual object placed in the space. The designer wants to estimate the theoretical performance of two alternative interactions with the context menu to check whether they are both worth implementing for physical testing. The two alternative interactions are described briefly below:

- **In-air direct touch:** The context menu will be activated by directly touching the centre *Edit* button. One of the four context menu buttons will then be selected by direct touch with the index cursor.
- **Smartwatch crossing:** The context menu will be activated by an initial touch on the smartwatch screen while visually focused on the target object via a gaze cursor. One of the four context menu buttons will then be selected using the smartwatch by an outward crossing trace.

We define selection time (*ST*) as the total time required to make a selection from the context menu. This can be expressed as

$$ST = MT + AT, \tag{5}$$

where activation time (*AT*) is the time required to open the context menu and movement time (*MT*) is the time required to select one of the four menu buttons.

The designer sizes the centre *Edit* button to be approximately 40 mm in diameter. Based on these dimensions, a rough estimate for

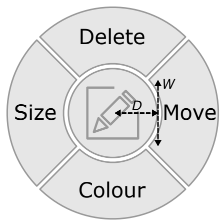


Figure 8: Anticipated layout of a radial context menu for an AR application. The application designer seeks to determine the theoretical performance of two alternative interaction schemes.

activation time using in-air selection is obtained by assuming a hand moving from an initial position by the user's side to the *Edit* button—a movement amplitude of approximately 500 mm. This yields an activation time of approximately 1.17 s based on the derived target acquisition model for in-air selection. The activation time using the smartwatch is simply the time required to place a finger on the touch surface. The designer builds a simple application and measures the activation times in a self-experiment to be 0.75 s in a seated position and 0.72 s in a standing position.

Upon activation, the movement time for each interaction technique can be estimated using the target acquisition model for in-air selection and using the goal crossing model for smartwatch selection. The designer approximates the target width W based on the chord length of the internal edge of a radial button to be 28 mm and the movement distance D to be 20 mm (half of the *Edit* button width). Movement time is then calculated to be 0.46 s and 0.84 s for in-air and smartwatch respectively. The resulting total selection times are thus 1.63 s for in-air and 1.59 s for smartwatch (in a seated position).

Based on these rough estimates, the designer is happy that the difference in performance does not render any of the techniques redundant and unworthy of physical evaluation. Clearly there are many other factors which may influence these results but the approximations provide the designer with some confidence that their intended interaction techniques are at least theoretically valid.

6.3 Limitations and Future Work

Selecting targets in a seated position with controlled lighting conditions could have favoured the in-air selection technique. The interactive NED vision painted in the introduction motivates future research involving an ecological evaluation of these techniques in a walking scenario in the wild. Changing lighting conditions and movement might shift the balance between both techniques and favour the indirect input on a smartwatch due to tactile sensation feedback and a resting, more subtle hand posture.

While no fatigue values were measured to compare individual tasks, higher fatigue was observed during the steering task which could result from the long selection time necessary [12]. Furthermore, the reported fatigue during in-air selection could be the result of the artificial set-up and the high number of trials inherent to a performance evaluation. The physical strain could be less prominent in an actual application. Nevertheless, the reported in-air performance can serve as a baseline to design and evaluate more ergonomic selection techniques. We hypothesise that improved hand tracking would likely increase performance and might also serve to reduce fatigue. This requires further investigation with alternative hand tracking hardware.

Having established the performance envelopes for in-air and smartwatch-based selection and cursor control, it is now possible to design a variety of content generation, annotation and editing interfaces containing user interface widgets leveraging the fundamental user interface actions of target acquisition, goal crossing or circular steering. Future work will deploy these two techniques for use in a practical AR interface task and evaluate their performance. Such an investigation would help to better articulate the relative benefits of the two techniques in a typical usage scenario. The empirically determined models presented in this paper can also provide the basis for simulations and predictive models of human performance for hypothetical interface designs as illustrated in the previous section. In addition, they can be incorporated into objective functions for automatic user interface optimisation methods.

6.4 Implications for Design

The findings of this work have several design implications for AR interfaces. These are summarized below:

- **Interaction Fatigue:** Within-reach interfaces can benefit from the high input speed of direct in-air selection, but suffer from fatigue effects. Thus, the application designer should ideally ensure such interactions are short and sparse, for example selecting a sub-view from a menu or one of a few elements in an interface.
- **Interaction at Distance:** Out-of-reach interfaces and tasks with high complexity and duration can plausibly benefit from the resting hand position and haptic feedback of indirect smartwatch selection. This is desirable for dragging tasks with multiple targets or continuous cursor interactions, such as scrolling down a long list of items. In contrast to more conventional 2D interfaces in which the user position can be readily inferred, the AR interface designer must consider the likely relative position of the user and how this might impact the most appropriate interaction technique.
- **Modal Fluidity:** The complementary strengths of both techniques suggest a combined usage, where mid-air selection is applied to select sub-menus or large widgets and smartwatch selection is applied to perform fine-grained interaction. Since both techniques do not require a hand-held device, the transition between both is smooth and fast. Designers should both support and exploit a high degree of modal fluidity to ensure users can choose input techniques according to their needs.
- **Context Sensitivity:** The preferable input technique can be highly context-specific. When interacting in a working scenario, for example, handling documents on a virtual desktop in the office, performance can be the main concern of users. During similar interactions in a public environment, unobtrusiveness can have a higher priority. Designers can accommodate such context sensitivity through a better awareness of the likely usage scenarios of their application and/or by providing users with a choice in selection of an interaction technique.

7 Conclusions

The experiment presented in this paper is a step towards the creation of non-encumbering interaction techniques for augmented reality applications. Two techniques, direct in-air selection and indirect smartwatch-based selection, were evaluated for three fundamental user interface actions: target acquisition, goal crossing, and circular steering. In-air direct control was significantly faster than smartwatch indirect control in the target acquisition and circular steering actions. The results demonstrate that Fitts' law and the steering law model these two tasks well for these circumstances. The goal crossing performance difference between conditions was marginal and the relatively low R^2 value suggests that the goal crossing model does not accurately model performance for the in-air input method.

Qualitative feedback from participants suggests that user comfort and social acceptance of in-air interaction can influence user preferences for interaction techniques. Such usability concerns may indeed dominate at low *ID* values at which performance levels converge.

This paper establishes the performance envelopes of two complementary interaction techniques, well suited to many AR applications. The performance envelopes in this paper can aid manual performance-conscious design of AR user interfaces and the model parameters can be used to guide user interface optimisation algorithms by incorporating the user interface action models in objective functions. Ultimately, the vision of an interactive NED replacing the smartphone will likely be achieved through a suite of diverse input techniques with various strengths and weaknesses.

Acknowledgments

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Understanding the Heisenberg Effect of Spatial Interaction: A Selection Induced Error for Spatially Tracked Input Devices

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Understanding the Heisenberg Effect of Spatial Interaction: A Selection Induced Error for Spatially Tracked Input Devices

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ABSTRACT
Virtual and augmented reality head-mounted displays (HMDs) are currently heavily relying on spatially tracked input devices (STID) for interaction. These STIDs are all prone to the phenomenon that a discrete input (e.g., button press) will disturb the position of the tracker, resulting in a different selection point during ray-cast interaction (Heisenberg Effect of Spatial Interaction). Besides the knowledge of its existence, there is currently a lack of a deeper understanding of its severity, structure and impact on throughput and angular error during a selection task. In this work, we present a formal evaluation of the Heisenberg effect and the impact of body posture, arm position and STID degrees of freedom on its severity. In a Fitt's law inspired user study (N=16), we found that the Heisenberg effect is responsible for 30.45% of the overall errors occurring during a pointing task, but can be reduced by 25.4% using a correction function.

Author Keywords
VR, virtual reality, pointing, Heisenberg effect

CCS Concepts
•**Human-centered computing** → **Empirical studies in HCI;** *Pointing devices;*

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INTRODUCTION AND MOTIVATION
Augmented and Virtual Reality head-mounted displays (HMDs) use the physical space around a user to superimpose information or fully immerse the user and can be classified as spatial computing devices [24]. Most spatial computing devices rely on spatially tracked input devices (STIDs) which allow the user to point at and select virtual content. All these STIDs are prone to the phenomenon that a discrete input such as a button press will disturb the position of the tracker and result in a different selection point (Heisenberg Effect of Spatial Interaction [3]).

Despite this phenomenon being observed by several researchers [4, 10], it is mostly ignored or compensated for by moving the selection to the non-pointing hand. This solution works inside a lab study but is difficult to apply for current consumer devices. Therefore, there is a current lack of understanding of the nature of the phenomenon (e.g., How much percentage of selection errors can be attributed to the Heisenberg effect? Does the Heisenberg effect follow certain characteristics? How can the effect be mitigated?).

To gain an understanding of the severity and characteristics of the Heisenberg effect, we conducted an ISO9241-9 inspired pointing task (N=16) using an HTC VIVE and measuring the Heisenberg effect and its impact on accuracy and throughput during selections in VR. To disentangle the spatial disturbance during discrete selections from ballistic movement during pointing, we collected both, stationary and ballistic data for each target. Additionally, we used body posture (standing, sitting), arm posture (stretched, bent) and degrees of freedom of the STID (3DoF, 6DoF) as independent variables.

We found that during ballistic selections the Heisenberg effect accounts for 30.45% of the selection errors. We also found that the Heisenberg effect is a systematic upwards shift. We hypothesize that this is related to the positioning of the trigger button of the HTC Vive. Our results further indicate that angular error increases with larger targets and longer click duration. Finally, we present a set of compensation techniques that can be applied to reduce the error down to 8.8%. We argue that with the progress of display quality and the ability to see and point at small targets further away, the Heisenberg effect will become more relevant but can be easily compensated for in software.

The main contributions of this work are

1. An in-depth analysis of the impact of the Heisenberg effect of spatial interaction on selection throughput and error rate.
2. An analysis of the unique characteristics of the Heisenberg effect and its systematic behavior during selection.
3. Compensation strategies for the Heisenberg effect during selection.

RELATED WORK

Selection in 2D and 3D

A widely used HCI technique for interacting with distant targets in 2D and 3D is via pointing. The current pointing position of a hand or STID is usually defined via ray-casting by extending the selecting hand or STID and calculating the intersection point with objects and planes along the ray [22]. Visualization techniques for the current pointing position include cursors [9, 11, 14, 18] and virtual hands [5, 23]. Depending on the STID used, pointing suffers from jitter and latency which can affect user performance with latency largely being more detrimental to selection performance [19]. STIDs for 3D selection such as VR controllers have been shown to suffer from additional positional [26] and rotational jitter [2]. These types of jitter do not affect selection precision significantly if target size is kept above a viable value. Teather et al. further concluded that similar to 2D input, latency in 3D selection is affecting human performance more than low spatial jitter [26].

In addition to tracking-induced jitter and inherent hand jitter of users, Bowman et al. observed the so called “Heisenberg Effect of Interaction”, a spatial disturbance that occurs during discrete selections on an STID [3]. While some researchers reverted to STID positions measured before the actual selection in order to avoid this effect [4, 10, 28] or asked participants “to click with the non-dominant hand on the button of a remote control” [15], we are motivated to formally evaluate this phenomenon in order to gain a deeper understanding of its severity and impact on selection precision and throughput.

Fitts’ Law

The Fitts’ law models the expected movement time in respect to the index of difficulty of a target via

$$MT = a + b \times ID_e, \tag{1}$$

where a and b are factors that are determined empirically via linear regression. While this relationship is of predictive nature, we are more interested in deriving the performance metric of throughput. As throughput can be affected by user performance, McKenzie et al. introduced an approach to correct the throughput for input errors by calculating the effective throughput (TP_e) [13]. According to the ISO 9241-9 pointing task, effective throughput can be modeled via

$$TP_e = ID_e / MT \tag{2}$$

where ID_e is the effective index of difficulty of the target and MT the mean movement time. According to the Shannon formulation of Fitts’ law [13], ID_e is defined as

$$ID_e = \log_2\left(\frac{D_e}{W_e} + 1\right), \tag{3}$$

where D_e is the effective distance between targets (i.e., standard deviation of over- and undershoots from the intended target center projected on the optimal path), and W_e is the effective width of the target (i.e., 4.133 standard deviations of the end-point positions) calculated as proposed by Soukoreff and MacKenzie [25]. Considering the end-point distribution, the effective width is a more precise estimate for the actual target width that the users were selecting. This model allows us to recalculate effective throughput for corrected end-point positions and thus compare the efficiency of compensation strategies.

THE HEISENBERG EFFECT

The Heisenberg Effect was originally observed by Bowman et al. as a side effect when using STIDs [3]. The authors gave a beautiful description of the effect that they observed during a user study:

"[..]a user wants to select an object using ray casting. She orients the ray so that it intersects the object, but when she presses the button, the force of the button press displaces the ray so that the object is not selected."

In Figure 1, we show an abstract depiction of the Heisenberg Effect that we created based on the insights gathered in our user studies. We present this model early in the paper to give the reader a visual understanding of the effect and its interplay with hand jitter, target size and direction.

The angular offset between selection start and selection end is in the following referred to as *Heisenberg Magnitude*. Selections that started within a target but were displaced due to the Heisenberg Effect and thus led to a miss are called *Heisenberg Errors*. Therefore, developers and researchers that want to avoid *Heisenberg Errors* at all cost, need to design targets with a radius larger than the *Heisenberg Magnitude*. In section 6, we will explain why this approach is not always desirable and present further correction mechanisms. Additionally, we found a systematic shift to the top left during our study. We partially explain this with the location of the physical trigger button on the controller.

EXPERIMENT

To explore the impact of the Heisenberg Effect on selection performance and quantify the influence of input parameters, we conducted a user study consisting of two pointing tasks. The first one was an ISO 9241-9 pointing task (in the following referred to as *ballistic*). The second task removed the ballistic motion from the selection to allow us to quantify the “pure” Heisenberg Effect (in the following referred to as *stationary*).

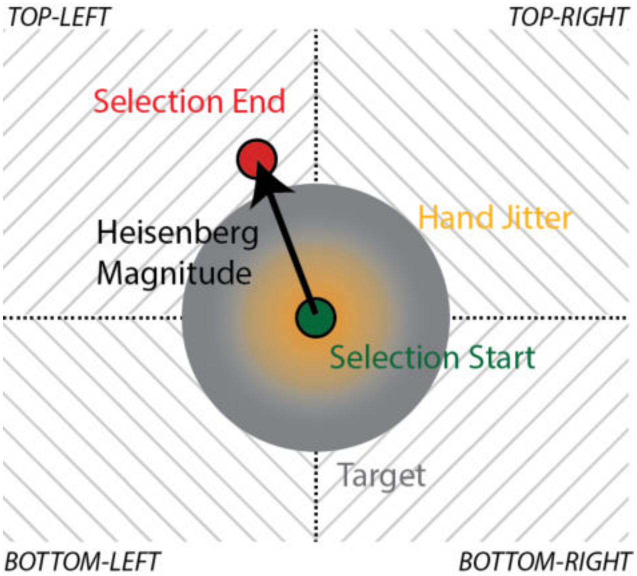

Figure 1: A theoretical model of the Heisenberg Effect for spatial interaction, showing the systematic shift to the top left, the relationship to hand jitter and the definition of a Heisenberg Error: Starting a selection inside the target but ending outside due to a disturbance of the input device.

Apparatus

We implemented the selection task inside a simple VR scene using Unity3D and an HTC Vive HMD (V 1.0) connected to a computer equipped with an i5-6600k (stock) processor and an Nvidia GTX 1080 graphics card. We used the trigger button of the HTC Vive controller as the selection button (as it is commonly used). The trigger button gives values about the trigger state of the button (starting from 0 for no contact and going linearly up to 1.0 depending on how far the user pushed the button in) and additionally fires a selection event when the trigger is completely pushed through.

To establish a baseline for the angular offset during a pointing task with a VR controller, the spatial jitter for the controller and HMD device was measured in a resting position lying on the floor. The Vive base stations (V 1.0) were 2.5 meters apart with the currently measured device being in the center of the tracking space. Angular data was recorded in a time frame of 120 seconds and resulted in a positional jitter of $0.025° - 0.085°$ mean-to-peak for the controller and $0.0094° - 0.059°$ mean-to-peak for the HMD.

Through a combination of optical tracking and inertial sensors the update rate of a Vive controller (V 1.0) is reported to be between 250 Hz and 1000 Hz. The update rate accessible via the API is significantly lower and depends on the performance of the computer used. To measure the temporal jitter, i.e. the change of latency over time, the time difference between consecutive frames during several pointing tasks was analyzed. A histogram of these values revealed that over 96.5% of all updates happened in an interval of 9-11 ms and all remaining updates in an interval of 6-8 ms. Temporal and spatial jitter are therefore not considered an issue for the experiment.

Variables

Independent Variables: Our experimental design consisted of five independent variables (*BodyPosition*, *ArmPosition*, *DoF*, *Width* and *Distance*). Since the Heisenberg effect is a disturbance in the pointing accuracy resulting from the press of a physical button, we hypothesized that the stability of the pointing arm is a relevant factor that should probably influence the magnitude of the Heisenberg Effect. Therefore, we were choosing variable postures that all result in a different level of stability (e.g. extending an arm is less stable than applying it and similarly sitting is less stable than standing [27]). Inspired by previous work, the *BodyPosition* had two levels (*Sitting*, e.g., Barrera and Stuerzlinger [1] and *Standing*, e.g., Kopper et al. [12]). The *ArmPosition* had also two levels in which users either *Extended* their arm during pointing (e.g., Grossman and Balakrishnan [7] or Miller et al. [16]) or *Applied* it (elbow at 90 degrees, pressed against body, e.g., Gielen et al. [6]). The *DoF* of the STIDs were either *Three* degrees (only rotational) or *Six* degrees (rotation and translation). We selected *DoF* as a variable, since we were interested if the Heisenberg Effect would be stronger for 3DoF STIDs which are currently widely used for mobile VR HMDs (e.g. Oculus Go). The last two independent variables were contributed by the pointing task: *Width* of the targets (*15, 30, 50* cm) and *Distance* between the targets (*150, 350* cm). We want to emphasize that this distance refers to the distance between targets and not between user and target. In our study the user was always at a fixed distance to the selection targets (8m).

Dependent Variables: To be able to calculate what percentage of the overall pointing errors occurred due to the Heisenberg Effect and to quantify the severity of the Heisenberg Effect we measured *EffectiveThroughput*, *OverallError*, *HeisenbergError* and *HeisenbergMagnitude*.

The *EffectiveThroughput* was measured as proposed by Soukoreff and MacKenzie [25] and helped us to quantify how performance can be improved by compensating the Heisenberg Effect. The *OverallError* was measured as the overall percentage of missed targets. The *HeisenbergError* was measured as the percentage of targets in which the selection (start of button press) started inside the target but ended outside of the target (end of button press[2]). The *HeisenbergMagnitude* was measured as the distance in angular degrees between the start of the selection (button trigger value >0) and the end of the selection (button completely pushed through).

To be able to quantify the characteristics of the Heisenberg Effect, we recorded *FalsePresses*, *Left*, *Top* and *ClickDuration*. *FalsePresses* were defined as the amount of button presses with values higher than zero that were not completely pushed through. This is a good indicator of how often users accidentally started a selection without finishing it. To further quantify a systematic directional offset of the Heisenberg Effect, we

[2]As the end of the button press we used the event which is normally used as a selection event. With the HTC Vive controller this happens after the trigger is completely pushed through.

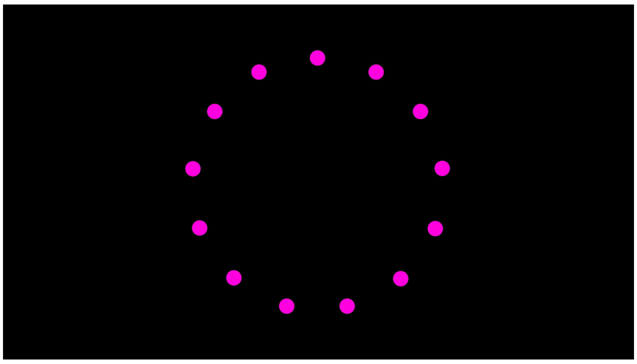

Figure 2: Participant view of the target plane in the study environment. Only one target at a time was shown during the pointing task.

counted the amount of target selections which ended up being above the target (*Top*) and the amount of target selections which ended up being left of the target (*Left*). Finally, we measured the time a fully executed selection (i.e., trigger value >0 leading to a trigger press) took from start (trigger value >0) to finish (trigger press) as *ClickDuration*.

Procedure

The study was executed inside a quite room at our institution. After an informed consent and demographics, participants were introduced to the experiment and asked to follow the instructions on the interface presented in the VR environment. The users saw a set of circular flat targets floating 8 meters in front of them and could select them using a ray cast metaphor with the HTC Vive controller.

The *ballistic* task was the ISO 9241-9 pointing task where flat circular targets with a given width (*Width*) are arranged on a circle with a given diameter (*Distance*, see Figure 2). For each *Width* x *Distance* combination, participants had to select 13 disks.

To be able to measure the "pure" Heisenberg Effect (i.e., the offset induced by a button press from a stationary position while a regular selection error consists of the disturbance using the button and the overshooting from a ballistic motion) and hand jitter without ballistic over- or undershoot, we added a second pointing task. After each ballistic selection, participants had time to position themselves above the target (hence removing the ballistic motion). Once above the target, the pointer had to stay within the target for a duration of 500 ms while a visual indicator was filling up in a red color to display the remaining time (see Figure 3 left). After 500 ms the indicator turned green and participants had to perform a selection (press the trigger from value 0 to 1.0, see Figure 3 right). Participants were instructed to aim for the center of the target. Afterwards, the next ballistic target was activated. This separation into *ballistic* and *stationary* allowed us to be certain about the user's intended selection position in the *stationary* condition (i.e., the center of the target). In the following analysis the center of the target was always used as the intended start of the selection.

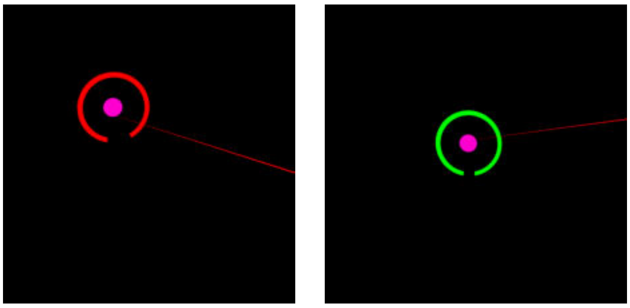

Figure 3: Participant view during the *stationary* selection. Left: A red visual indicator displays the remaining time before the participant has to click. Right: A green indicator symbolizes that the participant should perform a click.

Participants

16 participants (8 male, 7 female, 1 non-binary) were recruited via convenience sampling. Participants were aged between 20 and 30 (M = 24.5, SD = 2.85). 15 participants were right-handed and 7 had corrected-to-normal vision. All but three participants had prior VR experience and 8 participants reported to play VR games where pointing was the main task (e.g., shooting or selecting).

RESULTS

A total of 19968 selections were recorded and analyzed using a repeated measures ANOVA with Greenhouse-Geisser correction where sphericity was violated. Pairwise comparisons are reported with Bonferronni adjusted p-values. For the sake of readability, all statistical results are presented in Table 1 and Table 2. In the following result section, we will only highlight briefly a subset of significant results.

Characteristics of the Heisenberg Effect

Hand jitter was measured during a time frame of 500 ms during stationary selections. Departure from normal distribution for all three angular offset distributions caused by hand jitter during the *Width* conditions was tested with D'Agostino and Pearson's test and was found to be not significant [20] (p>.05). Therefore, a normal distribution was assumed for hand jitter during all selections.

Irrelevant of the target position, the Heisenberg Effect expressed a systematic upwards shift (see Figure 4 top). Aggregated selection offsets over target width can be found in (Figure 4 bottom). For smaller targets, a higher percentage of selections ended outside of the target, leading to a higher *HeisenbergError*.

Sampling over the angular offsets during a button press (sampling rate: click duration/10), resulted in a nearly linear relationship between button press value and angular offset: $\rho = .737, p < .001$ (see Figure 5).

Impacting Factors

ArmPosition: During both selection tasks, *ClickDuration* was significantly higher in the applied *ArmPosition* condition (stationary: M=308.303 ms, SE=58.858 ms; ballistic:

			OverallError			HeisenbergError			HeisenbergMagnitude			TP_e		
		df	*F*	*p*	η^2	*F*	*p*	η^2	*F*	*p*	η^2	*F*	*p*	η^2
BodyPosition	stationary	1,15	.10	ns	.007	.42	ns	.027	.39	ns	.025	–	–	–
	ballistic	1,15	.46	ns	.029	.01	ns	.001	0.43	ns	.028	.45	ns	.029
ArmPosition	stationary	1,15	1.16	ns	.072	3.33	ns	.182	.16	ns	.010	–	–	–
	ballistic	1,15	.16	ns	.011	.17	ns	.011	2.37	ns	.136	.01	ns	.000
DoF	stationary	1,15	1.44	ns	.088	2.70	ns	.153	.28	ns	.018	–	–	–
	ballistic	1,15	1.83	ns	.108	6.63	$*$	.307	4.19	.059	.218	18.19	$**$	.548
Width	stationary	2,30	158.90	$***$	.914	115.18 ($\varepsilon = .658$)	$***$	.885	16.03 ($\varepsilon = .564$)	$**$	.517	–	–	–
	ballistic	2,30	592.43	$***$	.975	13.76	$***$	.479	1.39	$*$	.266	16.51	$***$	.524
Distance	stationary	1,15	.25	ns	.016	.04	ns	.003	6.34	$*$	.297	–	–	–
	ballistic	1,15	25.58	$***$	.630	2.52	ns	.144	5.44	$*$	.266	117.91	$***$	.887

Table 1: Results for dependent variables split by stationary and ballistic task. Significant results are marked with $*$ (p<.05), $**$ (p<.001) and $***$ (p<.0001). Greenhouse-Geisser-corrected F-values are reported with ε-values.

			FalsePresses			Top			Left			ClickDuration		
		df	*F*	*p*	η^2	*F*	*p*	η^2	*F*	*p*	η^2	*F*	*p*	η^2
BodyPosition	stationary	1,15	.63	ns	.040	.68	ns	.043	2.10	ns	.123	.57	ns	.036
	ballistic	1,15	.28	ns	.018	.08	ns	.005	0.2	ns	.001	1.56	ns	.094
ArmPosition	stationary	1,15	4.31	.055	.223	2.81	ns	.158	.10	ns	.007	6.40	$*$	.299
	ballistic	1,15	2.76	ns	.155	.26	ns	.017	5.02	$*$	.251	6.63	$*$	.306
DoF	stationary	1,15	.65	ns	.041	1.61	ns	.097	.02	ns	.001	.25	ns	.016
	ballistic	1,15	2.75	ns	.155	1.21	ns	.075	2.89	ns	.161	.82	ns	.052
Width	stationary	2,30	.28	ns	.019	.34	ns	.022	.42	ns	.027	15.61 ($\varepsilon = .509$)	$**$	.510
	ballistic	2,30	.29	ns	.019	1.07	ns	.067	4.56	$*$	.233	15.73 ($\varepsilon = .507$)	$**$	.512
Distance	stationary	1,15	.07	ns	.005	.88	ns	.055	3.76	.072	.20	3.16	ns	.174
	ballistic	1,15	11.80	$*$	.440	2.76	ns	.156	7.33	$*$	.328	12.36	$*$	.452

Table 2: Results for Heisenberg characteristics split by stationary and ballistic task. Significant results are marked with $*$ (p<.05), $**$ (p<.001) and $***$ (p<.0001). Greenhouse-Geisser-corrected F-values are reported with ε-values.

M=272.426 ms, SE=46.555 ms) than in the stretched *ArmPosition* condition (stationary: M=250.870, SE=60.403; ballistic: M=231.754, SE=50.021). Furthermore, significantly more selections were shifted to the left during ballistic selections with an applied *ArmPosition* (M=0.512, SE=0.020) than with a stretched *ArmPosition* (M=0.548, SE=0.023).

DoF: *HeisenbergError* for a *DoF* of *SIX* (M=0.112, SE=0.016) was significantly lower than for a *DoF* of *THREE* (M=0.124, SE=0.018). Furthermore, *EffectiveThroughput* for a *DoF* of *SIX* (M=1.793, SE=0.105) was significantly higher than for a *DoF* of *THREE* (M=1.656, SE=0.082). This was a rather surprising insight for us as we expected that more degrees of freedom would lead to a higher *HeisenbergError* (due to higher probabilities of disturbing the input via rotation and translation). However, this indicates that the Heisenberg Effect is less influenced by a translational disturbance but more by a rotational.

There were no significant differences between the *BodyPosition* conditions.

Target Width and Distance: We found that the *OverallError*, *HeisenbergError* and *ClickDuration* all increased for smaller targets while the *HeisenbergMagnitude* decreased (see Figure 6). This means that smaller targets lead to a higher *HeisenbergError* while having a smaller *HeisenbergMagnitude*. This further indicates that the *HeisenbergMagnitude* is also influenced by the visual representation of the targets.

In the *stationary* condition, we found that *HeisenbergMagnitude* for a *Distance* of 150 cm ($M = 0.652°, SE = 0.043°$) is significantly lower than for a *Distance* of 350 cm ($M = 0.680°, SE = 0.036°$); p=0.024. Similar results were found in the *ballistic* condition. *HeisenbergMagnitude* for a *Distance* of 150 ($M = 2.536°, SE = 0.695°$) is significantly lower than for a *Distance* of 350 cm ($M = 4.538°, SE = 1.54°$); p=.034. Unsurprisingly, *Overall Error* for a *Distance* of 150 (M=0.351, SE=0.029) was significantly lower than for a *Distance* of 350 (M=0.423, SE=0.026, p<.001) in the ballistic condition which can be attributed to the inertia of ballistic movements.

Correlation of Dependent Variables

There was a significant correlation between *ClickDuration* and *HeisenbergMagnitude* ($p < .001, \rho = 0.327$), *ClickDuration* and *HeisenbergError* ($p < .001, r = -0.04$), *ClickDuration* and *FalsePresses* ($p < .001, \rho = -0.599$), *ClickDuration* and *Top* ($p < .001, r = -0.126$), and *ClickDuration* and *Left* ($p < .001, r = 0.075$).

Discussion

Characteristics of the Heisenberg Effect

Our results indicate that the Heisenberg Effect is responsible for 81.98% of the errors during stationary and 30.49% during ballistic selections. The low percentage of Heisenberg Errors in the ballistic condition can be explained by the low number of selections that started in a target (43.3%). For these selections, the Heisenberg Error value for the ballistic condition was

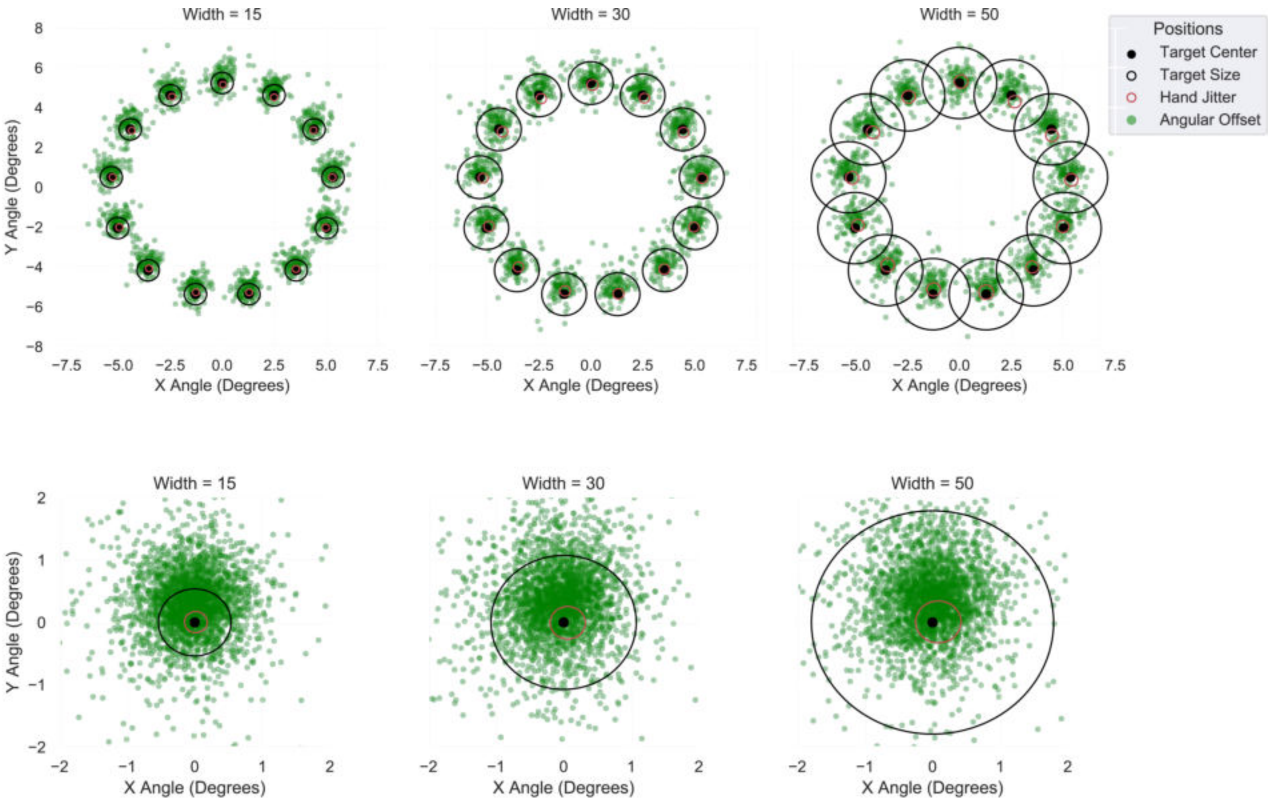

Figure 4: Heisenberg Magnitude in angles (degrees) by target width, aggregated over target distance (top) and distance and position (bottom). The green dots (Angular Offset) outside the target boundaries show the selections which where disturbed by the Heisenberg Effect of spatial interaction.

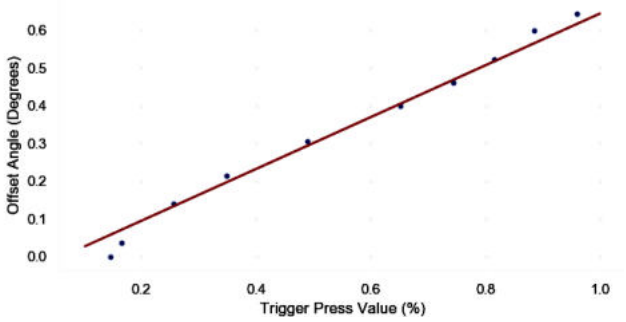

Figure 5: Relationship between trigger press value and angular offset during a selection.

26.6% which is more consistent with the stationary condition (23.2%).

We found an upward shift for 77.8% of all selections in the stationary and 64% in the ballistic selection. This systematic shift can be mostly attributed to the Heisenberg Effect since 89.75% of all Heisenberg Errors had an upward shift in the stationary and 86.65% in the ballistic condition. We hypothesize that this directional shift is related to the position of the trigger button on an HTC Vive controller. Further tests are necessary to evaluate the directional shift for other button types and positions. Additionally, we found a horizontal shift to the left in the ballistic condition while stationary selections showed only vertical shifts with a tendency to the top. This again supports our finding of a systematic upward shift due to the Heisenberg Effect.

Angular error increased with target width from 0.587° for the smallest to 0.745° for the largest target. This is also consistent with hand jitter that increased from 0.169° to 0.335°. A possible explanation could lie in the model of anticipatory postural adjustments that leads to a varying muscle tension and arm posture depending on the perceived target size [17]. This is also reflected in an increasing click duration for smaller targets.

Impact on the Heisenberg Effect

No significant differences could be found for the body position probably due to no impact on the pointing arm. Arm position, however, seems to influence click duration with a stretched arm posture leading to a shorter click duration. This might be explained by the more stable arm position and increased tension in the lower arm and fingers [21].

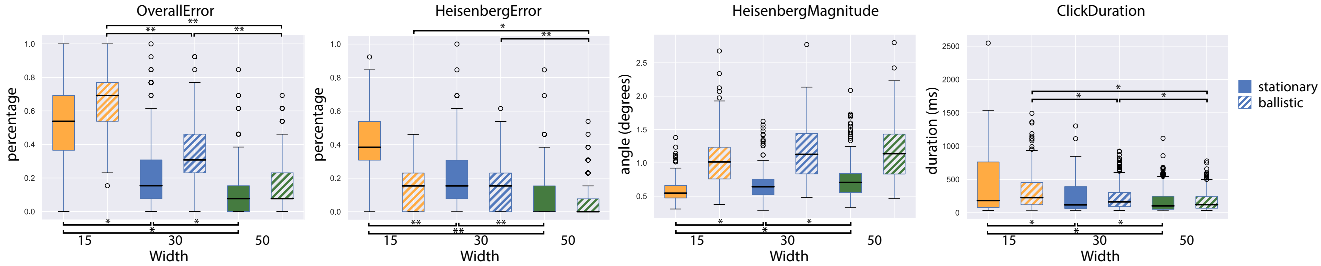

Figure 6: Results of pairwise comparisons for target width. Significant differences are marked with ∗ (p<.05) and ∗∗ (p<.001).

Angular error increased with target distance. This could be explained be the steeper arm angle required to select targets further from the center. While targets in the small distance condition were positioned at an angle of 5.4° from the participant, targets in the large distance condition were positioned at 12.6°.

Degrees-of-freedom showed no significant differences in the stationary condition which suggests no correlation with the Heisenberg Effect. In the ballistic condition, six DoF led to a significantly higher Heisenberg Error, shorter movement time between selections and a higher effective throughput. We hypothesize that participants did not change their selection behavior in the three DoF condition and continued to move their whole arm instead of rotating the wrist. Since the pointer origin was fixed during the three DoF condition, it would require a wider arm movement to move the pointer by the same amount of degrees as in the six DoF condition.

DEALING WITH THE HEISENBERG EFFECT

Our results have clearly shown that the Heisenberg Effect is always present during selections with a trigger button. We argue that this will be the case for other hardware buttons as well, as long as force has to be applied to the input device in order to confirm a selection. This chapter will now present and discuss mitigation and compensation strategies.

Time Shift to Initial Press

Since discrete input via a physical button is the cause of the spatial disturbance and thus the Heisenberg Effect, a naive assumption could be to shift back in time to the initial position where the user started pressing the button. However, an analysis of the initial press positions revealed that on average 7% occurred outside of the target in the stationary and 55.7% in the ballistic condition ($F_{1,15} = 87.613, p < .001, \eta^2 = 0.854$). As can be seen in Table 3, the percentage of initial presses that happened outside of the target in the ballistic condition differs significantly between the target distance conditions ($F_{1,15} = 55.314, p < .001, \eta^2 = 787$) and width conditions ($F_{1.385,20.774} = 97.991, p < .001, \eta^2 = 0.867$). A naive time shift to the initial press position in a ballistic condition would therefore induce an error of 37.4% for the largest target width tested which is higher than the raw Heisenberg Error of 26.6% and almost as high as the Overall Error of 38.7%. Only the stationary condition shows an improvement for all target distance and width conditions compared to the raw Heisenberg Error of 24.9% and the Overall Error of 28.3%.

		Stationary	Ballistic
Distance	150	6%	50.4%
	350	7.9%	61%
Width	15	14.3%	75.4%
	30	4.7%	54.3%
	50	1.9%	37.4%

Table 3: Percentage of trigger presses outside of the target.

Time Shift to Position Before Click

As presented in the subsection *Correlation of Dependent Variables*, the duration of a full click correlates with the magnitude of the Heisenberg Effect and the probability to make a Heisenberg Error. Thus, a logical assumption could be to shorten the click duration by using a trigger press value lower than 1.0. However, for a total of 19968 selections, 17318 so called 'false trigger presses' were recorded, resulting in 0.87 false trigger presses for each valid selection, where participants pressed the trigger button and released it completely without fully clicking. The mean trigger press value at which the button was released over all conditions was as high as 0.55 (±0.22) with a trigger value of 1.0 being a full click. As can be seen in Figure 7, 95% of all false trigger press values lie below a trigger press value of approximately 0.83. Values below this threshold would increase the Type I error (accept a false trigger press as a click), while values above would reduce the benefit of the reduced click duration and thus increase the Heisenberg Magnitude and the Heisenberg Error. Accepting a click at a trigger press value of 0.83 would reduce the average Heisenberg Magnitude from 0.66° to 0.53° for stationary selection (see Figure 5).

Correction Function

As an alternative to the above mentioned naive strategies, we propose to distill a correction mechanism from the gathered data similar to touch-position correction in previous work [8]. To this end, the offset vectors of the Heisenberg Error for all stationary selections were collapsed globally (*Global*) and group-wise by the independent variables (*GroupWise*) to create correction vectors that can be subtracted from the selection

		Effective Throughput			Heisenberg Error			Overall Error		
		c_{none}	c_g	c_{gw}	c_{none}	c_g	c_{gw}	c_{none}	c_g	c_{gw}
BodyPosition	SITTING	2.908	2.948	2.988	0.117	0.095	0.089	0.392	0.362	0.348
	STANDING	2.911	2.976	3.016	0.118	0.095	0.087	0.383	0.349	0.334
ArmPosition	APPLIED	2.953	3.015	3.058	0.116	0.091	0.083	0.390	0.348	0.338
	STRETCHED	2.866	2.908	2.946	0.120	0.099	0.092	0.384	0.363	0.344
DoF	SIX	3.010	3.064	3.102	0.112	0.088	0.083	0.379	0.349	0.339
	THREE	2.809	2.859	2.902	0.124	0.102	0.092	0.396	0.362	0.343
OVERALL		2.909	2.962	3.002	0.118	0.095	0.088	0.387	0.356	0.341

Table 4: Impact of Heiseberg effect compensation on effective throughput, *HeisenbergError* and *OverallError* by independent variable. Correction strategies are none (c_{none}), global correction (c_g), and group-wise correction (c_{gw}).

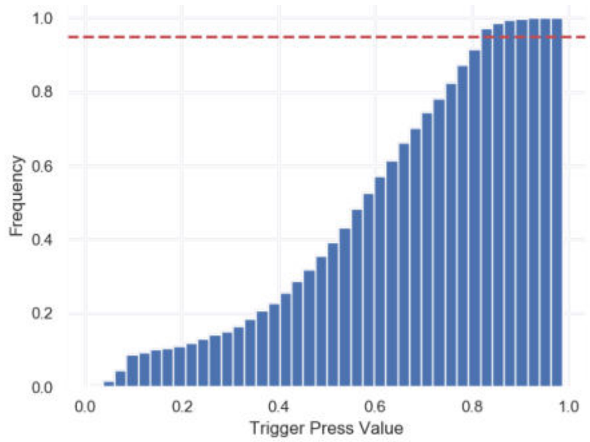

Figure 7: Cumulative histogram of false trigger presses by trigger value. 95% of all false trigger presses lie below a trigger press value of approximately 0.83.

position. Results on the benefit of the correction mechanisms on effective throughput, *HeisenbergError* and *OverallError* against uncorrected values (*Raw*) can be found below and are summarized in Table 4.

A repeated measures ANOVA revealed significant differences in the *EffectiveThroughput* for the *Correction* strategies; $F_{2,30} = 10.139, p < .001, \eta^2 = 0.403$. Pairwise comparisons with Bonferronni correction revealed that *EffectiveThroughput* for the *GroupWise* condition (M=3.002, SE=0.125) is significantly higher than for the *Raw* condition (M=2.909, SE=0.132, p=.001).

A repeated measures ANOVA with Greenhouse-Geisser correction revealed significant differences in the *HeisenbergError* for the *Correction* strategies; $F_{1.260,18.902} = 13.438, p = .001, \eta^2 = 0.473, \varepsilon = 0.630$. Pairwise comparisons with Bonferronni correction revealed that *HeisenbergError* for the *GroupWise* condition (M=0.088, SE=0.011) is significantly lower than for the *Raw* condition (M=0.118, SE=0.017, p=.006). Furthermore, the *HeisebergError* for the *Global* condition (M=0.095, SE=0.014) is significantly lower than for the *Raw* condition (p=.005).

A repeated measures ANOVA revealed significant differences in the *OverallError* for the *Correction* strategies; $F_{2,30} = 11.702, p < .001, \eta^2 = 0.438$. Pairwise comparisons with Bonferronni correction revealed that *OverallError* for the *GroupWise* condition (M=0.341, SE=0.020) is significantly lower than for the *Raw* condition (M=0.387, SE=0.027, p=.004). Furthermore, the *OverallError* for the *Global* condition (M=0.356, SE=0.023) is significantly lower than for the *Raw* condition (p=.022).

As can be seen in Table 4, the *Global* correction, a mechanism that can be easily implemented, reduces the Heisenberg Error and Overall Error. With additional information on the current body position, arm position and DoF, a further improvement in accuracy and throughput can be achieved via *GroupWise* correction. We argue that this information can be easily inferred from the HMD position (*BodyPosition*), controller distance to the HMD (*ArmPosition*) and hardware platform used (*DoF*).

Minimum Viable Heisenberg Compensated Target Size

Since the Heisenberg Effect is unconscious and is likely to vary with the hardware button built into the controller, a minimum target size can be calculated to reduce the Heisenberg Error to a desired percentage. Since *HeisenbergMagnitude* showed significant differences for the *Width* conditions (see subsection 5.2), a separate analysis for each target width tested was performed (see Figure 8). As can be seen in the cumulative histograms, 95% of Heisenberg Errors have an angle of at least 1.7° for the largest target width. Assuming that a user is pointing at the exact center of the target, the minimum target width necessary is therefore:

$$distance\_controller\_to\_target \times \sin(1.7°) \times 2 \quad (4)$$

Some example values for a given controller to target distance can be found in Table 5. Since this naive calculation assumes that the pointer is perfectly centered at the target and the overall Heisenberg Magnitude does not further increase for a larger target, the required minimum target width should be higher rendering this compensation strategy less viable in a real-world deployment.

LIMITATIONS

Although we could show a systematic upwards shift for the Heisenberg Effect, it remains to be evaluated whether this directional shift and its severity is tied to a certain button position and type (i.e., force of resistance). Only one type of controller was evaluated. Other controller types would be tracked by different hardware (e.g., IMU) and would therefore

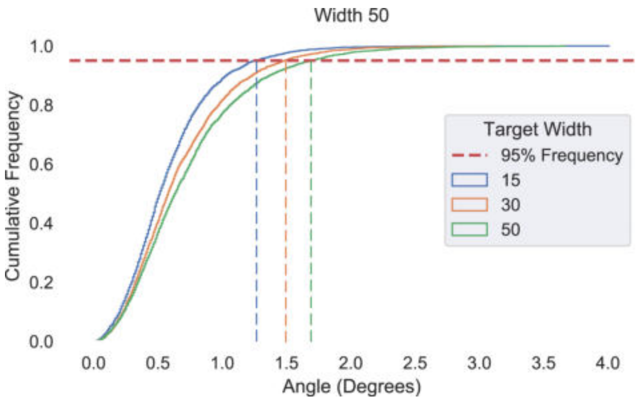

Figure 8: Cumulative histogram of Heisenberg Magnitude in degrees during the stationary condition by target width.

	Distance to Target (m)						
	1	2	3	4	5	6	7
Width (cm)	5.9	11.9	17.8	23.7	29.7	35.6	41.5

Table 5: Minimum target distance required (in cm) for a given controller to target distance (in m) to compensate approximately 95% of the Heisenberg Error.

yield different results due to inherent system jitter and varying tracking resolution.

CONCLUSION

In this work, we presented an evaluation of the Heisenberg Effect of spatial interaction and its impact on selection error and throughput. To measure the influence of body posture, arm posture and degrees-of-freedom, we performed a Fitts' law inspired user study (N=16). We could show that the angular offset has a systematic upwards shift and is relatively large in comparison to hand jitter. Surprisingly, body and arm posture had no impact on the Heisenberg Effect while degrees-of-freedom affected the effective throughput. Furthermore, target width and target distance had a significant impact on the Heisenberg Effect, with smaller targets leading to a higher Heisenberg Error. This implicates that with HMDs increasing in resolution, smaller targets will be possible which in turn would increase the impact of the Heisenberg Effect. To compensate for its impact on selection error and throughput in future experiments, we presented compensation strategies.

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Augmenting Teleportation in Virtual Reality With Discrete Rotation Angles

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Augmenting Teleportation in Virtual Reality With Discrete Rotation Angles

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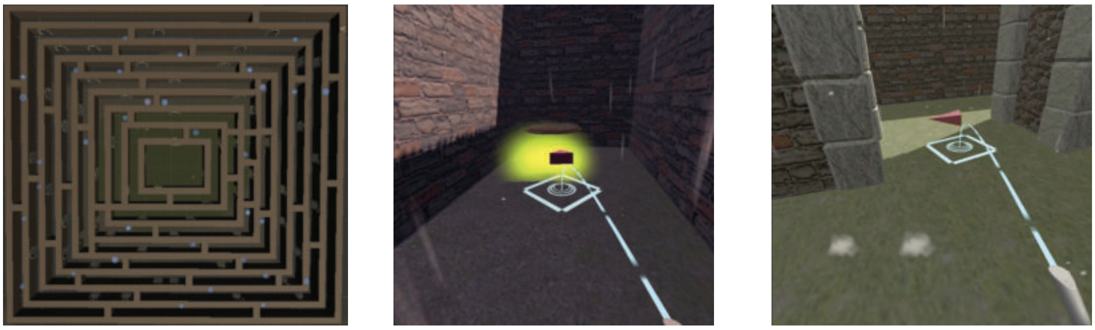

(a) Study environment (b) Collectible item (c) *TeleTurn* indicator

Fig. 1. The study environment was designed as a labyrinth (a) with semi-randomly distributed items (b) to enforce rotations on the spot, i.e. *InPlace* or during teleportations, i.e. *TeleTurn*. In conditions with *TeleTurn* not set to *None*, an arrow indicates the currently selected rotation direction (c).

Locomotion is one of the most essential interaction tasks in virtual reality (VR) with teleportation being widely accepted as the state-of-the-art locomotion technique at the time of this writing. A major draw-back of teleportation is the accompanying physical rotation that is necessary to adjust the users' orientation either before or after teleportation. This is a limiting factor for tethered head-mounted displays (HMDs) and static body postures and can induce additional simulator sickness for HMDs with three degrees-of-freedom (DOF) due to missing parallax cues. To avoid physical rotation, previous work proposed discrete rotation at fixed intervals (InPlace) as a controller-based technique with low simulator sickness, yet the impact of varying intervals on spatial disorientation, user presence and performance remains to be explored. An unevaluated technique found in commercial VR games is reorientation during the teleportation process (TeleTurn), which prevents physical rotation but potentially increases interaction time due to its continuous orientation selection. In an exploratory user study, where participants were free to apply both techniques, we evaluated the impact of rotation parameters of either technique on user performance and preference. Our results indicate that discrete InPlace rotation introduced no significant spatial disorientation, while user presence scores were increased. Discrete TeleTurn and teleportation without rotation was ranked higher and achieved a higher presence score than continuous TeleTurn, which is the current state-of-the-art found in VR games. Based on observations, that participants avoided TeleTurn rotation when discrete InPlace rotation was available, we distilled guidelines for designing teleportation without physical rotation.

CCS Concepts: • **Human-centered computing → Interaction techniques**; *Empirical studies in HCI*; Virtual reality.

Additional Key Words and Phrases: virtual reality, teleportation, locomotion, rotation

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1 INTRODUCTION

Virtual reality offers its users a potentially unlimited space to explore. Navigating this vast environment is a non trivial task and has been the focus of a large body of related work. Although walking in VR has been shown to be superior to walk-in-place and controller-based techniques [41], spatial restrictions set limits to how far a user can walk in a straight line. To circumvent these restrictions, researchers propose to manipulate the virtual output presented to users redirecting them on a curved path (redirected walking with curvature gain) [28]. However, the large radius required to trick the users' perception renders a naive implementation of this technique unpractical for daily application [31]. These limitations amongst others led to the rise of a seemingly "unnatural" and yet very efficient locomotion technique: teleportation (e.g., [7]). By simply pointing and pressing a button users can teleport to their destination in an instant. This technique allows to overcome spatial restrictions of a small tracking space and has been shown to induce less simulator sickness than controller-based continuous locomotion [13].

A major drawback of state-of-the-art teleportation is a missing rotation component. Considering the tethered design of many commercial head-mounted displays (HMDs), users could get entangled by the cables during physical rotation. Furthermore, physical rotation might not be feasible (e.g., due to a physical impairment) or desirable depending on the context (e.g., during a sitting or lying body posture). In addition, the optical flow during physical rotation can cause a feeling of vection, i.e., the illusion of moving, and thus, induce simulator sickness [29]. Especially low-class HMDs with only three degrees-of-freedom (DoF) are missing important parallax cues, which are necessary to compensate for postural changes during a physical rotation. The result is a mismatch between virtual and physical motion, which can induce simulator sickness and reduce the user experience [43].

In an effort to extend teleportation-based locomotion by a rotation component, we identified two promising opportunities: rotation around the users' position (henceforth "*InPlace*") and rotation around the desired teleportation target (henceforth "*TeleTurn*"), which can be found in commercial VR games (e.g., Robo Recall [1]).

To prevent any physical rotation, Sargunam et al. compared controller-based rotation techniques (*InPlace*) in terms of simulator sickness and disorientation and found discrete rotations at fixed intervals to induce the least simulator sickness [36]. While they suggested an interval of 30°, this value stems from a preliminary study with no evaluation of the impact on user presence, disorientation, and preference.

A commercially available, yet underexplored rotation technique is reorientation during the teleportation process (*TeleTurn*). While selecting a teleportation destination, users can choose the new orientation that the user avatar should assume at the new destination point. This new orientation is typically selected via a continuous gesture on a joystick or touchpad and is displayed as an abstract arrow (see Figure 1 c) or the users' avatar. However, a continuous gesture for orientation selection has been shown to slow down the interaction and reduce user acceptance of this technique [7]. We are therefore interested in exploring the potential of a discrete version of *TeleTurn* to reduce interaction time and increase the overall usability. Furthermore, it is unclear how users would apply *InPlace* and *TeleTurn* if both techniques are made available for direct comparison.

Results of our exploratory user study (N=12) indicate that users preferred discrete *InPlace* rotation over discrete *TeleTurn* with the largest rotation parameter (45°) being the favorite. However, discrete *TeleTurn* rotation showed an improvement over the current state-of-the-art, which is a continuous gesture for orientation selection.

Our contributions are therefore:

- Evaluation of a range of parameters for *InPlace* rotation and *TeleTurn* rotation

[1] https://www.epicgames.com/roborecall/en-US/home

- Insights from our exploratory study (n=12) regarding user preference and performance with *InPlace* rotation and *TeleTurn* rotation

2 RELATED WORK

2.1 Locomotion in VR

To navigate through virtual environments (VEs), previous work proposed upper-body leaning [24] and several joystick- and keyboard-based locomotion techniques (e.g., [5, 33]). However, physical movement through VEs has been largely shown to provide a better sense of orientation [10], target direction [42], and feeling of presence [41] even with a moderate level of visual detail [32].

Due to spatial limitations of the tracking space, variations of physical walking were proposed. While some approaches included treadmills (e.g., [4]), walking-in-place [38, 40, 46] or jumping-in-place [48] to prevent users from reaching the physical boundaries of their tracking space, other techniques tried to “trick” the users’ perception by using manipulations without being recognized [39]. Since visual calibration has been shown to occur when the presented self-speed was manipulated [21], Williams et al. increased the users’ reach by scaling the translational gain, i.e., the users’ velocity [44]. In a follow-up study, Williams et al. extended this technique by “resetting” the users’ orientation when a physical boundary was reached, therefore forcing the users to physically reorient themselves towards the tracking space [45]. Another variation of visual manipulation is redirected walking where users are nudged to walk on a circular path by virtually rotating their view (e.g.,[28]). This technique, however, has been shown to be impractical in its naive implementation since the required walking radius would exceed the size of a typical tracking space [31]. To circumvent this limitation, resetting techniques and alternative approaches to substitute physical turns to keep the user within a limited physical space were proposed (e.g. [30]).

Another well-explored locomotion technique is teleportation. According to the classification of locomotion techniques for VR by LaViola et al., teleportation is a selection-based travel technique [18]. The users’ viewpoint is instantly shifted to the destination that the user is pointing or looking at to prevent optical flow and the possibly accompanying motion sickness (e.g., [3, 8]). While some variants of teleportation limit the users to fixed teleportation destinations (i.e., fix-point teleportation), studies have shown that free teleportation leads to a lower discomfort [13]. Although teleportation can lead to disorientation [2, 6], it was subjectively preferred over joystick input in a study by Langbehn et al. in 2018 [17].

2.2 Rotation in VR

Physical rotation in VEs has been shown to be less time consuming [25] and less error prone than controller-based rotation [1]. A study by Ruddle and Péruch, however, reported contradicting findings regarding the sense of direction when they compared physical and non-physical rotation in VEs [34]. Since physical rotation can be impractical due to a static body posture or tethering [36], there have been approaches to reduce or prevent physical rotation completely. Similar to translational gains by Williams et al. [44], Kuhl et al. proposed to scale the users’ physical rotation, therefore reducing the physical rotation needed for a full turn [16]. This approach could be a benefit for setups with very limited tracking space (e.g., frontal tracking as used by the Oculus Rift CV1) or when tethering is an issue. Alternatively, Lin et al. propose to apply a smaller field-of-view (FOV) to reduce simulator sickness at the cost of user presence [19]. To combat this limitation and allow movement in a stationary position, Fernandes and Feiner suggest subtle dynamic changes in the users’ FOV [11]. However, a study by Sargunam et al. compared controller-based rotation techniques to prevent physical rotation and found that discrete rotation induced significantly less simulator sickness than reduced field-of-view and continuous rotation techniques [36]. Since a frame of reference (usually egocentric) and landmarks are very important for the users' orientation in VEs [12, 22, 23], the question arises how large these discrete rotation intervals can become until users become disoriented. A study by Rahimi et al. applied discrete rotation between 45° and 130° without a significant increase in disorientation, however no evaluation of the effect of rotation magnitude was performed due to the randomized design of the experiment [27]. The underexplored impact of varying rotation parameters on user performance and presence led us to investigate a range of discrete rotation angles in a user study.

3 USER EXPERIMENT

To evaluate how varying rotation parameters of the techniques *InPlace* and *TeleTurn* impact user performance, presence, and simulator sickness, a repeated measures 3×4 factorial design study was conducted. Rotation parameters included discrete rotation and the respective state-of-the-art for each technique.

3.1 Method

Our within-subject experiment had two rotation techniques as independent variables: *InPlace* and *TeleTurn*. Both techniques were available in each condition and participants were free to choose one or alternate between them.
Rotation around the participants' position was defined by *InPlace* and had three levels: physical rotation (*Physical*), representing the current state-of-the-art, and two levels of discrete, button-based rotation at fixed angles (22.5° and 45°). Rotation during the teleportation process was defined by *TeleTurn* and had four levels: no rotation (*None*), which represents state-of-the-art teleportation from related work, *Continuous* rotation via circling the thumb on a touchpad, which is state-of-the-art in commercial VR games, and two levels of discrete, button-based rotation at fixed angles (22.5° and 45°). The currently selected direction is indicated via a visual indicator (see Figure 1 c). Our experiment therefore consisted of $3 \times 4 = 12$ conditions that were fully counter-balanced.

3.2 Implementation

To explore the potential of controller-based discrete rotation, the study environment for the experiment was implemented for the Oculus Go HMD and its three DOF controller in Unity3D. Holding down the trigger button activated a teleportation parabola, releasing the button executed the teleportation to the selected destination point. For consistency, discrete rotation for both, *InPlace* rotations (i.e., yaw axis rotations around the users' position) and *TeleTurn* (i.e., rotations during the teleportation process) was controlled by pressing either on the left or right side of the touchpad to initiate a rotation to the left or right, respectively. The angle of discrete rotation depended on the condition (either 22.5° or 45°). Only during the *Continuous TeleTurn* condition, the relative position of the users' thumb on the touchpad defined the angle. Similar to previous work, we opted for fractions of 90° to allow fast 90° rotations that were necessary to navigate an environment with orthogonal walls such as our labyrinth (see Figure 1 a). The complexity of our level design was inspired by previous work. It has been shown that while a rotation oriented within-subject experiment requires an environment that enforces repeated rotations, a lack of complexity (e.g., simple rooms) leads to learning effects [26, 35].

3.3 Participants

We recruited 12 volunteers (6 male, 6 female) from our institution with a mean age of 22.75 (SD=2.38). All participants had normal or corrected-to-normal vision. Five reported previous VR experience and all but one reported to use physical rotation in VR instead of controller-based techniques.

3.4 Measures

After each condition, participants were asked to fill out questionnaires assessing their experience. Affective state was measured as valence, arousal, and dominance using the three 5-point pictorial scales of the the self-assessment manikin (SAM) [9]. Simulator sickness was assessed with the Simulator Sickness Questionnaire (SSQ [15], 16 items on a 4-point scale), while presence was measured with the igroup presence questionnaire (IPQ [37], 14 items on a 7-point scale). Objective measures logged during each condition were the number of teleportations, the number of rotations, the duration of teleportations (i.e., the time required to initiate and complete a teleportation including *TeleTurn* rotation), and the score achieved (number of items collected). In a final questionnaire, participants were asked to rank all 12 conditions by preference and provide general comments.

3.5 Procedure

After an introduction, participants completed informed consent forms and provided information on their demographic background, including their VR experience. Afterwards, participants were explained the functionality of the HMD and the controller and had the opportunity to try the different rotation techniques. In each of the 12 conditions, participants were asked to navigate through a labyrinth via teleportation and collect as many items as possible within two minutes (see Figure 1 b). In each condition, participants started at the center of the labyrinth. Items were spawned in a semi-random manner with equal difficulty. To estimate the users' disorientation, they were asked to return to the center of the labyrinth after each collected item, thereby gaining a score. Afterwards, they had to fill out the questionnaires and were asked to take a break to reduce carry-over effects of simulator sickness. All conditions were counter-balanced and only during conditions where *InPlace* was set to *Physical* participants were allowed to rotate physically, otherwise rotation was performed via the controller. After the last condition, participants were asked to fill out the final questionnaire including a ranking of the conditions and general comments. Each participant received five currency (anonymized for review) of compensation at the end of the experiment.

3.6 Results

Due to the non-normal distribution of the collected data and multi-factorial design of the experiment, analysis was performed with the Aligned Rank Transform by Wobbrock et al. with Bonferonni correction for pairwise comparisons [47]. For readability's sake, descriptive statistics are presented in tables 1 to 4. For clarity of presentation, only significant main effects and interactions will be reported below.

3.6.1 Presence. IPQ Total Score: There was a main effect for *InPlace* ($F_{2,22} = 3.642$, p=.029) and *TeleTurn* ($F_{3,33} = 5.913$, p<.001). Post-hoc pairwise comparisons of *InPlace* revealed that 45° (M=3.76, SE=0.17) was significantly higher than *Physical* (p=.023, M=3.52, SE=0.18). Post-hoc pairwise comparisons of *TeleTurn* showed that *None* (M=3.91, SE=0.23) was significantly higher than 22.5° (p=.003, M=3.50, SE=0.16) and 45° (p=.002, M=3.54, SE=0.21).

IPQ General Item: There was a main effect for *InPlace* ($F_{2,22} = 3.236$, p=.043) and *TeleTurn* ($F_{3,33} = 5.911$, p<.001).

CONDITION		IPQ_G		IPQ_{SP}		IPQ_{INV}		IPQ_{REAL}		IPQ_P	
InPlace	*TeleTurn*	*M*	*SD*	*M*	*SD*	*M*	*SD*	*M*	*SD*	*M*	*SD*
Physical	*None*	4.25	1.60	3.82	0.65	4.21	1.43	3.33	0.94	3.90	0.89
Physical	*Continuous*	4.17	1.34	3.43	0.77	3.85	1.23	2.96	1.10	3.60	0.87
Physical	22.5°	3.08	1.00	3.55	0.45	3.67	1.20	2.98	0.78	3.32	0.54
Physical	45°	3.17	1.40	3.43	0.68	3.58	1.37	2.77	0.95	3.24	0.73
22.5°	*None*	4.17	1.34	3.82	0.76	4.17	1.17	3.17	1.02	3.83	0.96
22.5°	*Continuous*	3.83	1.03	3.63	0.62	4.15	1.05	2.79	0.97	3.60	0.59
22.5°	22.5°	3.58	1.31	3.67	0.51	3.92	1.38	3.08	1.11	3.56	0.70
22.5°	45°	3.83	1.11	3.82	0.54	3.67	1.07	3.08	0.90	3.60	0.70
45°	*None*	4.67	0.78	3.68	0.76	4.50	1.13	3.10	1.11	3.99	0.77
45°	*Continuous*	3.83	1.27	3.63	0.43	4.06	1.01	3.00	0.87	3.63	0.40
45°	22.5°	4.17	1.03	3.68	0.43	3.65	1.26	3.00	1.01	3.62	0.63
45°	45°	4.33	.098	3.70	0.75	4.15	1.29	2.94	1.05	3.78	0.90

Table 1. Descriptive statistics by condition for the IPQ sub-scales general (IPQ_G), spatial (IPQ_{SP}), involvement (IPQ_{INV}), experienced realism (IPQ_{REAL}), and the IPQ presence score (IPQ_P).

Post-hoc pairwise comparisons of *InPlace* revealed that 45° (M=4.25, SE=0.17) was significantly higher than *Physical* (p=.043, M=3.67, SE=0.25). Post-hoc pairwise comparisons of *TeleTurn* revealed that *None* (M=4.36, SE=0.31) was significantly higher than 45° (p=.008, M=3.79, SE=0.29) and 22.5°(p=.001, M=3.61, SE=0.26).

IPQ Spatial Presence: There were no main effects and no interaction.

IPQ Involvement: There was a main effect for *TeleTurn* ($F_{3,33} = 4.146$, p=.008). Post-hoc pairwise comparisons of *TeleTurn* revealed that *None* (M=4.29, SE=0.32) was significantly higher than 22.5° (p=.013, M=3.74, SE=0.35) and 45° (p=.023, M=3.80, SE=0.32).

IPQ Expected Realism: There was a main effect for *TeleTurn* ($F_{3,33} = 3.622$, p=.015).

3.6.2 Affective State. SAM Valence: There was a main effect for *InPlace* ($F_{2,22} = 5.892$, p=.003) and *TeleTurn* ($F_{3,33} = 9.390$, p<.001). Post-hoc pairwise comparisons of *InPlace* revealed that *Physical* (M=3.40, SE=0.26) was significantly lower than 22.5°
(p=.008, M=3.96 SE=0.19) and 45° (p=.013, M=3.88, SE=0.17). Post-hoc pairwise comparisons of *TeleTurn* revealed that *Continuous* (M=3.31, SE=0.25) was significantly lower than 22.5° (p=.003, M=3.92, SE=0.17), 45° (p=.043, M=3.72, SE=0.24), and *None* (p<.001, M=4.03, Se=0.24).

SAM Arousal: There was a main effect for *TeleTurn* ($F_{3,33} = 6.180$, p<.001). Post-hoc pairwise comparisons of *TeleTurn* revealed that *None* (M=3.36, SE=0.34) was significantly higher than 22.5° (p<.001, M=2.83, SE=0.26) and 45° (p=.007, M=2.92, SE=0.29).

SAM Dominance: There was a main effect for *InPlace* ($F_{2,22} = 11.156$, p<.001) and *TeleTurn* ($F_{3,33} = 11.715$, p<.001). Post-hoc pairwise comparisons of *InPlace* revealed that *Physical* (M=3.10, SE=0.23) was significantly lower than 22.5°(p<.001, M=3.79 SE=0.18) and 45° (p<.001, M=3.79, SE=0.17). Post-hoc pairwise comparisons of *TeleTurn* revealed that *None* (M=3.97, SE=0.26) was significantly higher than 22.5° (*p*=.009, M=3.64, SE=0.23), 45° (*p*=.005, M=3.50, SE=0.16), and *Continuous* (*p*<.001, M=3.14, Se=0.25). Furthermore, 22.5° was significantly higher than *Continuous* (*p*=.041).

Condition		SAM_V		SAM_A		SAM_D	
InPlace	*TeleTurn*	*M*	*SD*	*M*	*SD*	*M*	*SD*
Physical	*None*	4.08	1.08	3.58	1.38	4.17	1.11
Physical	*Continuous*	2.83	1.19	2.75	0.97	2.42	1.16
Physical	22.5°	3.33	0.78	2.92	0.90	3.00	1.21
Physical	45°	3.33	1.15	2.83	1.03	2.83	1.03
22.5°	*None*	4.17	0.83	3.25	1.29	3.83	1.11
22.5°	*Continuous*	3.42	1.00	3.08	1.08	3.50	1.00
22.5°	22.5°	4.25	0.75	2.83	1.03	4.00	0.74
22.5°	45°	4.00	0.85	2.83	1.03	3.83	0.72
45°	*None*	3.83	0.94	3.25	1.22	3.92	1.24
45°	*Continuous*	3.67	0.78	3.42	1.16	3.50	0.80
45°	22.5°	4.17	0.72	2.75	1.22	3.92	0.90
45°	45°	3.83	0.94	3.08	1.24	3.83	0.58

Table 2. Descriptive statistics by condition for the SAM dimensions valence (SAM_V), arousal (SAM_A), and dominance (SAM_D).

Condition		SSQ_N		SSQ_O		SSQ_D		SSQ_T	
InPlace	*TeleTurn*	*M*	*SD*	*M*	*SD*	*M*	*SD*	*M*	*SD*
Physical	*None*	11.93	12.29	15.80	13.11	18.56	24.71	17.45	14.99
Physical	*Continuous*	8.75	10.34	8.84	11.12	18.56	19.08	12.78	12.70
Physical	22.5°	7.16	9.21	13.27	13.38	11.60	20.42	12.47	14.73
Physical	45°	8.75	16.50	15.16	24.83	17.40	47.90	15.58	30.25
22.5°	*None*	11.93	14.74	15.16	15.16	20.88	36.83	17.77	21.46
22.5°	*Continuous*	7.95	10.63	12.00	15.98	19.72	28.75	14.34	18.59
22.5°	22.5°	5.57	11.11	8.84	17.05	13.92	35.61	10.29	21.82
22.5°	45°	3.98	11.11	7.58	12.93	13.92	31.41	9.04	18.90
45°	*None*	11.93	13.57	13.27	12.57	15.08	15.08	15.27	13.76
45°	*Continuous*	4.77	6.43	8.84	11.58	12.76	20.95	9.66	12.80
45°	22.5°	5.57	13.77	11.37	21.56	15.08	35.34	11.84	25.31
45°	45°	5.57	11.83	11.37	23.86	15.08	40.02	11.84	26.68

Table 3. Descriptive statistics by condition for the SSQ sub-scales nausea (SSQ_N), oculomotor (SSQ_O), and disorientation (SSQ_D), and the total SSQ score (SSQ_T).

3.6.3 Simulator Sickness. SSQ Total Score: There was a main effect for *TeleTurn*
($F_{3,33}$ = 6.280, *p*<.001). Post-hoc pairwise comparisons of *TeleTurn* revealed that *None* (M=16.83, SE=4.41) was significantly higher than 22.5° (*p*=.013, M=11.53, SE=5.83) and 45° (*p*<.001, M=12.16, SE=7.15).

SSQ Nausea: There was a main effect for *TeleTurn* ($F_{3,33}$ = 2.957, *p*=.035). Post-hoc pairwise comparisons of *TeleTurn* revealed that *None* (M=11.93, SE=3.59) was significantly higher than 45° (*p*=.030, M=6.10, SE=3.45).

SSQ Oculomotor: There was a main effect for *TeleTurn* ($F_{3,33}$ = 3.705, *p*=.014). Post-hoc pairwise comparisons of *TeleTurn* revealed that *None* (M=14.74, SE=3.69) was significantly higher than 45° (*p*<.014, M=11.37, SE=5.75) and *Continuous* (*p*=.048, M=9.90, SE=3.10).

SSQ Disorientation: There was a main effect for *TeleTurn* ($F_{3,33}$ = 2.983, p=.034). Post-hoc pairwise comparisons of *TeleTurn* revealed that *Continuous* (M=17.01, SE=5.81) was significantly higher than 45° (p=.045, M=15.74, SE=11.40).

CONDITION		TELEPORT		DURATION		$Rotations_{IP}$		$Rotations_{TT}$	
InPlace	*TeleTurn*	*M*	*SD*	*M*	*SD*	*M*	*SD*	*M*	*SD*
Physical	*None*	97.17	40.50	487	348	–	–	–	–
Physical	*Continuous*	57.67	20.46	1427	518	–	–	32.33	13.43
Physical	22.5°	60.00	27.48	1754	1042	–	–	115.33	23.64
Physical	45°	62.25	25.59	1507	792	–	–	77.75	27.68
22.5°	*None*	78.33	30.93	538	398	165.42	51.58	–	–
22.5°	*Continuous*	69.17	25.32	741	404	109.58	56.65	14.83	9.93
22.5°	22.5°	71.83	34.73	1884	1686	131.58	59.22	39.25	53.88
22.5°	45°	65.25	25.69	869	336	88.58	40.94	31.08	38.83
45°	*None*	89.58	41.91	452	336	127.08	39.79	–	–
45°	*Continuous*	66.33	26.43	997	787	84.33	44.34	14.67	13.23
45°	22.5°	71.83	37.05	749	434	134.00	65.02	28.50	34.05
45°	45°	72.00	23.28	679	480	97.42	40.23	23.83	34.74

Table 4. Descriptive statistics by condition for the number of teleportations (TELEPORT), duration of teleportation (in ms), number of discrete rotations in place ($Rotations_{IP}$), and number of discrete rotations during teleportations ($Rotations_{TT}$).

3.6.4 *Number of Teleportations.*

There was a main effect for *TeleTurn* ($F_{3,33}$ = 9.774, p<.001). Post-hoc pairwise comparisons of *TeleTurn* revealed that *None* (M=88.36, SE=9.69) was significantly higher than 22.5° (p<.001, M=67.89, SE=8.81), 45° (p<.001, M=66.50, SE=6.17), and *Continuous* (p<.001, M=64.39, SE=6.13).

3.6.5 *Duration of Teleportation.*

A two-way repeated measures ANOVA with Greenhouse-Geisser correction revealed a significant main effect for *InPlace* on the participants' teleportation duration ($F_{(1.30,14.25)}$ = 9.56, p=.005, η_p^2=.47, ϵ=.648). Pairwise t-tests with Bonferonni correction revealed that the duration of teleportation was significantly higher in the *InPlace Physical* condition than in the *InPlace* 45° condition (p<.001). In addition, there was a significant main effect for *TeleTurn* ($F_{(1.71,18.83)}$ = 11.57, p=.001, η_p^2=.51, ϵ=.571). Pairwise t-tests with Bonferonni correction revealed that the duration of teleportations was significantly lower in the *TeleTurn None* condition than in the *TeleTurn Continuous* (p=.001), *TeleTurn* 22.5° (p=.005), and *TeleTurn* 45° condition (p=.001). Furthermore, there was a significant interaction between *InPlace* and *TeleTurn* ($F_{(2.61,28.75)}$ = 4.80, p=.010, η_p^2=.30, ϵ=.436). While teleportation duration was mostly unaffected by the *InPlace* level during *TeleTurn None* conditions, teleportation duration in the *TeleTurn* 22.5° and *TeleTurn* 45° conditions was lowest with *InPlace* levels at 45°.

3.6.6 *Number of Discrete Rotations.*

Rotations were divided into rotations that happened in place, i.e. around the participants' position, ($Rotations_{IP}$) and rotations during teleportation, i.e. rotating the indicator arrow during teleportation, ($Rotations_{TT}$, see Figure 1 c). A Wilcoxon Signed Rank test revealed that the $Rotations_{IP}$ ranks for the *InPlace* 22.5° condition (mean rank = 27.04) were significantly higher than in the *InPlace* 45° condition (mean rank = 23.46, Z=-2.15, p=.032). Median (IQR) $Rotations_{IP}$ levels for the *InPlace* 22.5° and *InPlace* 45° condition were 127.00 (81.50 to 163.00) and 117.50 (78.50 to 139.00), respectively.

A Friedman's ANOVA revealed significant differences in the $Rotations_{TT}$ values for the three *TeleTurn* conditions *TeleTurn Continuous*, *TeleTurn* 22.5°, and *TeleTurn* 45° (X^2(2)=9.31, p=.009). Median (IQR) $Rotations_{IP}$ levels for the

TeleTurn Continuous, *TeleTurn* 22.5°, and *TeleTurn* 45° conditions were 16.00 (7.25 to 32.00), 58.50 (1.50 to 112.75), and 43.50 (1.00 to 82.50), respectively. Wilcoxon Signed Rank tests were performed with a Bonferonni adjusted p-value of .017. $Rotations_{TT}$ ranks were significantly higher in the *TeleTurn* 22.5° condition (mean rank = 22.78) than in the *TeleTurn Continuous* condition (mean rank = 8.77, Z=-3.12, p<.001) and $Rotations_{TT}$ ranks were significantly higher in the *TeleTurn* 22.5° condition (mean rank = 18.59) than in the *TeleTurn* 45° condition (mean rank = 11.17, Z=-3.06, p=.002). Furthermore, $Rotations_{TT}$ ranks were significantly higher in the *TeleTurn* 45° condition (mean rank = 24.07) than in the *TeleTurn Continuous* condition (mean rank = 9.75, Z=-3.09, p=.002).

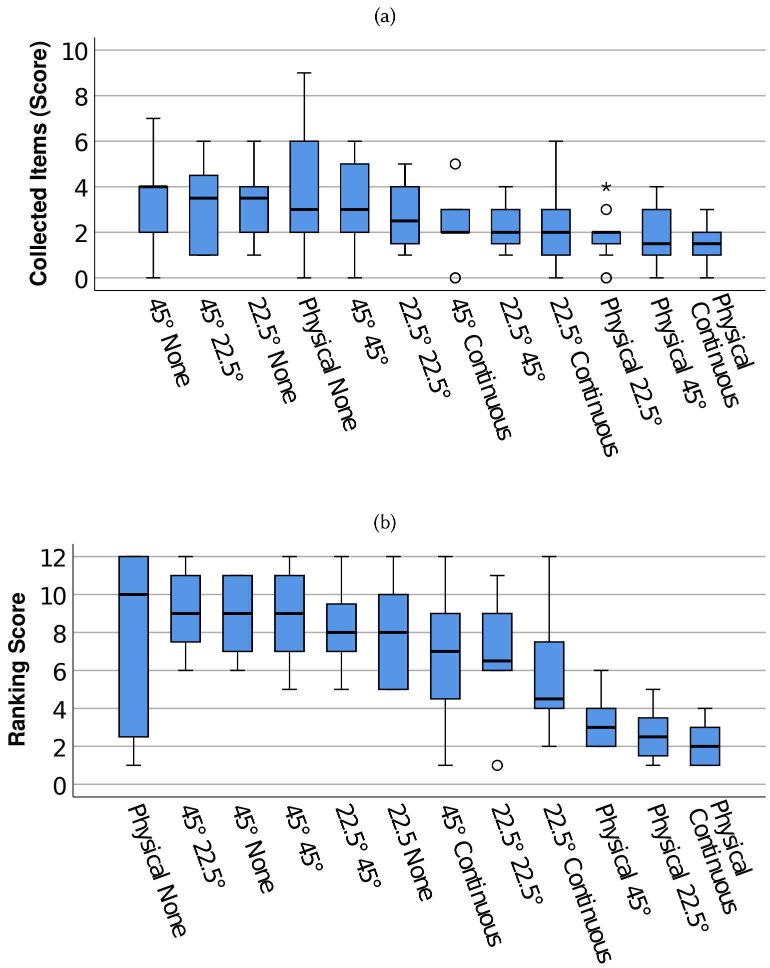

Fig. 2. Participants' score (a) and ranking of the conditions (b) in descending order.

3.6.7 Participant Score. There was a main effect for *InPlace* ($F_{2,22}$ = 4.188, *p*=.017) and *TeleTurn* ($F_{3,33}$ = 5.306, *p*=.002). Post-hoc pairwise comparisons of *InPlace* revealed that 45° (M=3.00, SE=0.30) was significantly higher than *Physical* (*p*=.013, M=2.23, SE=0.26). Post-hoc pairwise comparisons of *TeleTurn* revealed that *None* (M=3.47, SE=0.45) was significantly higher than *Continuous* (*p*<.001, M=1.92, SE=0.24). On average, the *Physical None* condition achieved the highest and the *Physical Continuous* condition the lowest score (see Figure 2).

3.6.8 Ranking of Conditions. There was a main effect for *InPlace*
($F_{2,22}$ = 42.439, *p*<.001) and *TeleTurn* ($F_{3,33}$ = 9.452, *p*<.001). Post-hoc pairwise comparisons of *InPlace* revealed that 45° (M=8.38, SE=0.35) was significantly higher than 22.5° (*p*=.047, M=7.23, SE=0.34) and *Physical* (*p*<.001, M=3.90, SE=0.30). Furthermore, 22.5°was significantly higher than *Physical* (*p*<.001). Post-hoc pairwise comparisons of *TeleTurn* revealed that *None* (M=8.17,
SE=0.69) was significantly higher than 22.5° (*p*=.043, M=6.25, SE=0.36) and *Continuous* (*p*<.001, M=4.81, SE=0.60). Furthermore, 45° was significantly higher than *Continuous* (*p*=.002). On average, the 45° 22.5° condition achieved the highest rank, while the *Physical Continuous* condition achieved the lowest rank (see Figure 2).

4 DISCUSSION

4.1 *InPlace*

Our results indicate that independent of the rotation interval, participants felt more pleased and in control with discrete *InPlace* rotations (i.e., *InPlace* conditions 22.5° and 45°) than with physical rotation. Even the largest rotation interval did not affect simulator sickness and spatial disorientation levels. In contrast, participants were able to navigate the labyrinth more efficiently, which is reflected in the higher number of collected items. Both discrete *InPlace* conditions were preferred over physical rotation, with the highest rotation interval (45°) being the favorite. Although rotations at 45° were considered "easier" (P7), they were not fast enough for some participants, calling for a "higher rotation interval" (P4) or the possibility to "hold down the rotation button" (P12). Higher rotation intervals should therefore be considered in future studies of *InPlace* rotation.

Implications: Some participants considered repeated button presses for both rotation types as too slow, while others considered the rotation intervals as too large and imprecise. Depending on the user preference and environment, it should be possible to adjust the rotation interval similar to adjusting the scrolling speed of a computer mouse.

4.2 *TeleTurn*

Since *TeleTurn* is a novel interaction technique included in a limited set of commercial VR games, we included the *None* condition, which represents teleportation from related work (e.g., [7]), in addition to the *Continuous* state-of-the-art in our user experiment. While participants preferred discrete *TeleTurn* rotations over the *Continuous* condition and felt more pleased and in control, the *TeleTurn None* condition was superior in terms of interaction time (teleportation duration) and performance (participant score). This could be explained by the lack of experience regarding *TeleTurn* rotation. P9 considered *TeleTurn* rotation as "tedious" and preferred a "sequence" of *InPlace* rotation and straight teleportation. This is consistent with the number of rotations observed. In conditions with discrete *InPlace* rotation, the number of *TeleTurn* rotations was lower since participants were free to choose between either of the rotation modes.

Implications: Participants mostly preferred rotation around their position (*InPlace*) over rotations during teleportation (*TeleTurn*), since the technique was "intuitive to use [...] but difficult to get used to" (P5). While a preview of the new orientation direction in form of a visual indicator was helpful, some users might benefit from a preview of the perspective to be assumed in order to see a benefit in *TeleTurn* over *InPlace* rotation. Similar to Liu et al., a portal or a video screen floating next to the user could serve as a medium to achieve this effect [20]. Furthermore, the *TeleTurn* condition was new to most participants, suggesting that interaction time could be reduced due to learning effects, making the technique more efficient. Since the current experimental setup set a time restriction, participants could have been in favor of the fastest technique. Considering other applications, such as shooters, where teleporting blindly to a new position might be dangerous, the time needed to select a new orientation via *TeleTurn* might be put into a new perspective.

4.3 Summary

Overall, teleportation with physical rotation (*Physical None* condition), which is the current state-of-the-art of most VR applications that feature teleportation, achieved the highest ranking score. A combination of 45° *InPlace* rotation and no *TeleTurn* rotation (*None*) achieved the highest score and was the third most preferred condition, offering a viable alternative for scenarios where physical rotation is impractical or impossible (e.g., sitting or lying). The novel *TeleTurn* technique with *Continuous* rotation in combination with physical *InPlace* rotation, as it is implemented in some commercial VR games, achieved the lowest score and was the least preferred condition of our participants. Since a combination of 45° *InPlace* and 22.5° *TeleTurn* rotation achieved the second highest score and was the second most preferred condition, we consider that *TeleTurn* could successfully be improved over its *Continuous* state-of-the-art and was well accepted by our participants.

5 LIMITATIONS

The experiment was performed with a three DoF HMD. Nevertheless we argue that the results can also be transferred to six DOF tracking, since the focus of the study was on rotation and not translation. The small sample size in our experiment could have been too low to find small effects between conditions and we explored only a limited range of rotation angles that might have been in favor of our game level design. Values beyond the investigated range could yield other results in terms of simulator sickness and player performance. Furthermore, spatial orientation was measured via the number of collected items and the respective SSQ subscale. Alternatively, orientation could have been measured via spatial updating which could result in a different outcome [14].

6 CONCLUSION

In this work we investigated the nature and potential of discrete rotation in VR to avoid physical rotation and maintain user presence, performance, and prevent simulator sickness. Two rotation techniques, rotation in-place (*InPlace*) and rotation during the teleportation process (*TeleTurn*), were evaluated with fixed rotation intervals against their respective state-of-the-art. Our results indicate that discrete *InPlace* rotation was preferred over physical rotation and significantly improved user presence and performance. The discrete *TeleTurn* variation was preferred over continuous *TeleTurn*, which is the current state-of-the-art, and led to significantly lower disorientation. *InPlace* rotation was largely preferred over *TeleTurn*. As a result, participants adapted a locomotion style that combined discrete *InPlace* rotations with straight teleportation without *TeleTurn* suggesting a complementary usage. From our findings we conclude that teleportation without physical rotation is feasible while maintaining user experience and performance.

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Face/On: Multi-Modal Haptic Feedback for Head-Mounted Displays in Virtual Reality

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Face/On: Multi-Modal Haptic Feedback for Head-Mounted Displays in Virtual Reality

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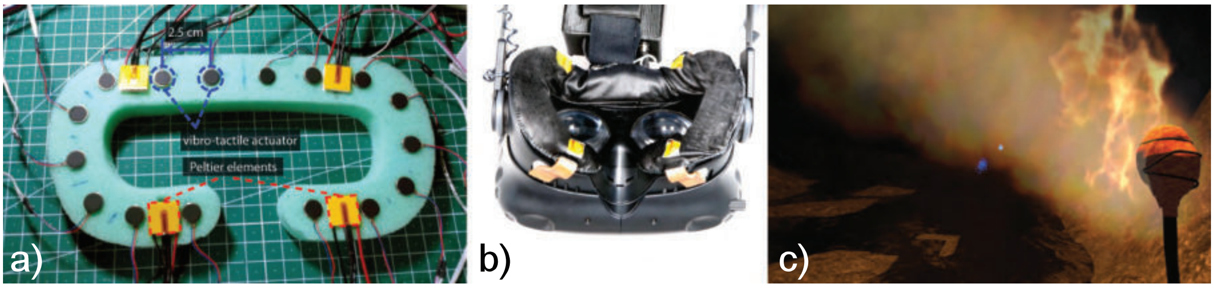

Fig. 1. Face/On combines a high density of vibrotactile actuators with additional thermal sources in a compact form factor (a). The surface area of the cushion offers space for additional actuators to further increase multi-modality (b). With its high resolution and multi-modality, Face/On can create feedback for a complex effect such as the wind force of a moving torch in front of the user's face and the heat of its flame on the user's skin.

Abstract—While the real world provides humans with a huge variety of sensory stimuli, virtual worlds most of all communicate their properties by visual and auditory feedback due to the design of current head mounted displays (HMDs). Since HMDs offer sufficient contact area to integrate additional actuators, prior works utilised a limited amount of haptic actuators to integrate respective information about the virtual world.
With the Face/On prototype complex feedback patterns are introduced that combine a high number of vibration motors with additional thermal sources to transport multi-modal and spatial information. A pre-study determining the boundaries of the feedbacks' intensities as well as a user study showing a significant increase of presence and enjoyment validate Face/On's approach.

Index Terms—VR, haptic feedback, multi-modal, thermal feedback.

1 Introduction

In 1965, Ivan Sutherland proposed his visionary idea of an ultimate display that would offer users total immersion [43]. Since then, there have been many suggestions on how to increase immersion in virtual environments (VEs) [40]. Usually, these solutions include wearable devices like haptic gloves [14], grounded force-feedback devices [16] or ambient feedback generators [34].

Most of these solutions have two common limitations: (1) users require additional instrumentation (e.g. a separate neck attachment [37]) and (2) their low actuator resolution provides only limited feedback (e.g. actuating the whole HMD with vibration [33]). Therefore, on our common endeavour to bring sensations of the physical world to virtual environments [35] we should focus on overcoming these limitations by exploring alternative approaches.

Most VR experiences that incorporate haptic feedback do so via the hand held controllers of the VR device being used. Some experiences and/or VR systems also make use of gloves and haptic vests embedded with small motors. Such devices expand the usage of tactile feedback by providing focused haptic feedback to enhance interaction and therefore immersiveness of the experience [31]. However, many state-of-the-art VR experiences include the users' head as a collision object without providing appropriate haptic feedback. Adding haptic sensations to the facial area offers great potential to increase user presence in virtual environments and provide an additional artistic tool to VR experience designers. In this paper, we explore the potential of high-resolution vibrotactile feedback with additional thermal sources in the facial region.

The main contributions of this paper are:

- the design and implementation of a modular and interchangeable feedback system in form of a VR face cushion
- the design and evaluation of complex feedback patterns that leverage Face/On's high vibrotactile resolution
- design guidelines for multi-modal haptic feedback for the facial area

2 A Modular Multi-Modal Haptic Feedback Approach

With *Face/On*, we present an approach to tackle the low resolution feedback of haptic devices and investigate effects of multi-modality in the facial region. Similar to how users get accustomed to perpetual skin contact with wrist-watches, clothes, and glasses, they can be expected to shift their attention from the facial contact area with the HMD towards the virtual environment [32, 46]. This allows *Face/On* to provide haptic feedback that blends with the virtual experience rather than distract from it by the use of additional instrumentation. To this end, all actuators were embedded inside an HMD face cushion as can be seen in Fig. 1 a. Our vision is the use of a modular hardware design to allow for interchangeable VR cushions to fit different requirements. A cushion for a diving simulation for example could incorporate additional pressure actuators to create a sense for the current under-water depth while a cushion for a flight simulator could explore vibrotactile feedback with fewer but more-powerful actuators to better simulate wind turbulence and high speed. In this work, we explore a combination of vibrotactile and thermal feedback. To achieve a compact form factor with mobility in mind, all hardware controllers are contained in

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Fig. 2. For the final *Face/On* prototype small openings were cut into the synthetic cushion cover to increase skin contact with the thermal elements. Custom designed copper heat-sinks were attached to the HMD via Velcro to remove excessive heat. This way, no actuators require a separate set-up and are 'attached' to the face along with the HMD itself.

a single 3D-printed case on top of the HMD (see Fig. 2). Currently, *Face/On* requires a separate electrical cord as the USB connection of an HTC Vive HMD does not provide enough energy. In future, less power-consuming versions of *Face/On* could be powered by a medium-sized battery and, thus, be completely mobile.

3 Related Work

The role of multi-sensory feedback has been identified as an important factor significantly influencing the feeling of presence in VR applications [7, 10]. Haptic feedback is one of them and is sub-divided into several modalities, like for example recognising touch or temperature [28]. This work draws from findings in the field of vibrotactile and thermal feedback. Due to the vast amount of work on body-worn haptic feedback in VR, we limit our focus to related work targeting the facial area and do not consider non-vibrotactile haptic feedback such as suction [21], pressure [3], EMS [27] or wind [39].

3.1 Vibrotactile Feedback

Vibrotactile stimuli as a channel for directional information has been explored for different body parts [22]. Kaul and Rohs investigated the performance of vibrotactile directional cues on the head against visual and auditory cues [23]. Their results indicate that vibrotactile feedback outperforms spatial audio (using a generic head-related transfer function) and is only marginally outperformed by visual cues (96.4% vs. 99.7% success rate respectively). This dominance of visual over auditory cues has been demonstrated for non-VR applications as well [44]. Funk et al. explored haptic, visual, and auditory feedback to signal errors in a manual assembly workplace suggesting that a combination of visual and haptic feedback might increase perception speed of error messages [11]. Wolf and Kuber explored coding schemes for vibrotactile feedback to increase situational awareness with a headband [45]. Their results suggest that a careful mapping of the signals to the different areas of the head must be performed to achieve optimal performance. This sort of mapping is vital since their study demonstrated that some participants struggled to interpret multi-parameter coding. Dobrzynski et al. investigated vibrotactile feedback on the head as an additional information channel for visually impaired users [8]. Their findings suggest that users perform better at localising single motors than multiple vibrotactile stimuli. This is consistent with previous work by Jones and Safter [20] and could be explained by the way vibrations are propagated through our skull [29]. A further explanation of this behaviour is the 'funneling illusion' where two vibrotactile stimuli are perceived as one [25]. Kerdegari et al. report this effect as being strongest for an inter-tactor distance of at least 2.5 cm. While it can be misleading for directional cues, this motivated us to leverage this effect for directed feedback via a high-density of vibrotactile actuators.

3.2 Thermal Feedback

Three of the main factors of thermoception are the site of the actuated skin, the amplitude and the rate of temperature change [19]. Due to its high density of thermoreceptors in the skin, the facial area is highly suitable for thermal feedback [13]. This potential was recognised by Peiris et al. in 2017 and motivated them to embed Peltier actuators in a VR HMD to provide directional cues [34]. A preliminary evaluation of their ThermoVR prototype suggested that users felt an increased sense of presence in virtual environments with thermal feedback. However, participants also reported discomfort resulting from the pressure the actuators put on their faces. This motivated us to focus on a small, comfortable form factor for our design.

Follow-up studies explored further use cases for ThermoVR such as checking the weather [5] and providing dynamic thermal feedback [4]. A combination of ThermoVR feedback with low frequency vibration resulted in a sensation of wetness [33] which motivated us to combine vibrotactile and thermal actuators to further explore the potential synergy effects between both actuator types.

Ranasinghe et al. presented Ambiotherm, a wearable accessory that provided thermal and wind feedback on the head [36]. Instead of the facial area, the back of the neck was chosen for thermal feedback due to its proximity to the thermoregulatory centre of the central nervous system [17]. Their results indicate that adding thermal and wind feedback contributed to an enhanced sense of presence compared to traditional VR experiences. In a follow-up project, Ranasinghe et al. added a third, olfactory actuator to the Ambiotherm prototype [37]. Participants' sense of presence was increased with respect to traditional VR experiences by adding any of the two modalities and improved even further by providing a combination of both modalities. This finding further supports our bi-modal design.

As a conclusion, we think that although vibrotactile and thermal feedback has been investigated for the head area, the potential of high-resolution multi-modal feedback in the facial area for VR applications is still under-explored. In contrast to prior works having a focus on precise localisation of individual stimuli (as explored by e.g. [12, 34]) Face/on builds on respective findings but is designed to investigate the complex effects and synergies that can be created with multi-modal and high-resolution haptic feedback.

4 Implementation

4.1 Hardware Prototype

During the design of *Face/On*, we drew from findings of related work regarding the optimal distribution of vibro-tactile actuators to create 'funneling illusions' - sensations that would allow to simulate continuous movements along the users face [25]. Therefore, 16 3V vibration motors with 12 mm diameter (coin type, 75mA, 12500 rpm) were embedded inside an 18 mm face cushion for the HTC Vive HMD with a distance of 2.5 cm to each other (see Fig. 1 a). Four 15×15 mm Peltier cooler modules (ET limited, 8.6 W, 3.6 V, 3.9 A) were distributed below the eyes and on the forehead as proposed by Peiris et al. [34]. The temperature actuation was measured via NTC-type thermistors calibrated according to the Steinhart-Hart equation [42] (see Fig. 3). Due to the modules inherent inefficiency the excess heat had to be conducted away via copper heat pipes that were attached to each module (see Fig. 2). Each actuator type was connected to a separate Adafruit 16-channel 12-bit PWM/servo driver as a module controller (see Fig. 3 and Fig. 4). Additionally, we installed H-bridges between Peltier modules and their respective module controller. All module controllers were interfaced via I^2C by an ESP32 micro-controller that was plugged into the Vive HMD via USB. All modules and micro-controllers were placed inside a 3D-printed case and attached to the top strap of the HMD (see Fig. 2).

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This way, the additional weight could be distributed evenly on the users' head to increase comfort. Due to the high power consumption of the Peltier elements, *Face/On* is powered by a separate 3.3 V, 6 A power supply. The HMD was connected to a PC with an Intel Core i7-4790K CPU (4.0 GHz), an AMD Radeon R9 390 GPU (8 Gb, GDDR5) and 32 Gb RAM.

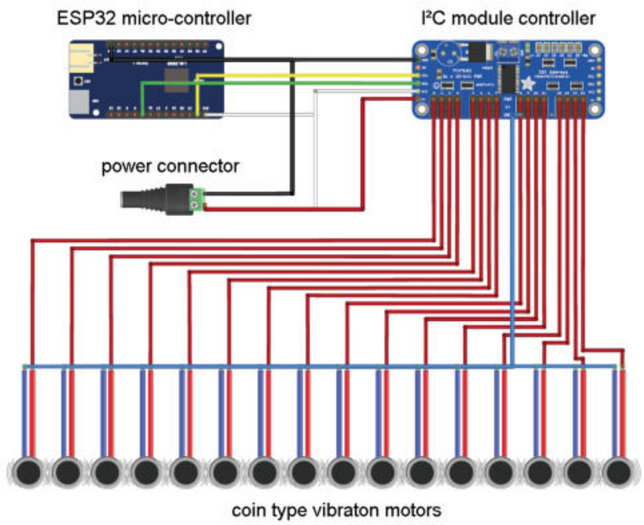

Fig. 3. A schematic view of the vibrotactile module.

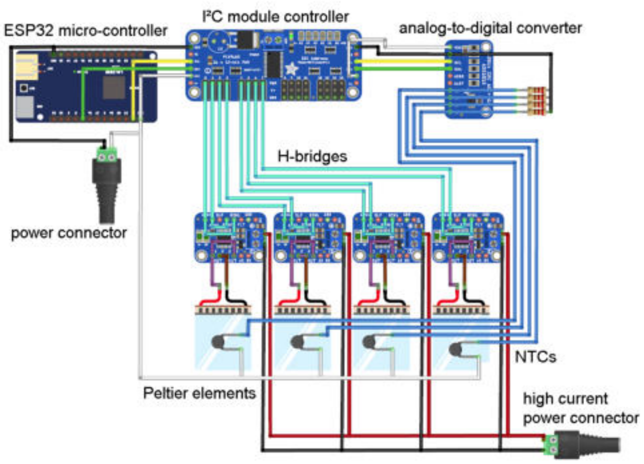

Fig. 4. A schematic view of the thermal module.

5 Application Examples

With its high-resolution and multi-modal design, Face/On is able to generate a broad range of effects via haptic feedback. We identified four major categories of effects that can be supported by the prototype: environmental effects, game events, forces, and the player state.

5.1 Environmental Effects

Haptic feedback plays an integral role of perceiving the climate of an environment and has been shown to increase user presence significantly when added to a virtual environment [34]. Environmental effects such as rain are usually continuous and particle-based rather than discrete and punctual. Therefore a high spatial resolution of vibrotactile actuators to simulate the impact of many individual water drops is necessary (see Fig. 5). As shown in previous work, combining cold thermal actuation with vibrotactile actuation can induce the effect of wetness [33]. With a low intensity and frequency of vibrotactile feedback, a rain effect can be changed to represent falling snow (see Fig. 6). Particle-based feedback can also be used to represent swarms of living organisms such as insects or bats (see Fig. 7).

To simulate the temperature of an environment such as a desert, all thermal actuators should be activated simultaneously. The direction of natural heat sources such as warm sun rays on the user's skin can be approximated with individual thermal actuators. The high resolution of vibrotactile feedback also allows to simulate the natural turbulence of a storm.

Three exemplary effects of this category were chosen for the user study: a sprinkler (see Fig. 5), falling snow (see Fig. 6), and a swarm of bats (see Fig. 7).

Fig. 5. Cold water is spraying from the ceiling as the player passes by.

Fig. 6. As the train passes a mountain site snow flakes are falling on the player's face.

5.2 Game Events

Game events include game-specific effects that can not be attributed to physical forces such as a notification of the player gaining a level. Typically such effects are presented via the acoustic and visual channel being the only available sources. Face/On is capable of generating directed and animated haptic feedback, allowing designers to guide the user's attention towards a certain direction or encode more information into a notification via a complex feedback pattern. The design of Face/On allows the use of various matching feedback patterns such as directed swipes that can for example serve as notifications.

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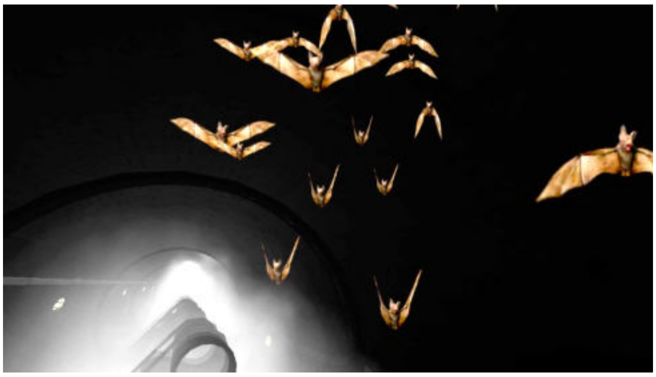

Fig. 7. A swarm of bats is attacking the player and is perceived as many single impact points.

5.3 Forces

With its high density of vibrotactile actuators, Face/On is able to approximate the point of impact of small objects with haptic feedback. The 'funneling illusion resulting from the small gap between the actuators allows to simulate high speed forces such as the pressure of an aircraft turbine (see Fig. 8). The additional inclusion of thermal feedback further enhances the design space of feedback patterns as well as the possibilities to enhance VR experiences. The combination of hot thermal feedback with a short burst of vibrotactile feedback can for example be used to simulate the blast of an explosion (see Fig. 9). By adding cold thermal feedback, however, the effect of a falling avalanche can be created (see Fig. 10). For the user study, three exemplary effects of the 'forces' category have been created: the pressure of an aircraft turbine, an explosion, and an avalanche.

Fig. 8. A hostile aircraft is flying over the train at high-speed generating a strong turbulence.

5.4 Player State

Among others, the representation of the internal state of a player can include a health bar and various status effects such as being wounded or frozen. A common effect in games to represent a critical health level is the acoustic feedback of a beating heart. Since an elevated blood pressure increases the perception of one's heartbeat throughout the body [26], Face/On can support this effect with a vibrotactile heartbeat pattern. Since the actuators are activated simultaneously during this effect, they are perceived as one large entity rather than multiple individual actuators. By adding hot and cold thermal feedback, player states such as burning or being frozen can be represented, respectively. As an example for player states, a heartbeat pattern that can represent different heart rates has been integrated into Face/On.

Fig. 9. A hostile aircraft is being chased and shot down by another aircraft. The explosion can be felt by the player from afar as heat and a blast of wind.

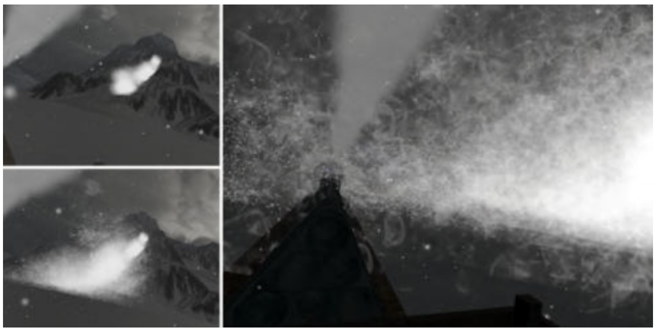

Fig. 10. After a lightning bold strikes a nearby mountain top, a massive avalanche is threatening to crush the train. The player perceives a cold and turbulent wind with snow.

6 Actuation Modes

To create the effects described above, a set of complex vibrotactile feedback patterns is necessary. A naive approach would result in a high number of serial-commands to control each vibrotactile actuator individually. This amount of traffic could increase the response time for haptic feedback although it has been shown to be even more sensitive to delays than visual feedback [18]. In addition, sending such serial commands requires in-depth knowledge of the underlying implementation. This circumstance makes it difficult for application designers to integrate additional feedback into an application. Based on the presented application examples different modes were developed, which abstract from the underlying complexity of serial commands. These actuation modes were created to trigger the feedback by a single command in JSON format and are then interpreted on the micro-controller as a series of actuations. The resulting actuation modes *continuous*, *pulse*, *heartbeat*, *random*, and *dash* are able to cover all effects described in Sect. 5.

6.1 Continuous Mode

As the name implies, the *continuous* mode provides continuous actuation on all specified vibrotactile actuators. The list of parameters expects an intensity value between 0 and 100 for each of the 16 actuators. It is therefore possible to vary the local intensity of vibration, allowing to create sensations such as a continuous, one-sided collision of the user's head. An actuation command for the example in Fig. 11 can be now expressed as:

```
{"id":0, "mode": "continuous",
"values": [0,0,0,0,0,0,0,0,0,0,70,100,100,70,0,0,0]}
```

6.2 Pulse Mode

The *continuous* mode requires a separate message to stop the actuation resulting in a delay for short actuation. To cover short collisions and

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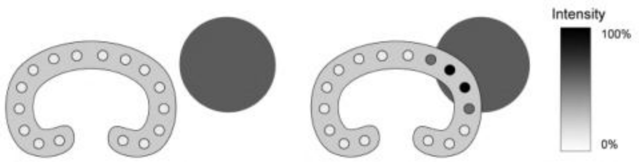

Fig. 11. A visualisation of vibrotactile feedback during a collision. Actuators closest to the point of impact receive a higher intensity than neighbouring actuators.

fast repetitive impulses, the *pulse* mode was implemented to accept additional parameters for the pulse width (*OnDurationsMs*), pulse frequency (*IntervalMs*), and *repetitions* (see Fig. 12). Interpreting the example in Fig. 11 as a short collision the corresponding command could be:

```
{"id":0, "mode": "pulse", "repetitions":1,
"values": [0,0,0,0,0,0,0,0,0,70,100,100,70,0,0,0],
"OnDurationsMs":100,"intervalMs":0}
```

This would result in a single short (100 ms) impulse of the selected vibrotactile actuators.

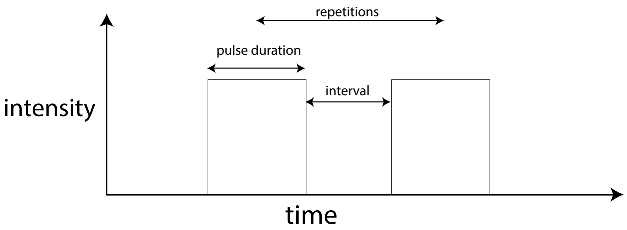

Fig. 12. Pulses can be defined via pulse width, intensity, interval, and repetitions.

6.3 Heartbeat Mode

An often used design element of virtual experiences is the acoustic representation of the user's heartbeat to convey a sensation of panic or high concentration. Previous work has shown that vibrotactile feedback can be sufficient to convey a heartbeat [9] and, thus, influence the user's emotional state [1]. As heartbeat feedback requires a distinct pattern to simulate the beginning and the end of the systole, a separate *heartbeat* mode was implemented as a variation of the *pulse* mode to accept a pulse duration (*OnDurationMs*) for both pulses, an intensity value between 0 and 100 for each of the 16 vibrotactile actuators, and an interval value (*intervalMs*) between consecutive pairs of pulses (see Fig. 13). The interval between the pulses that represent the systole was set to 280 ms which is within the typical range reported in the literature [2]. The parameters are passed in the following form:

```
{"id":0, "mode": "heartbeat",
"values":
    [60,60,60,60,60,60,60,60,60,60,60,60,60,60,60,60],
    "OnDurationsMs":100,"intervalMs":400}
```

6.4 Random Mode

Simulating environmental particle-based effects such as rain, hail or snow requires an actuation mode that seems random. Therefore a separate continuous mode was implemented that randomly selects two vibrotactile actuators and activates them for a given duration (*OnDurationMs*). This process is repeated after a predefined interval (*intervalMs*). The intensity values range from 0 to 100. A light summer rain could thus be simulated via:

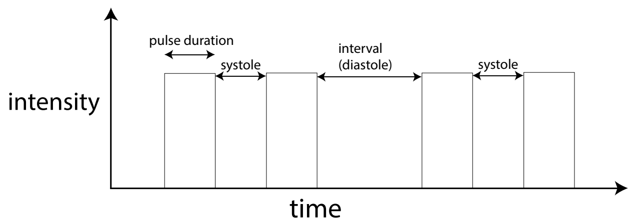

Fig. 13. In *heartbeat* mode, the cardiac cycle is modelled via two consecutive pulses (systole) and intervals between each pair (diastole).

```
{"id":0, "mode": "rain",
"values":
    [60,60,60,60,60,60,60,60,60,60,60,60,60,60,60,60],
    "OnDurationsMs":100,"intervalMs":40}
```

6.5 Dash Mode

To simulate high-speed movement such as a strong wind directed at the users' face, the *dash* mode creates a dynamic wave-like pattern that originates from the centre of the cushion and moves outwards symmetrically (see Fig. 14). With 16 vibrotactile actuators this results in four states with four actuators being active at the same time. The parameters for intensity (a value between 0 and 100) and duration (*OnDurationMs*) control the intensity and speed of the wave. There are no intervals between the states to create a smooth transition between actuators and leverage the funneling illusion. A fast wave with three repetitions can be created via:

```
{"id":0, "mode": "dash", "repetitions":3,
"values":
    [60,60,60,60,60,60,60,60,60,60,60,60,60,60,60,60],
    "OnDurationsMs":100}
```

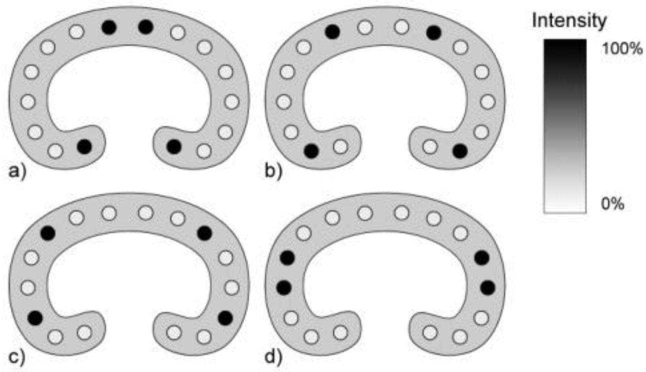

Fig. 14. A symmetrical wave simulates a frontal wind in *dash* mode.

7 Pre-Study

7.1 Procedure

To evaluate comfortable intensity parameters for the vibrotactile and thermal actuators, a pre-study with 8 participants (3 female) from our institution was performed. Participants were seated in a room with constant temperature. The participants were equipped with an HTC Vive HMD and the described prototype. The virtual scene was created in Unity3D and was only showing textual instructions on a white neutral background. In a randomised order, participants were asked to increase the intensity of the current actuator type to a noticeable level using

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the touchpad of a Vive controller. Vibration was increased in steps of 10%, temperature in steps of $1°C$ in a safe range from $20°C$ up to $30°C$ starting from the participants' individual skin temperature. Temperature was divided in cold and hot actuation, changing temperature levels below and above skin temperature, respectively. Participants were free to increase and decrease the intensity until satisfied with the level. With the trigger button of the controller participants confirmed their selection and were asked to select the maximum comfortable intensity. After a confirmation the next actuator type was selected.

7.2 Results - Vibration

The median for the minimum level of vibration intensity was 40% and 95% for the maximum level. A comfortable range satisfying all participants was found at an intensity between 60% and 80% which is consistent with frequencies used in related work [23] (see Fig. 15).

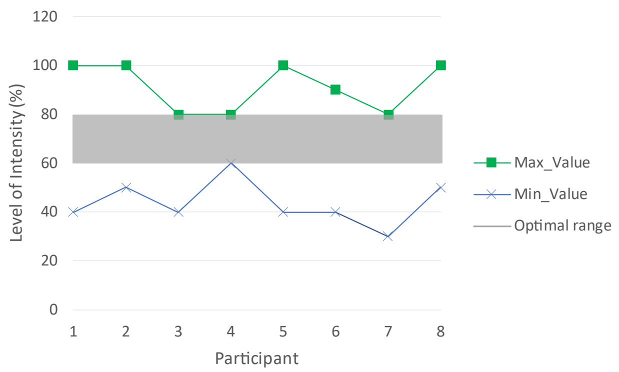

Fig. 15. Ranges of vibration intensity selected by participants.

7.3 Results - Temperature

All values are reported relatively to participants' skin temperature. The median for the minimum level of hot actuation was $+0.5°C$ and $+1.5°C$ for the maximum level . With the exception of participant 6, a comfortable range for hot actuation was found to be between $+0.5°C$ and $+1.5°C$. The median for the minimum level of cold actuation was $-1.0°C$ and $-7.5°C$ for the maximum level. A comfortable range for cold actuation for all participants was found to be between $-0.5°C$ and $-4.5°C$ (see Fig. 16).

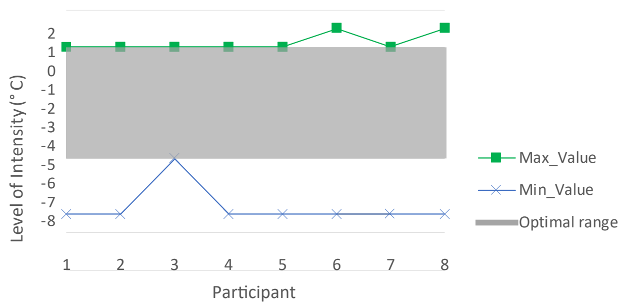

Fig. 16. Comfortable temperature ranges relative to participants' skin temperature.

8 User Study

To evaluate the effect of multi-modality and synergies between both actuator types on the sense of presence, enjoyment, and simulator sickness score, a repeated measures 2×2 factorial design study was conducted with 16 participants. Both actuators were defined as variables with two states: on and off. As described in Sect. 5, the range of effects that can be created with Face/On is broad. Therefore, only a partial quantity of exemplary effects were chosen for the user study. The study was approved by the local ethics committee. An informed consent was obtained from all individual participants included in the study.

8.1 Study Design and Measures

The study had two independent variables *vibration* and *temperature* with two levels *(on, off)* which resulted in 4 conditions.

For every condition, each participant watched the three scenes described below in a still standing position in a room with constant temperature without taking off the HMD. The scenes used *Face/On* for haptic feedback and an HTC Vive for visual and auditory feedback. All scenes and conditions were fully counterbalanced by a Latin-square. The baseline condition was [*vibration_off*, *temperature_off*] in which the scenes were viewed without any additional stimuli. After each condition, the participants completed the SSQ questionnaire [24], the E^2I questionnaire (immersion, engagement and enjoyment) [30] as well as Slater et al.'s SUS questionnaire [41] to measure presence. In a final questionnaire, participants were asked to rank the actuator combinations and provide optional responses on if and how they would like to use *Face/On* haptic feedback along with general comments. The study took on average 60 minutes and participants received 10 €. The vibration motors created a noticeable noise but it was barely heard due to the acoustic effects of the scenario playing inside the headphones. All intensity levels used in this study were based on the comfortable ranges found in our pre-study (see Sect. 7).

8.2 Participants and Procedure

Four of the 16 participants were female. They were aged between 22 and 40 years ($M = 27.13, SD = 4.12$) and were recruited from our institution. Participants reported their average time spent in VR between 0 and 8 hours per week ($M = 0.94, SD = 2.08$).

Using the exemplary effects described in Sect. 5, three different scenes were implemented for the user study. To ensure that each participant experiences all effects in the same way, the scenes were designed as a passive train ride. To prevent simulator sickness due to forward or angular acceleration, the train followed a straight path with constant speed [38]. The intensity settings for all effects were based on ranges found in the pre-study (see Sect. 7). At the beginning of the first scene, participants enter a tunnel where they are soon attacked by a swarm of bats (see Fig. 7). The *dash* mode was applied here to simulate the high speed of both, player and bats. Before leaving the tunnel, the train passes a sprinkler that showers the player with cold water. This effect is achieved using the *random* mode while actuating the thermal sources at minimum temperature settings.

At the exit of the tunnel, the train is teleported into a snowy mountain site (see Fig. 6). Similar to the sprinkler, the effect of falling snow was created with a combination of short bursts of cold actuation and the *random* mode. The vibrotactile intensity, however, was kept very low to create the sensation of light snowflakes landing on the participant's skin. As the train passes a mountain, a heavy avalanche hits the train (see Fig. 10). To convey the sensation of heavy snow masses, all 16 vibrotactile actuators were activated via the *continuous* mode.

After passing a portal, the train arrives at a foreign planet where the participant is soon attacked by an aircraft (see Fig. 8). During a nosedive, the aircraft creates a strong pressure with its turbine that is conveyed via the *dash* mode and a high vibrotactile intensity setting. Soon after, the aircraft gets shot out of the sky by another aircraft and crashes on the rocks (see Fig. 9). The hot blast of the explosion is simulated with a hot actuation of all thermal sources at the highest comfortable setting and a short vibrotactile actuation in the *dash* mode. After the explosion, the train gets teleported back to a train station and the participant receives a text prompt to take off the HMD. This concludes the trial.

8.3 Results

8.3.1 Enjoyment

A Friedman ANOVA revealed significant differences in Enjoyment for the four different conditions, $\chi^2(3) = 22.804, p < .001$. Post hoc analysis with Wilcoxon signed-rank tests was conducted with a Bonferroni correction applied, resulting in a significance level set at $p < 0.0083$. Median (IQR) Enjoyment levels for the baseline, vibration, temperature and vibration+temperature trial were 3.0 (2.5 to 4.0), 4.13 (2.88 to 4.75), 4.38 (3.13 to 5.38) and 5.0 (3.31 to 5.88), respectively. There was a significant difference between the vibration+temperature and the baseline trials ($Z = -3.370, p = .001$), the vibration+temperature and vibration trials ($Z = -2.994, p = .003$) and the vibration and the baseline trials ($Z = -3.066, p = .002$).

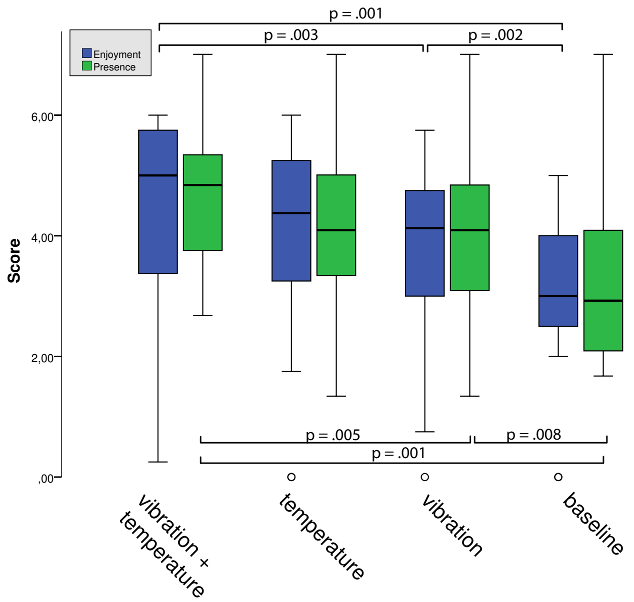

Fig. 17. Box plots of enjoyment and presence scores for all four conditions.

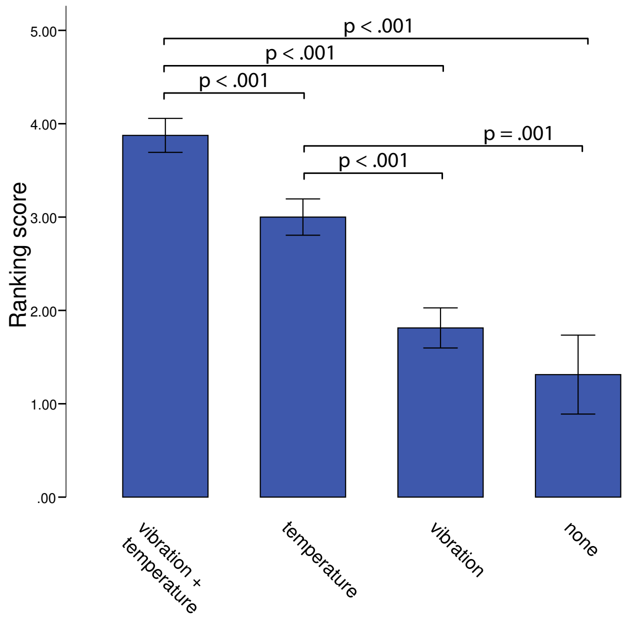

Fig. 18. Bar chart of condition ranking sorted by user preference in descending order.

8.3.2 Presence

A Friedman ANOVA revealed significant differences in Presence for the four different conditions, $\chi^2(3) = 18.120, p < .001$. Post hoc analysis with Wilcoxon signed-rank tests was conducted with a Bonferroni correction applied, resulting in a significance level set at $p < 0.0083$. Median (IQR) Presence levels for the baseline, vibration, temperature and vibration+temperature trial were 2.92 (2.04 to 4.13), 4.08 (3.04 to 4.83), 4.08 (3.25 to 5.08) and 4.83 (3.71 to 5.42), respectively. There was a significant difference between the vibration+temperature and baseline trials ($Z = -3.234, p = .001$), vibration+temperature and vibration trials ($Z = -2.787, p = .005$), and vibration and baseline trials ($Z = -2.643, p = .008$).

8.3.3 Simulator Sickness

An analysis of the SSQ revealed no significant difference in simulator sickness scores over all conditions ($M = 9.875, SD = 12.851$) compared to the control condition ($M = 8.65, SD = 10.1$).

8.3.4 Correlations

Fig. 18 shows the user ranking across all conditions in a descending order which suggests a correlation with the enjoyment and presence scores in Fig. 18. This correlation was analysed using Spearman's correlation coefficient. There was a significant positive correlation between *ranking* and *enjoyment* ($p = .004, \rho = 0.352$) and *ranking* and *presence* ($p = .001, \rho = 0.389$). Further more we found significant positive correlations between *enjoyment* and *presence* ($p < .001, \rho = 0.556$). A Friedman ANOVA revealed significant differences in the ranking scores of the four different conditions, $\chi^2(3) = 38.625, p < .001$. A Kendall's W test revealed a high concordance value for the ranking scores, $W = 0.805, p < .001$. Post hoc analysis with Wilcoxon signed-rank tests was conducted with a Bonferroni correction applied, resulting in a significance level set at $p < 0.0083$. Median (IQR) ranking score levels for the baseline, vibration, temperature and vibration+temperature trial were 1.0 (1.0 to 1.0), 2.0 (2.0 to 2.0), 3.0 (3.0 to 3.0) and 4.0 (4.0 to 4.0), respectively. There was a significant difference between the vibration+temperature and temperature trials ($Z = -3.5, p < .001$), the vibration+temperature and vibration trials ($Z = -3.753, p < .001$), the vibration+temperature and baseline trials ($Z = -3.646, p < .001$), the temperature and vibration trials ($Z = -3.755, p < .001$) and the temperature and baseline trials ($Z = -3.256, p = .001$).

8.4 Discussion

Our results indicate that the presence of two forms of feedback - vibrotactile and thermal - demonstrates better results in terms of presence and enjoyment. The combination of both modalities was ranked higher than single-modality conditions which also resonates in the participant responses where participants stated for example that 'the combination of temperature and vibration reinforces the overall impression more than the individual actuators' (P15) and 'vibration and temperature work very well together'(P2). These synergy effects were described with the fact that 'the cold doesn't feel punctual when combined with vibration but is spread'(P10). This is consistent with previous work and indicates that multi-modality has a positive impact on user presence. Adding further modalities such as kinesthetic feedback generators could further increase the benefit and could be evaluated in the future. The SSQ scores did not change significantly possibly due to a rather small sample size.

9 Limitations

Although the copper heat pipes improved heat dissipation for the Peltier elements drastically, temperature actuation was limited to a bare minimum. Tests with continuous cold actuation over short periods of time ($t = 30s$) showed an accumulation of heat in the heat pipes of over $40°C$. Shortly after the actuation period ($t < 3s$), the actuator side facing the users' skin reached a peak temperature of $32°C$ which was higher than the comfortable maximum value reported in the pre-study (see Sect. 7). Therefore, thermal actuation was provided in short impulses rather than continuous actuation. A more sophisticated and active cooling system such as fans or liquid cooling could mitigate the heat dissipation issue. As stated in Sect. 4.1, the temperature change rate was approximately $3°C/s$ which resulted in a noticeable delay. Providing feedback for sudden, non-scripted events therefore requires an approach as reported in HapticTurk [6]. Here, the authors implemented a mechanic that probes the environment for incoming user-environment events such as collisions to compensate for feedback delay. Similarly, events such as projectile impact could be predicted via ray-casting to synchronise the haptic and visual feedback. Although no participant complained about hearable vibrations or any other sounds affecting the experience in a negative way, there is the possibility of bone conducted sound affecting the experience.

10 Design Considerations

The findings of this work have implications on the design of haptic feedback for VR. Designers of VR experiences may consider the following three aspects when creating haptic feedback for the facial area.

10.1 Hardware Design

The results of our study validate the benefit of a multi-modal design. We expect that adding further modalities like kinesthetic feedback (as done in e.g. [15]) would create additional synergies and increase the range of effects that can be generated. To keep the compact form factor of the current prototype, additional actuators should be mounted on the contact area between cushion and skin or within the remaining space inside the cushion. An alternative would be to create interchangeable cushions with different actuator constellations that can be changed depending on the current content.

Most effects presented in this work would not have been feasible with a low-resolution design. Therefore, we argue that an increased resolution of actuators results in a larger design space for haptic feedback. However, not all types of actuators require the same level of resolution. In this work, we have demonstrated how low-resolution thermal feedback can be combined with high-resolution vibrotactile feedback. Similar asymmetric constellations might be feasible for other types of actuators and require further exploration.

10.2 Software Design

In this work, we created complex effects by using feedback modes that can be triggered by a single command. This on one hand reduces communication traffic between software and prototype and therefore reduces the delay of haptic feedback and on the other hand allows for easier integration into VR applications. The level of abstraction allows to keep the code clean and to rapidly implement and evaluate new effects. Designers of effects for Face/On or other haptic feedback devices could consider adapting a similar abstraction layer for any new actuator type. Since our experiment was limited to a few exemplary effects out of a broad range of possibilities, there might be value in evaluating more effects regarding their impact on user presence and enjoyment.

10.3 Application Design

From our experience, haptic feedback in the facial area should be kept sparse to stay comfortable. If continuous or long effects (e.g. precipitation) are necessary, the intensity should be kept low and the effect subtle. Big effects like an explosion should use multiple modalities to create a strong impression. Effects like these can create an impressive presentation of the virtual world. To create more intricate haptic feedback, future VR designers could translate audio signals into haptic feedback. Especially low frequencies could result in haptic feedback that leverages an audio signal. Due to the high resolution of vibrotactile actuators, Face/On could represent the direction of the audio signal by actuating the corresponding face region.

11 Conclusion

In this paper, we have presented the design and evaluation of Face/On, a multi-modal haptic feedback device for VR HMDs. By combining high-resolution vibrotactile haptic feedback with thermal sources inside the compact form factor of a face cushion, complex feedback patterns can be generated to create unique effects for virtual environments. We implemented exemplary effects for three virtual scenes, that have demonstrated and validated how complex haptic feedback can increase user presence and enjoyment. In the future, Face/On can be extended by additional actuators to create more synergies and more complex feedback patterns.

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JumpVR: Jump-Based Locomotion Augmentation for Virtual Reality

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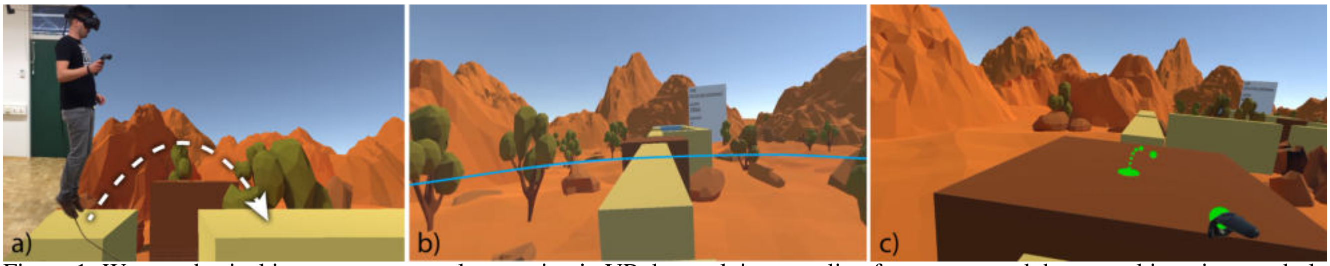

Figure 1: We use physical jumps to augment locomotion in VR, by applying a scaling factor to extend the natural jumping parabola by forward motion (a). The range of the previous jump is indicated to users by a radius indicator (b). We compared this scaled jumping to a teleportation baseline (c).

ABSTRACT

One of the great benefits of virtual reality (VR) is the implementation of features that go beyond realism. Common "unrealistic" locomotion techniques (like teleportation) can avoid spatial limitation of tracking, but minimize potential benefits of more realistic techniques (e.g., walking). As an alternative that combines realistic physical movement with hyper-realistic virtual outcome, we present *JumpVR*, a jump-based locomotion augmentation technique that virtually scales users' physical jumps. In a user study (N=28), we show that jumping in VR (regardless of scaling) can significantly increase presence, motivation and immersion compared to teleportation, while largely not increasing simulator sickness. Further, participants reported higher immersion and motivation for most scaled jumping variants than forward-jumping. Our work shows the feasibility and benefits of jumping in VR and explores suitable parameters for its hyper-realistic scaling. We discuss design implications for VR experiences and research.

Author Keywords

VR; virtual reality; jumping; super human; immersion; hyper realism.

CCS Concepts

•**Human-centered computing** → **Interaction techniques;** *Empirical studies in HCI;*

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INTRODUCTION

Modern virtual reality (VR) provides an environment with theoretically unlimited possibilities. We can assume different roles, gain new abilities and explore fictional worlds, in a technologically and emotionally immersive world overlaid on top of real life. While a large body of research focuses on achieving increasingly "realistic" experiences in VR such as feeling haptic feedback when touching virtual walls [4], getting hit by objects [38], or climbing physical steps [32, 23], there is no reason to restrict our imagination to physical limitations set by the world we know. As children, we are often inspired by superheroes, dreaming of gaining similar abilities one day [24]. In growing older, children learn to distinguish between fact and fiction, but we argue that a yearning for this kind of experience never entirely goes away. Thus, we are motivated by the design and implementation of hyper-realistic experiences such as superhuman strength and speed in order to realize a common childhood fantasy, by creating and evaluating unique and engaging user experiences in VR (a motivation termed "*mixed reality empowerment*" in prior work [12]).

Fictional characters with superhuman strength often achieve unnatural jump heights, scaling mountains and roof-tops in the blink of an eye. We aim to give players the chance to experience this exciting and entertaining sensation. For this purpose, we introduce physical jumping as a realistic input technique and apply a virtual forward motion through scaling factors to create a hyper-realistic experience of increased jump strength. We aimed to explore how users experience physical jumping in VR (i.e., while wearing the headset and controllers), to explore its feasibility for VR games and experiences in general. Further, we compared the impact of different scaling factors (i.e., how far the user's jump was scaled in terms of forward motion), and how scaled jumping in VR performs as an alternative to teleportation, currently one of the most common locomotion techniques in VR.

In a within-subjects lab study (N=28), we compared teleportation to scaled jumping and forward-jumping by letting users navigate a virtual parkour scene. Our results show that physical jumping in VR (regardless of scaling) can significantly increase presence, motivation and immersion while largely not increasing simulator sickness. Additionally, most scaled jumping conditions achieved a significantly higher immersion and motivation rating than forward-jumping. Combining these results with participants' self-reported preferences, we found scaling factors that maximize user experience and comfort while minimizing negative effects such as simulator sickness. We conclude with design implications for VR experiences that aim to benefit from hyper-realistic output.

With this work, we contribute an evaluation of the feasibility of physical jumping in VR, including an exploration of the parameters for virtually scaling hyper-realistic jumps. Based on this, we discuss how hyper-realistic jumping can be designed for inclusion in VR games and experiences, as well as other potential hyper-realistic movement representation in VR.

RELATED WORK

Locomotion in VR

Early work has shown that walking in VR is perceived to be more natural than walk-in-place or controller-based techniques [35]. However, then as well as today, walking in virtual environments is restricted by the spatial boundaries of the tracking space. Previous work has explored methods for VR users to walk endlessly in virtual worlds; for example, Razzaquev et al. introduced a redirected walking technique that creates the illusion of an unlimited walking space by tricking users to walk on a curved path [25]. However, curvature gains that are entirely unnoticeable to the user generally still require too much physical space to be practical [27]. In current VR applications, an "unrealistic" locomotion technique is becoming increasingly established: teleportation. With this method, VR users point-and-click to move in virtual space, with a parabola indicating the currently selected new location (see Figure 1c) [3]. This technique creates less simulator sickness than touchpad-based locomotion (i.e., moving the virtual camera forward by moving the finger forward on the touchpad) [8] and avoids spatial restrictions of the tracking space. Another option (closer to real-life locomotion than such button-based techniques) is walk-in-place, i.e., performing swinging gestures with the arms to virtually move forward [34]. Although this remains less realistic than real-life locomotion, it motivated us to explore a jump-in-place technique.

While walk-in-place and jump-in-place are both missing the sensation of vection, a study by Rietzler et al. suggests that missing movement feedback can be substituted by rotational feedback to trick the vestibular system into perceiving a forward motion [28]. We explore whether a similar approach can be used by applying virtual forward movement to scaled vertical-only jumps. We hope that combining a natural movement with hyper-realistic output presentation in VR can make users accept a vertical jump as containing forward momentum, thus yielding user acceptance of jumping in VR and leverage positive side effects of embodied interaction on player experience. Interaction based on whole-body movement in virtual spaces has been shown to have a high potential for engaging and enjoyable user and player experiences [2, 15, 21, 29], suggesting potential benefits from employing physically engaging locomotion techniques.

Highly Physical Movement in Virtual Experiences

There is evidence that embodied interaction and physically highly engaging movements are in themselves beneficial to a human's mood [9], brain plasticity [37] and stress relief [13].

This is increasingly being explored in mixed reality experiences. For example, Finkelstein et al. presented Astrojumper, a CAVE-based experience that required autistic children to physically jump to overcome obstacles [6]. Preliminary results with healthy participants were positive. Mixed reality is also increasingly being used for exergames, i.e., games developed to induce physical exertion and use physical movement as an input mechanism [39]. This has been explored by integrating workout machines into virtual spaces (e.g, a cycling ergometer or rowing machine [5, 17]). It has also led to the inclusion of whole-body movement in the form of functional training sessions in augmented reality (e.g., the ExerCube [22]). In generally exploring whole-body movements in VR, Rogers et al. found that realism is not always necessary; sometimes an approximation of physical challenge is enough or even preferred [29]. Further, highly realistic or physically engaging movements in VR must be designed in consideration of trade-offs with usability (i.e., through "unrealistic" abstraction) and onlooker effects (e.g., feeling self-conscious). These examples show that (fully as well as partially) virtual experiences can incorporate increased physical movements for the purpose of also increasing engagement, enjoyment, and motivation.

Finally, we note that jumping itself has previously been explored in the VR context focusing on exergaming. Ioannou et al. [14] explored a very similar jump-in-place concept with applied forward motion, and found increased immersion and motivation for the addition of augmentation, but also incurred motion sickness when participants were running in VR. While they included different scaling factors of augmenting the jump, they explored a smaller range for jumping in place (theoretically up to 2.5m upwards motion for a physical jump of 10 cm). In contrast, we extend this range to reach up to 30m at our highest scaling factor for jumping in place. However, they only explored effects of jumping alongside effects of running in place in VR, i.e., existing forward motion was preserved or used to augment forward motion. How jumping as an isolated experience affects player experience remains unanswered. Further, likely due to the focus on exergames, they did not compare their system against teleportation, i.e., the de facto standard in VR locomotion.

(Hyper-)Realism in VR

Several related works have explored hyper-realism in VR experiences. For example, Birdly by Max Rheiner is an installation for VR that allows users to experience a sensation of flying like a bird via a wing-flapping mechanism [26]. Although no formal evaluation was conducted, this work has become very popular due to its "realistic" flying, and is a great demonstration of how a seemingly unrealistic experience in VR can elicit a high amount of enjoyment in users. Hämäläinen et al. have termed this "*mixed reality empowerment*" [12], and in particular, lament a scarcity of systems that enable "*superhuman locomotion*" via manipulation of perceived gravity. In a follow-up study in the wild by Lehtonen et al., mixed reality empowerment was explored for exaggerated jumps on a trampoline in a multi-player game [20]. Their results suggest that "movement empowerment may support autonomy, competence, and relatedness". A related project by Granqvist et al. [10] explored hyperrealistic avatar flexibility in a martial arts VR game. They found that a medium degree of hyperrealistic flexibility was preferred over realism or strong exaggeration.

In a more subtle application of hyperrealism, Gugenheimer et al. provided kinesthetic feedback for head movements to create a sensation of increased gravity on an alien planet, by attaching fly-wheels to a head-mounted display (HMD) [11]. Their results indicate that users experienced higher immersion and presence than without kinesthetic feedback, but after virtual jumps (performed by pressing a button, while seated) lacked a sensation of impact when returning to the ground.

In a more physically involved example, Sasaki et al. presented a haptic feedback device for "virtual super-leaping" [31]. An upward directed force is generated by eight rotors in a handheld prototype to create the sensation of being pulled upwards during a physical jump. Unfortunately, no formal user evaluation has been conducted so far. Also incorporating a physical jump, virtual forward movement was presented in a work by Ishibashi et al. [16]. In this work, a web-shooter prototype for VR creates a pulling-force on the arm and simulates swinging from building to building like the popular comic superhero Spiderman. Preliminary results on user experience were promising. In contrast, Kim et al. proposed a cable-driven system to induce a sense of reduced gravity and enable users to physically take hyper-realistic jumps [19]. Their results show that scaled vertical jumps are accepted by users within a certain scaling range and have the potential to increase user presence. This approach largely increases time spent physically ascending and descending to manipulate perceived gravity while introducing a minor virtual scaling, while our approach leaves the physical jump unaffected and scales only the virtual output which results in a higher virtual jump height and distance.

RESEARCH FOCUS

Based on previous work we can conclude that both hyper-realistic experiences and physical movement in VR can enhance user experience. Additionally, there exists a range of (vertical) scaling factors for physical jumps that is accepted by users in VR. However, previous work has mostly relied on hardware prototypes to create hyper-realistic experiences while software-based solutions remain under-explored, despite benefits in terms of cost. Furthermore, we are interested how a mostly jump-based locomotion technique compares against teleportation which is the state-of-the-art locomotion technique for most VR experiences. To explore this comparison, we implemented a software VR prototype that allows us to evaluate a range of horizontal scaling factors for physical jumps, with the goal to improve player experience without inducing additional simulator sickness. We conducted a lab study to answer the following research question:
How does (scaled) physical jumping in VR compare against teleportation in terms of presence, immersion, enjoyment and simulator sickness?

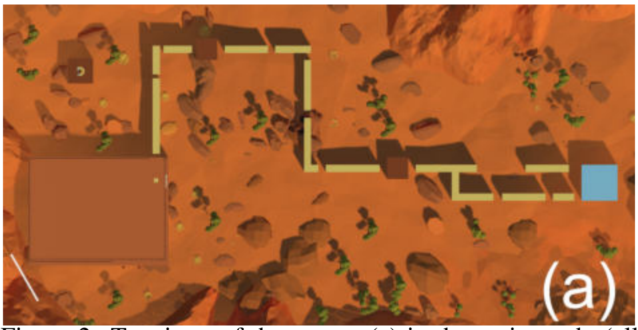
IMPLEMENTATION

We implemented a VR prototype called *JumpVR*, for which all virtual scenes were written in Unity3D with use of the *Virtual Reality Toolkit* (VRTK) [7] and displayed on an HTC Vive VR headset (v1.0). Players navigate a virtual platform course via *MoveInPlace*—a locomotion mechanism provided by VRTK, by which users can move through the scene by keeping the touchpad pressed and performing a walking gesture (up-down motions) with their arms. At 14 spots throughout the course, players have to cross differently spaced gaps between platforms by jumping across. Using MoveInPlace would result in players falling between platforms; depending on the game variation, players can either teleport across, or employ scaled jumping[1], as described in the following. While the player is in mid air, a virtual forward movement is applied based on the velocity of the headset calculated frame by frame.

Jumping in VR

While the player is standing or moving through the tracking space a baseline is calculated based on the headset's height. This *headset baseline* consists of the average height of the headset gathered over the last 100 frames of the game and adjusts itself to the players' behaviour. When the player bends their knees (i.e., the headset height decreases), the system is set into a monitoring state. If the headset's subsequent upwards acceleration surpasses the baseline in addition to an empirically defined threshold, the system recognises a jump

[1] Forward-jumping was conducted as an exploratory baseline condition on a smaller course, due to potential fatigue from jumping and to allow for unrealistically far scaled jumps in the main course.



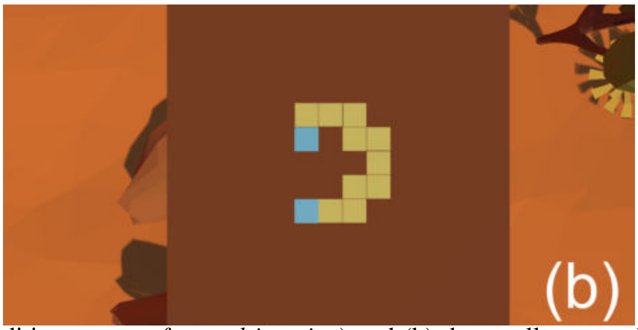


Figure 2: Topviews of the course (a) in the main study (all conditions except *forward-jumping*) and (b) the smaller second course used only for the *forward-jumping* condition. The brown blocks in the main-study course were checkpoints; upon falling, participants were re-set to the last passed checkpoint.

and applies a vertical scaling factor to the actual movement vector. Forward movement is applied linearly by scaling the player's initial forward vector in each frame during the jump phase. A longer airtime therefore results in a longer jump. As a lack of physical feedback during virtual jumps has been lamented in previous work [11], we utilize the natural haptic feedback of physical jumps' take-off and landing to simulate the start and end of a hyper-realistic jump; only the air-time is virtually scaled. To facilitate jump precision and learning, a *range indicator* in the form of a virtual ring around the user was introduced to visualize the jump range from the current position if the player were to repeat the previous jump (see Fig. 1b).

Jump States

The system monitors the current user state to detect when users are physically jumping, and which state of the jump they are in. This allows the virtual jump scaling manipulation to be enabled exactly and only during jumps. To do so, the system detects the following five states based on headset height, velocity, and acceleration:

OnGround

The user is standing or moving inside the tracking space (default state). During this time, a baseline is continuously built.

KneesBent

The headset height is lower than the baseline, i.e., the player is bending their knees. This triggers the system to be aware of a possible upcoming jump. To abort the jump, the user can simply straighten their legs again, bringing their headset to the *OnGround* height and corresponding system state.

Rising

When the user is accelerating upwards, the start of the jump is initiated as soon as the headset's baseline is passed. Virtual jump manipulations can now be applied, based on the position difference to the last frame. The first occurrence of the *Rising*-state triggers the system to log the timestamp and the start position of the physical jump (the moment the user leaves the ground), and to activate the scaling manipulation.

Falling

The user has passed the jump peak and is now falling back towards the ground. The scaling manipulation is now inverted to bring the user back to the ground in the virtual world.

Landing

As soon as they reach the baseline again, the jump is finished and scaling manipulation stops. The system then resets itself; the user is considered to be in the *OnGround*-state again.

EVALUATION

A scaling factor exaggerates the player's actual jump height and creates a sensation of vection due to forward movement. This could potentially induce motion sickness due to the mismatch between players' virtual and physical movements [1]. We conducted an in-lab user experiment to explore a range of scaling factors with regards to their effect on player immersion and presence, as well as simulator sickness.

Method

Our within-subjects experiment had a total of seven conditions, each representing one of the following locomotion variants of our *JumpVR* prototype: jumping scaled with five different factors, teleportation as a state-of-the-art baseline, as well as a secondary baseline of forward-jumping. All conditions were fully counterbalanced.

Jump Prototype Variants

The prototype was implemented with different sets of parameters, to compare varying degrees of manipulation applied to jumping in VR against two baselines: "realistic", i.e., unscaled physical jumping in VR, and a teleportation alternative without any jumping (state-of-the-art VR locomotion technique).

- *Forward-jumping*: Participants had to complete (a smaller version of) the parkour without virtual jump manipulation, teleportation, or *MoveInPlace*; every locomotion except for physical movement was disabled. Moving over gaps required realistic physical jumping (including forward motion) that was represented without manipulation in the virtual world. The parkour for this variant was smaller, constrained both by the tracking space, and due to the higher expected fatigue for realistic jumping (see Figure 2b).

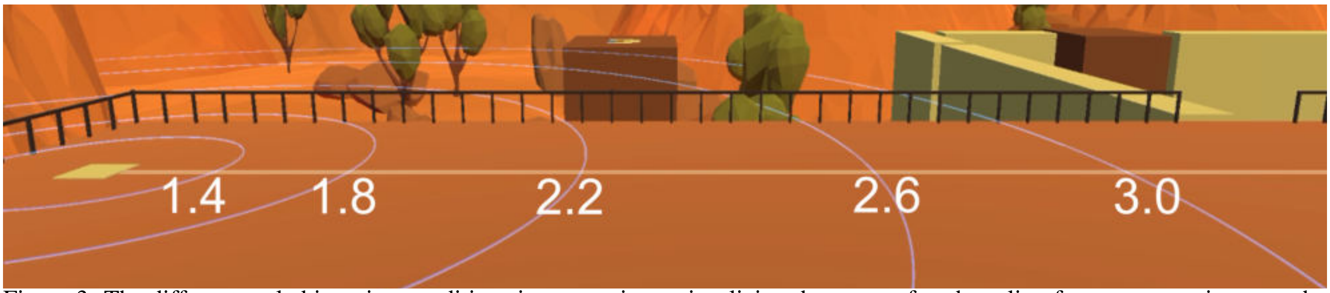


Figure 3: The different scaled jumping conditions in comparison, visualizing the range of each scaling for an average jump on the yellow square to the left.

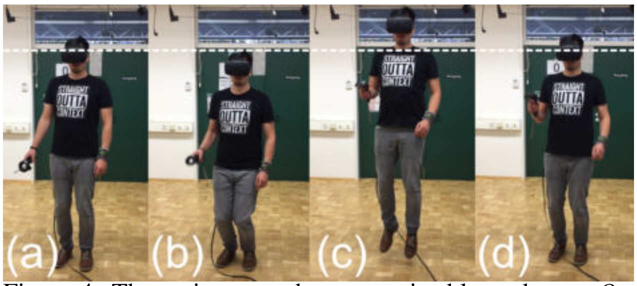


Figure 4: The main states the system is able to detect: *On-Ground* (a), *KneesBent* (b), *Rising/Falling* (c), *Landing* (d). The dashed line symbolises the measured baseline.

- *Teleportation*: In this baseline condition, players were asked to use teleportation only to navigate the main parkour (Figure 2a). Teleportation was implemented using the default mechanism provided by VRTK. Pressing and holding the trigger on the controller enabled an indicator showing the currently selected future position. Upon release of the trigger, users are teleported to the selected position. The maximum range was limited so that users were not able to teleport for more than two blocks at once. Participants were instructed not to jump; *MoveInPlace* was disabled.
- *Scaled Jumping*: vertical physical jumping was required, while forward motion was applied virtually through different scaling factors (SFs) in five different variants: *SF 1.4* (corresponding to ~2 m in real world), *SF 1.8* (~5 m), *SF 2.2* (~10 m), *SF 2.6* (~18 m), and *SF 3.0* (~30 m). The different conditions are illustrated in Figure 3 (all shown jumps were executed with a mean airtime of 250ms). For each of these forward vectors in terms of scaled horizontal motion, corresponding vertical factors were applied to achieve a close-to-natural jump parabola. For the sections on the platforms of the main parkour (Figure 2a), *MoveInPlace* was also enabled.

Along the main parkour, three checkpoints were defined: the start, and the two small brown blocks seen in Figure 2a. If participants virtually fell between platforms, they were transported back to the last passed checkpoint prior to reaching the ground of the virtual world.

Technical Setup
The experiment was conducted with the HTC Vive HMD and controllers in a tracking space sized 3.2 x 3.5 meters. We used a computer equipped with an i5-6600k (stock) processor and an Nvidia GTX 1080 graphics card. The software ran with 60 frames per second.

Participants
We recruited 28 participants (10 female, 18 male, 0 other) from our institution with a mean age of 25.90 (*SD*=2.63). All participants had normal or corrected-to-normal vision. With regards to VR experience, 2 participants reported owning a VR headset themselves and 9 reported having access to a VR headset[2]. For those with VR experience (*N*=21), the mean duration of their VR sessions was reported as 1.92 hours (*SD*=0.76), with a mean of 1.77 breaks per hour (2.17 generally, 1.36 due to discomfort of some kind—three participants reported the headset weight as a reason for taking breaks).

Measures
Participants' experiences were assessed via questionnaires at the end of each study condition. This post-condition set of questionnaires covered simulator sickness (Simulator Sickness Questionnaire (SSQ) [18], 16 items on a 4-point scale), motivation (interest/enjoyment from the Intrinsic Motivation Inventory (IMI) [30], 7 items on a 7-point scale), presence (Inter Group Presence Questionnaire [33], 14 items on a 7-point scale), and immersion and mastery (two subscales with corresponding names of the Player Experience Inventory (PXI) [36], 4 items each on a 7-point scale).

A final questionnaire at the end of the study recorded the perceived number of jumps during the study, custom questions about general comfort with the HMD (7-point scale, 7 items) and the usability of the range indicator (7-point scale, 4 items), as well as participants' general playing habits, e.g., whether they enjoy physically engaging games (7-point scale, 3 items). Finally, we asked them to choose their preferred condition and to give general feedback on the prototype.

Procedure
After an introduction to the concept of *JumpVR* and the study, and the completion of consent forms, participants provided information on their demographic background, as well as their VR experience and habits. They were then asked to experience the prototype seven times, followed by questionnaires. Depending on the current condition, participants were asked to

[2] 6 HTC Vive, 1 Oculus Rift/Go, 1 Pimax 8k, 1 Oculus Quest, 1 Google Cardboard, 1 Sony Playstation VR.

reach the end of the parkour by either jumping or teleporting over the gaps between platforms (see Figure 1). A condition was considered finished if the target platform was reached, or a maximum of three minutes had passed. If a participant fell from a platform, they were automatically teleported back to the last checkpoint they had passed. All conditions were balanced with a Latin Square. Between conditions (after questionnaires), participants could take an optional break in case of fatigue. All movement data including jump height, duration, and frequency was logged. After the last condition, participants additionally filled out the final questionnaire covering general feedback and their preferred condition.

RESULTS

A summary of the results of the SSQ, IMI, IPQ and PXI questionnaires can be found in Table 1. The following paragraphs contain only significant results.

Simulator Sickness (SSQ)

A Friedman's ANOVA revealed significant differences in the SSQ total score (SSQ_TS) between the conditions, $X^2(6)$=24.517, $p<.001$. Dunn's pairwise tests with Bonferroni correction were carried out for each pair of groups (all Z and p values of these comparisons are listed in Table 1). SSQ_TS scores were significantly higher for the *scaled-1.4* condition than for the *teleportation* condition (see Table 2 for an overview of the descriptive statistics).

Interest/Enjoyment (IMI)

A Friedman's ANOVA revealed significant differences in the IMI's interest/enjoyment score between conditions, $X^2(6)$=68.889, $p<.001$). Dunn's pairwise tests with Bonferroni correction were carried out for each pair of groups (all Z and p values of these comparisons are listed in Table 1). Interest/enjoyment scores were significantly higher for *scaled-1.8*, *scaled-2.2*, *scaled-2.6*, and *scaled-3.0* than for the *teleportation* condition. Further, the *forward-jumping* condition yielded significantly lower interest/enjoyment than conditions *scaled-1.8*, *scaled-2.2*, *scaled-2.6*, and *scaled-3.0* (see Table 2 for an overview of the descriptive statistics).

Presence (IPQ)

A Friedman's ANOVA indicated significant differences in the presence between conditions, $X^2(6)$=45.021, $p<.001$. Dunn's pairwise tests with Bonferroni correction were carried out for each pair of groups (all Z and p values of these comparisons are listed in Table 1). Presence scores were significantly lower for *teleportation* than for the *forward-jumping* condition, for *scaled-1.4*, for *scaled-1.8*, for *scaled-2.2*, for *scaled-2.6*, and *scaled-3.0* (see Table 2 for an overview of the descriptive statistics).

Immersion and Mastery (PXI)

A final Friedman's ANOVA reported significant differences in the immersion score between conditions, $X^2(6)$=62.078, $p<.001$. Dunn's pairwise tests with Bonferroni correction were carried out for each pair of groups (all Z and p values of these comparisons are listed in Table 1). Immersion was reported as significantly lower for the *teleportation* condition than for conditions *scaled-1.4*, for *scaled-1.8*, for *scaled-2.2*, for *scaled-2.6*, and *scaled-3.0*. Immersion was also significantly lower for the *forward-jumping* condition than for conditions *scaled-1.4*, for *scaled-1.8*, for *scaled-2.2*, for *scaled-2.6*, and *scaled-3.0*.

A final Friedman's ANOVA reported significant differences in the mastery scores between conditions, $X^2(6)$=16.864, $p<.05$. Dunn's pairwise tests with Bonferroni correction were carried out for each pair of groups (all Z and p values of these comparisons are listed in Table 1). Mastery scores were significantly higher for the condition *scaled-1.8* than for conditions *scaled-1.4* and *forward-jumping* (see Table 2 for an overview of the descriptive statistics).

An overview of the components of player experience components (immersion, interest/enjoyment, and presence) across conditions is displayed in Figure 5.

Performance: Jumps and Falls

On average, participants guessed they had jumped a total of 85 times over all conditions (*SD*=44.37). Results on actual jumps, falls and fall/jump ratios per condition (and total) can be found in Table 3.

Perceived Comfort

The majority of participants were comfortable jumping while wearing the HMD, although they did feel its weight, and they felt it applied pressure to their face. Participants mostly denied being afraid of damaging or losing the HMD during their experience; in fact, many had at some point forgotten about the HMD. The results for these custom comfort questions are shown in Figure 7.

Range Indicator

Participants mostly agreed that "*the range indicator helped to understand the system faster*" (M=5.07, SD=0.93), and mostly disagreed that the "*the range indicator was confusing*" (M=1.29, SD=0.96) or "*[...] affected the game experience negatively*" (M=1.07, SD=0.68). Further, they mostly disagreed that "*the indicator was unnecessary after [they] understood the mechanic*" (M=2.18, SD=1.60).

Preferred Condition

The most preferred condition was *scaled-1.8* (32.14%), followed by *scaled-2.2* (25%) and *scaled-2.6* (25%), see Figure 6.

Qualitative Feedback

With regards to preferences, only a single participant preferred the *teleportation* condition, as it eliminated the "*risk of falling*" (P4). Others, however, perceived it as "*unrealistic and boring*" (P5), "*less immersive*" (P21), or "*felt like the actual jumping was way more fun than the teleportation, although exhausting. It felt like the movement was real.*" (P14). Additionally, P28 reportedly experienced less simulator sickness with this condition: "*tend to get simulator sickness from teleportation, which I didn't experience [with physical jumps]*". None of the participants preferred the *forward-jumping* condition. According to P7, "*[m]oving through the actual room in the [*forward-jumping*] condition did not feel as comfortable/secure as just jumping up and down*". For some this was due to a "*fear to collide with something*" (P23) in the

Condition Pair	SSQ		IMI		IPQ		PXI-Immersion		PXI-Mastery	
	Z	*Adj. Sig.*	*Z*	*Adj. Sig.*	*Z*	*Adj. Sig.*	*Z*	*Adj. Sig.*	*Z*	*Adj. Sig.*
teleportation - forward-jumping	.875	1.000	-.179	1.000	1.821	**.034**	.161	1.000	-1.375	1.000
teleportation - scaled-1.4	-2.464	**.000**	-1.554	.150	-2.625	**.000**	-2.036	**.009**	1.339	.427
teleportation - scaled-1.8	-1.750	.051	-2.768	**.000**	-3.321	**.000**	-2.679	**.000**	-.429	1.000
teleportation - scaled-2.2	-1.107	1.000	-2.679	**.000**	-3.036	**.000**	-2.911	**.000**	.607	1.000
teleportation - scaled-2.6	-1.661	.084	-3.107	**.000**	-2.393	**.001**	-2.571	**.000**	.482	1.000
teleportation - scaled-3.0	-1.393	.333	-3.089	**.000**	-2.804	**.000**	-2.268	**.002**	.625	1.000
forward-jumping - scaled-1.4	-1.589	.124	-1.375	.362	-.804	1.000	-1.875	**.024**	-.036	1.000
forward-jumping - scaled-1.8	-.875	1.000	-2.589	**.000**	-1.500	.197	-2.518	**.000**	-1.804	**.037**
forward-jumping - scaled-2.2	-.232	1.000	-2.500	**.000**	-1.214	.744	-2.750	**.000**	-.768	1.000
forward-jumping - scaled-2.6	-.786	1.000	-2.929	**.000**	-.571	1.000	-2.411	**.001**	-.893	1.000
forward-jumping - scaled-3.0	-.518	1.000	-2.911	**.000**	-.982	1.000	-2.107	**.006**	-.750	1.000
scaled-1.4 - scaled-1.8	.714	1.000	-1.214	.744	-.696	1.000	-.643	1.000	-1.768	**.046**
scaled-1.4 - scaled-2.2	1.357	.394	-1.125	1.000	-.411	1.000	-.875	1.000	-.732	1.000
scaled-1.4 - scaled-2.6	.804	1.000	-1.554	.150	.232	1.000	-.536	1.000	-.857	1.000
scaled-1.4 - scaled-3.0	1.071	1.000	-1.536	.164	-.179	1.000	-.232	1.000	-.714	1.000
scaled-1.8 - scaled-2.2	.643	1.000	.089	1.000	.286	1.000	-.232	1.000	1.036	1.000
scaled-1.8 - scaled-2.6	.089	1.000	-.339	1.000	.929	1.000	.107	1.000	.911	1.000
scaled-1.8 - scaled-3.0	.357	1.000	-3.21	1.000	.518	1.000	.411	1.000	1.054	1.000
scaled-2.2 - scaled-2.6	-.554	1.000	-.429	1.000	.643	1.000	.339	1.000	-.125	1.000
scaled-2.2 - scaled-3.0	-.286	1.000	-.411	1.000	.232	1.000	.643	1.000	.018	1.000
scaled-2.6 - scaled-3.0	.268	1.000	.018	1.000	-.411	1.000	.304	1.000	.143	1.000

Table 1: Pair-wise comparisons between conditions for simulator sickness (SSQ), interest/enjoyment (IMI), presence (IPQ), immersion and mastery (PXI).

Condition	SSQ		IMI		IPQ		PXI-Immersion		PXI-Mastery	
	M	*SD*	*M*	*SD*	*M*	*SD*	*M*	*SD*	*M*	*SD*
forward-jumping	17.63	20.66	4.16	1.29	3.40	.79	4.80	1.12	4.77	1.17
teleportation	10.55	16.26	3.74	1.48	2.81	.83	4.72	1.18	5.21	1.07
scaled-1.4	21.10	20.31	5.31	1.16	3.87	.90	5.66	.85	4.64	.92
scaled-1.8	17.63	17.48	5.69	0.98	4.01	.83	5.87	.65	5.46	.90
scaled-2.2	14.96	14.54	5.60	1.02	3.94	.91	5.90	.69	5.10	1.27
scaled-2.6	18.43	20.68	5.72	1.07	3.78	.88	5.79	.84	5.02	1.06
scaled-3.0	17.90	20.16	5.82	1.10	3.79	.83	5.76	.80	4.94	.90

Table 2: Descriptive statistics by condition for simulator sickness (SSQ), interest/enjoyment (IMI), presence (IPQ), immersion and mastery (PXI).

Condition	Jumps		Falls		Fall/Jump	
	M	*SD*	*M*	*SD*	*M*	*SD*
forward-jumping	7.36	3.27	–	–	–	–
scaled-1.4	49.93	32.48	3.64	2.90	0.10	0.09
scaled-1.8	27.36	10.30	1.21	1.13	0.04	0.04
scaled-2.2	28.82	10.32	5.46	3.29	0.17	0.08
scaled-2.6	27.43	10.63	8.43	5.12	0.28	0.11
scaled-3.0	21.93	8.14	8.86	4.34	0.39	0.11
Total	163.82	54.85	27.82	10.51	0.17	0.05

Table 3: Player jump statistic by condition. The lowest fall/jump ratio for scaled jumping was achieved in scaled-1.8.

forward-jumping condition, wherein the physical space was mostly realistically utilised.

For scaled jumping, while some participants liked "*the physical challenge to achieve a longer jump*" (P17), the smallest scaling factor (*scaled-1.4*) was the least preferred scaled jumping condition (e.g., "*required more jumps [and thus] more effort*" P27). This trade-off between between exertion and accuracy is likely what led to *scaled-1.8* being preferred by most participants: a "*sweet spot between too exhausting and too imprecise*" (P25). It allowed them to feel "*more in control of the length of a jump*" (P1). Interestingly, this condition was often referred to as "*natural*" (P15) even though the virtual jump was much longer than possible for most in real life. P14 summarised it as "*not too far of a [j]ump that seemed like i could not do it in real life, but it was also far enough that i could feel like some kind of superhuman.*"

Condition *scaled-2.2* came second in preference, considered "*the most controllable out of all the jumping conditions [where] larger jumps where still possible*" (P26). P27 could "*reach the blocks with less effort*" in this condition while "*[l]arger jumps were difficult to control*". In contrast, *scaled-2.6* "*allows [you] to do more than [you] can in real life but is still manageable*" (P22). "*The longer range gave [them] the feeling of being faster which makes [them] feel better*" (P6). Generally, the "*higher difficulty of guessing the jump range made the task more challenging*" (P10). For some, this yielded greater interest and enjoyment in the strongest manipulation (*scaled-3.0*): it "*allowed the most interesting jumps*" (P7), and "*[j]umping really far just feels good if you hit the track*" (P23).

Overall, the jump-in-place concept was well received and allowed participants "*to forget that [they were] in the laboratory because [they] didnt fear to collide with something*" (P23) in scaled jumping. The combination of walk-in-place and jump-in-place was considered "*really good*" (P21). Walk-in-place

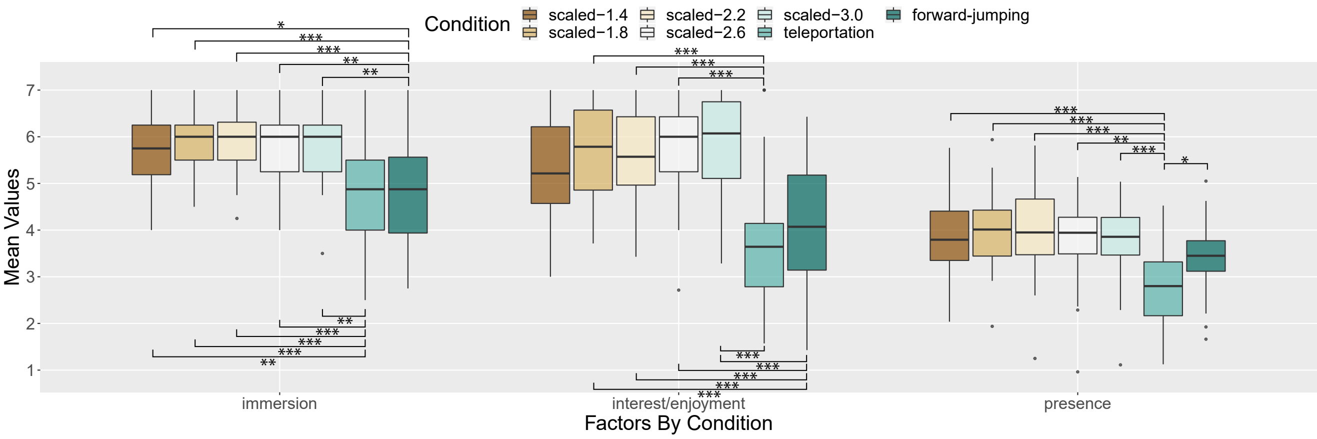


Figure 5: Immersion, interest/enjoyment, and presence were rated higher for the scaled jumping conditions than compared to teleportation (and largely also compared to forward-jumping). Significant differences are highlighted with $*$ (p<.05), $**$ (p<.01) and $***$ (p<.001).

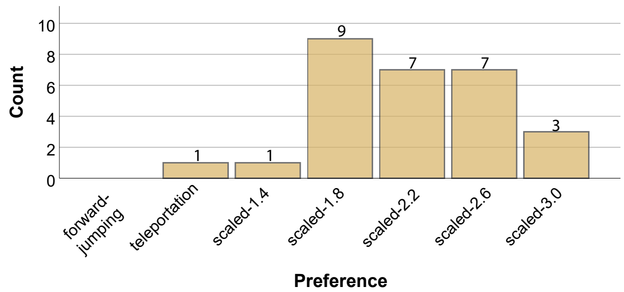


Figure 6: Results of participants' most preferred condition.

enabled staying "*in the correct space to not collide with obstacles of the outside*", i.e., granular refinement of position. In contrast, "*jumping on the other hand gave [...] the feeling of being really in the game. It made a lot of fun*" (P21). Some participants would like to see *JumpVR* "*integrated into games*" (P10) and "*exergames in VR*" (P22), as they "*like doing extraordinary stuff inside a game*" (P23). P16 considered *JumpVR* as a "*very innovative way of moving in VR*" but would "*not like this as [the] only option of travelling in the virtual world*". Similarly, P17 would like to see jumping interaction in specific scenarios where "*you have to jump across a gap or want to climb something / reach something atop*".

Discussion

Our results showed that *JumpVR* was very well received by participants. With the exception of the *scaled-1.4* condition, all scaled jumping conditions elicited significantly higher presence, interest/enjoyment, and immersion in comparison to teleportation. For the most part, scaled jumping thus showed significant benefits in comparison to the state-of-the-art locomotion technique in most VR experiences. It therefore represents a viable extension or augmentation of existing walk-in-place locomotion techniques [34].

Scaled Jumping: Scaled-1.4 vs. Other SFs

All physical jump conditions except for *scaled-1.4* did not significantly increase simulator sickness in comparison to teleportation. This indicates that the manipulation of participants' forward motion was largely accepted by our VR users and was even considered natural by many. This suggests that we successfully built on previous findings that a missing stimulus in VR (e.g., forward movement) can be replaced or roughly substituted with another (in our case, upwards-only movement), without compromising user or player experience [28, 29].

It is interesting to note that *scaled-1.4* was the only condition to increase simulator sickness compared to teleportation. This may provide insight with regards to mismatch theories of simulator sickness [1], i.e., ascribing simulator sickness symptoms to a mismatch between participants' visual and vestibular input (what they see vs. what they feel). The lack of significantly increased simulator sickness for the scaled jumping conditions with stronger manipulation is surprising from this perspective, as they represent a greater mismatch. However, we argue that it could be precisely because of the more obvious mismatch that participants accepted scaled jumping with factors higher than 1.4 as its own technique, rather than interpreting it as noise in their perceived visual and vestibular input. Alternatively, the higher simulator sickness for condition *scaled-1.4* could be related to the relatively high number of jumps performed in that condition compared to the others (this did not translate to a similarly high number of falls).

Scaled vs. Forward Jumps

Scaled jumps elicited higher interest/enjoyment and immersion than forward-jumping, while not significantly increasing simulator sickness. This indicates that the hyperrealism of jumping further than in real life—compared to what is either possible at all, or possible for that degree of effort—is what significantly improved player experience. If the *forward-jumping* condition had been just as well received, the higher immersion and interest/enjoyment could have been caused by either the hyperrealism, or the embodied interaction, i.e., the enjoyment of physical engagement in VR. However, while

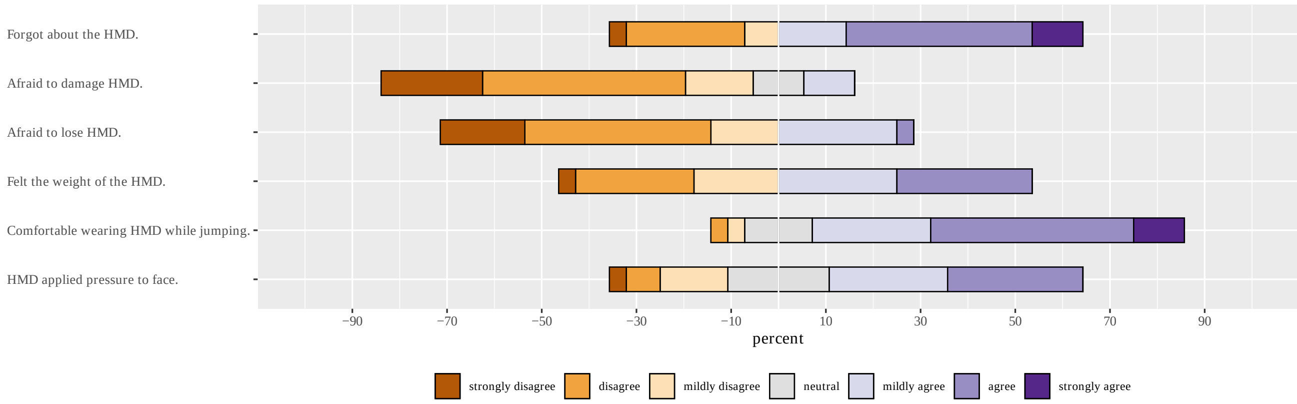


Figure 7: Comfort with HMD.

we do believe that physical engagement remains an important experiential factor in VR [29], it appears that here, hyperrealism was the decisive one for improved player experience. Furthermore, the qualitative feedback indicates that moving through the tracking space in a physically realistic manner made some participants feel "*insecure*" (P7). Jump-in-place thus has a minimizing effect on risk of physical collisions, which likely affected participant preferences. We argue that the decrease in perceived risk could have mitigated distraction from this worry, thus increasing immersion. Our results are particularly interesting in the context of related work by Granqvist et al. [10] on hyperrealistic avatar flexibility; here too, a moderate degree of hyperrealism was preferred over realism (as well as stronger degrees of hyperrealism).

Design Implications for Jumping in VR

Overall, condition *scaled-1.8* was preferred by most participants, described as balancing exhaustion and accuracy while allowing them to feel like a "*superhuman*" (P14). This is consistent with its high presence, immersion, and mastery score and lowest fall-to-jump ratio. We thus suggest this factor as the most suitable for applications and research employing scaled physical jumping. The range indicator was generally considered helpful even after multiple conditions of usage, although some participants asked for an option to deactivate it. For some, this was explained by a preference for increased challenge in accurately reaching platforms via a higher scaling factor—i.e., further away—without help from the range indicator. As such, we suggest implementing a feature of this kind as (optional) scaffolding. Overall, *JumpVR* could thus be employed as either an alternative locomotion technique to teleportation (when increased exertion is not an issue), or as an additional one, to introduce a more physically engaging, hyperrealistically augmented element to a VR experience.

Further Extending Hyperrealism in VR

Although *scaled-1.8* was considered a balanced condition between accuracy and exhaustion, there may be value in exploring larger scaling factors to find the break-even-point where increased simulator sickness outweighs the benefit of increased enjoyment. Since participants considered large scaling factors to make landing on a target spot more challenging, higher scaling factors could be evaluated on a parkour that focuses more on free exploration rather than precise jumps, e.g., a canyon where users can perform Hulk-like super-jumps without aiming at a specific platform. In first exploratory tests, we have seen that the moment of virtual landing can be delayed somewhat from the real landing, to create a perception of longer jumps without the user noticing a mismatch. This concept could be explored further to find the maximum viable delay before a decrease in immersion is observed (and potentially, an increase in simulator sickness).

While we explored *JumpVR* as a pure locomotion augmentation, we believe that it shows further potential as a more general game mechanic. For example, it could be adapted to let players virtually experience jumping in a heavy mech suit, by simulating the force of a take-off blast and landing impact that destroys or stuns surrounding objects.

Limitations

The HMD weight and the attached cable could both have influenced the conditions in this study; while all conditions had the same weight and cable, it is possible that they were experienced differently while physically jumping (especially if the headset had not been properly fastened, or if the cable moved while the participant jumped). Further, it must be noted that exposure time slightly differed between conditions, i.e., in the teleportation condition, participants usually completed the course faster than in the scaled jumping conditions. We argue that this is a faithful representation of a strength of teleportation (faster completion time), however it must be noted that it is accompanied by a difference in exposure time to the condition in our experiment. Furthermore, the order of presentation might bias those participants that experienced a scaled condition first to believe that the scaled conditions are "normal". While the fact that participants could be accepting our hyper-realistic experience as normal is favourable for our experiment, it might have biased the results.

A fairly large number of our participants had some degree of prior VR experience, i.e., they were likely already familiar with teleportation as a locomotion technique. Compared to

VR novices, the jumping techniques could have thus yielded a stronger novelty effect than teleportation. Future work will have to explore user acceptance over prolonged exposure.

Finally, we acknowledge that our forward-jumping constitutes a weaker baseline, as it was operationalized with a smaller parkour. However, we note that it thus represents features inherent to the condition: forward-jumping is limited by the physical tracking space, while teleportation and scaled jumping enable users to roam a much larger virtual space than is physically available.

CONCLUSION

In this work, we have introduced and evaluated *JumpVR*, a jump-in-place locomotion augmentation technique for VR that scales physical jumps into virtual super-jumps in order to create the sensation of being a superhuman. Our user experiment (N=28) evaluated the impact of physical jumping in VR on user immersion, motivation, presence and simulator sickness in comparison to teleportation. Both quantitative and qualitative results indicate that most scaled physical jump conditions elicited a higher immersion and motivation while largely not increasing simulator sickness. We present insights on user preference and design implications that will help to incorporate physical jumping into future VR games and research.

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