

Exploring Proprioceptive Hand Interactions in Virtual Reality

by

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A thesis exhibition presented to OCAD University

in partial fulfilment of the thesis requirements for the degree of

Master of Design in the

Digital Futures Program

Toronto, Ontario, Canada, 2026

Abstract

VR can provide immersive user experiences, creating value in entertainment and productivity. Despite the advancement of hardware technology, design philosophies oriented around flat-screen user experiences are still the most prevalent in the currently available consumer VR software products (games or non-game alike). This research aims to explore proprioception-oriented user experiences that can better utilize the digital spatial space enabled by commercial-grade VR equipment. The research is conducted through a VR digital game, and tester feedback and gameplay data will be collected to form insights for designing proprioceptive user interactions that are unique to VR.

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Introduction

Background

Proprioception is the sensation of body position and movement (Tuthill and Azim 2018). Despite being able to track users' hand position, current consumer VR software rarely incorporate proprioceptive interaction in their UI. With recent commercial VR platforms, it is possible to create a VR application where the VR user's vision of the real world is blocked by a VR headset, and the user's hands are tracked by the VR hardware, which sends the tracking data to the VR application. This creates an asymmetry of information where the VR user cannot see their hand position, but the VR application "knows" where the user's hands are in the VR environment. This asymmetry opens opportunities to create VR experiences where the user must use proprioception to sense the hand's relative position to the body and perform different digital interactions within the VR environment.

This research project will build on existing research done in the field (Streli, Paul, Rayan Armani, Yi F. Cheng, and Christian Holz., 2023; van Beers, R., Sittig, A. & Denier van der Gon, J. 1998; Noel, Jean, Majed Samad, Andrew Doxon, Justin Clark, Sean Keller, and Massimiliano Di Luca. 2018; van Beers, Robert J et al. 2002) but focusing on experimental design for more accessible commercial VR platforms instead of custom-made, proprietary devices. Through exploring different proprioception-oriented user experiences and iterating the design through user testing and feedback, the iterative development process and aggregated user test data will help generate design insights for proprioceptive VR HCI (Human Computer Interaction).

Research Question

What HCI insights can be learned from exploring and testing proprioception-oriented VR interactions to help design reliable proprioceptive VR HCI?

Project Scope

The scope of this thesis consists of two parts. The main part is the development of a VR video game project running on the Meta Quest 3 VR system, which serves as the prologue of a larger video game project that will be carried out after the thesis is concluded. In this prologue, several individual proprioception-oriented hand-based VR activities were developed to explore different types of proprioceptive VR interactions. The second part is this accompanying thesis paper, which reviews related studies, documents the iterative development process of the VR project and user test results, and discusses the findings and thought process from them.

Although the developed project is the first component of a larger project, the developed content will explore a wide range of proprioceptive hand-based VR interactions and will be self-sufficient to gather test data and insights for the scope of this exploratory research. The insights gained from this research can relate to the HCI design space outside the realm of video game design, though specific applications like design for health or digital art are beyond the scope of this research.

It is important to acknowledge that this research is targeting current generation consumer VR hardware which cannot provide consistent finger tracking, therefore will not explore VR interactions from exclusive hand movement, such as moving the fingers. Instead, each hand (while holding the VR motion controller) will be acting as a single proprioceptive input and feedback point, and the hands will mainly be moved by the arms.

Content Overview

The remainder of this thesis is structured as follows: First, the Literature Review, covers the validity of VR as a research platform for proprioception-related studies, proprioception in video games, previous proprioceptive VR HCI studies, studies concerning proprioception and visuo-proprioceptive integration, and the benefits of proprioceptive VR HCI. Next, Methodology, explains the research methods and methodologies involved in this thesis and why they are used. Then, Design and Development Process, documents the thought process, design and development details, and user test results and critical reflections throughout the entirety of the project's development. Finally, Conclusion, reflects upon everything learned from this project and suggests potential future research directions.

Literature Review

To develop proprioceptive VR HCI and make sense of the data collected from user tests, a review of the literature has revealed 5 key points. First and foremost, is VR a reliable medium to conduct research on human proprioception? This is the foundation of the proposed research, because a flawed research method/environment cannot provide trustworthy data. Secondly, as the exploration is done through a VR game, it is crucial to understand the role of proprioception in video game experiences. Thirdly, existing VR HCI solution(s) that enable proprioceptive interactions and their related studies are examined. The knowledge from these studies will provide insights during the design process. Next, research findings on human proprioception will lay down the preliminary guidelines for designing proprioceptive HCI. Finally, the benefit of proprioceptive interactions in VR HCI is presented to support the significance of this research-creation project.

VR as a research platform for proprioception-related studies

Currently, in connection with the advent of virtual reality (VR) technologies, methods that recreate sensory sensations are rapidly developing. Activation of the proprioceptive sensory system, coupled with the activation of the visual system, allows you to achieve sensations of interaction with VR objects, identical to the sensations of the real physical world (Zakharov et al. 2021). Aside from its capability to simulate interactions in the real physical world, Virtual Reality can be used to manipulate vision while the user performs proprioceptive tasks. Through VR, we can manipulate individual sources of sensory information, be they visual, vestibular, or proprioceptive, which are physiologically bound together. This makes it possible to study the contribution of these individual sensory inputs and of multisensory integration to self-perception and motor control (Valori et al. 2020).

One of the main and important applications of VR is its use in the medical field to provide various tasks of physical rehabilitation and habilitation (Zakharov et al. 2021). Besides its frequent use in rehabilitation-related studies, VR enables proprioceptive interactions with various types of motion-tracking solutions and haptic feedback systems. Within the human-computer interaction community, it is generally acknowledged that spatial memory, proprioception, and kinesthesia can be exploited to support rich and efficient interactions (Streli et al. 2023).

These findings confirm the legitimate use of VR for studies in proprioception. In the next section, the role and use of proprioception in video game experiences will be examined to understand what proprioceptive aspects may exist in video games and how the proprioceptive interactions explored in this research can potentially provide design insights that are not presented in past studies.

The role of proprioception in video game experiences

This thesis explores proprioceptive interactions through a video game. In a 2008 journal article, Shinkle (2008) examined the proprioceptive aspects in the medium of video games, pointing out that the video game player's act of issuing system commands by means of a physical interface mobilizes not just sight and hearing, but also the 'hidden' kinaesthetic, proprioceptive and vestibular senses. Swink (2008), in his book *Game Feel*, described controlling something in a game via button or thumbstick pushes as "a kind of amplification" of the player's sense of space because they "get a huge amount of reactive mileage out of very little real-world motion", thus they are "using not a debilitated proprioceptive sense, but an amplified one."

These previous discussions covered the proprioceptive nature of the physical movement needed to input game commands and the amplified proprioception perceived through video games' visual feedback. Such proprioceptive aspects are, as Swink (2008) noted, "of being a person's subconscious awareness of the position of his or her own body in space." This thesis, however, will explore proprioceptive interactions that require the player to be more aware of their proprioception, bringing the sense from subconscious to conscious so that it is mechanically involved in the gameplay (human-computer) interactions rather than being just a felt sensation.

As Shinkle (2008) mentioned, the home gaming market has seen the appearance of a different kind of interface since 2003, and control systems like the Nintendo Wii and the Sony EyeToy extended the capability of supported physical activities to the entire body, accommodating a variety of physical inputs and playing styles. From there, physical movement has seen increased importance with the introduction of gaming hardware like the Nintendo Wii and Microsoft Kinect (Isbister and Mueller 2014).

Despite the development of movement-based game controller sensor technologies, surveying the role of proprioception in video games showed little mention of the conscious use of proprioception in both the commercial and the academic domains. This may partially be because most sensor data from the early motion-tracking video game interfaces are messy (Isbister and Mueller 2014), making the game systems unable to give user reliable proprioceptive feedback. But a study on the tracking precision of the Oculus Quest 2 system, the previous generation of the VR system (Meta Quest 3) used in this thesis project, reported constant movement recording accuracy of millimeters (Pereira et al. 2023). This vast improvement of recent consumer VR hardware platforms' capability to accurately track and estimate user movement opens new possibilities to explore proprioceptive HCI through video game activities.

Looking at past studies of proprioception in video games revealed the differences between the proprioceptive aspect explored in this thesis and the rest of the video game medium, highlighting the potential missing knowledge that may be gained from the insights generated by this exploration. Looking next at the broader HCI field, several studies involving the use of proprioception were carried out through VR systems, and they will be detailed in the next section.

Existing studies on proprioceptive VR HCI solutions

To help guide the design phase of this exploration, the following proprioceptive VR HCI studies are examined.

“FaceTouch”, a study of a novel interaction concept for mobile VR head-mounted displays (HMDs), was presented (Gugenheimer et al. 2016) to leverage the backside of the HMD as a touch-sensitive surface. This concept/prototype lets users point at and select virtual content inside their field-of-view (FOV) by touching the corresponding location at the backside of the HMD utilizing their sense of proprioception. User tests conducted on the FaceTouch prototype showed a low error rate of $\approx 2\%$, indicating the viability for everyday usage (Gugenheimer et al. 2016).

Proprioceptive interactions enabled by VR systems also made it possible for HCI studies that do not involve any visual elements. A study on eyes-free target acquisition in VR was conducted leveraging the sense of space and proprioception (Yan et al. 2018). Results of the study show that the eyes-free approach of acquiring a virtual object is significantly faster when compared with the eyes-engaged alternative, while also providing satisfying accuracy, and introduces less fatigue and sickness. The study also measured the accuracy of motion control and evaluated subjective experience of users when acquiring targets at different locations around the body and made suggestions on designing appropriate target layout and discussed several design issues for eyes-free target acquisition in VR (Yan et al. 2018).

“HOOV” is another study on a proprioceptive VR HCI solution, focusing on hand-based VR interactions outside of the effective tracking FOV of the built-in cameras on standalone VR HMDs (Streli et al. 2023). Their prototype wristband hardware provided haptic feedback to confirm users’ select, grab, and drop interactions, as well as tracking data that is unobtainable when users’ hands interact with virtual objects positioned outside of the effective tracking FOV of the VR HMD. Tests done on their prototype solution showed that its target-agnostic estimations had a mean tracking error of 7.7 cm, which allowed the study’s participants to reliably access virtual objects around their body without first bringing them into their visual focus. The study also demonstrated several applications

that leverage the larger input space the proposed method opens up for quick proprioceptive interaction, and discussed the potential of the technique (Streli et al. 2023).

These studies showed the clear potential of proprioceptive VR HCI with no visual cues. Combining the continued development of VR hardware and software technologies, it demonstrated the necessity of further exploration in this field.

General knowledge concerning proprioception and visuo-proprioceptive integration

To help design better proprioceptive VR HCI and avoid rudimentary design flaws, it is crucial to look at existing knowledge of human proprioception related to the scope of this project. The formation of proprioceptive sensation occurs due to the activity of various receptor systems located in the tissues of the human body, the largest number of which is in the muscular system (Zakharov et al. 2021). The central nervous system integrates information coming from proprioceptors and also from the vestibular system into an overall sense of body awareness (Sayar and Nübol 2017). When static, the information provides the sensation of the position of body parts relative to each other in space (Zakharov et al. 2021); during movement, proprioceptive information also tells the strength of effort being employed in movement (Sayar and Nübol 2017).

With the aforementioned sensory information, proprioception is involved in many aspects of the perception of self and the surroundings, including state estimation for planning and refining movements, central circuits for feedback control of movement, and distance estimation and navigation (Tuthill and Azim 2018). Proprioception is largely subconscious, in that it does not typically require directed attention. But in some cases, humans do have conscious access to proprioceptive sensory information (Tuthill and Azim 2018), which is the focus of this research-creation project.

The scope of this project mainly concerns hand-based proprioceptive VR HCI. The perception and action of hand position and rotation are based on information from multiple sensory modalities. In addition to proprioception, human vision also serves a critical role in providing such information. Information from both proprioception and vision is integrated to generate a single estimate of where the hand is in space. (Van Beers, Wolpert, and Haggard 2002). Classically, vision has been thought to dominate this process, with the estimate of hand position relying more on vision than on proprioception. However, a study showed that the weighting of the two senses varies with direction. Variation with direction was so strong that, in the depth direction, the estimate of hand position relies more on proprioception than on vision (Van Beers, Wolpert, and Haggard 2002). To fully utilize the design space of a 3D environment, VR HCI needs to break through

the design patterns of 2D interfaces and expand into the depth dimension. Based on the literature findings, it is evident that for depth-based VR HCI, user interactions that rely on proprioception can be more accurate than those that rely on vision and visual elements.

Studies on the perception of hand position through proprioception have revealed several characteristics. As Beer et al.'s (2002) study confirmed, the precision of visual and proprioceptive localization in a horizontal plane is nonuniform, with vision being more precise in azimuth than in depth ("in depth" means in the radial direction relative to the observer; "in azimuth" refers to the direction orthogonal to that) and proprioception being more precise in depth than in azimuth (R. J. Van Beers, Sittig, and Van Der Gon 1998). When visual information is occluded, proprioceptively perceived limb position can also drift (Wann and Ibrahim 1992), resulting in further inaccuracy in proprioceptive interactions. One other feature of proprioception is that proprioceptive signaling is not immutable — its effects on motor output can vary dramatically. One cause of this behavior is feedback gain: the ratio between the motor output and sensory input of the system (Tuthill and Azim 2018), meaning the perception of hand position can change over time. To accommodate the mutable inaccuracy in hand-position estimation, it is necessary to either design proprioceptive VR HCI that can dynamically adapt to the deviations or develop a middle layer that can correct the discrepancy between users' perceived hand position and the desired hand position.

Benefits of proprioceptive VR Interactions

A review of 3D user interfaces (UI) for virtual reality (VR) published in 2024 indicated that, despite the increased use of VR technologies over the last decade, traditional windows, icons, menus, and pointer user interfaces remain popular in software applications developed for VR. These 2D UI principles are sometimes not fully compatible with VR, as the 3D environment offers a whole new dimension of space to work with. Many existing VR application user interfaces consist of 2D UI components directly mapped onto a 3D environment. This approach might not be ideal for UX as humans consume information differently in 2D and 3D interfaces, making it unlikely that best practices for 2D UI design will always translate or apply in a 3D context. Therefore, navigating and interacting within 3-dimensional environments can still be challenging in virtual reality (Yeo et al. 2024).

Proprioception is an integral sense when interacting with a 3D VR environment via movement-based input methods. As mentioned in the section about existing proprioceptive VR HCI research, the studied solutions have shown faster interaction speed, introduced less fatigue and sickness (Yan et al. 2018), and allowed the user to operate in a larger input space compared to visual-based VR HCI (Streli et al. 2023).

While the tasks performed in these studies are relatively simple, they demonstrate the benefits of using proprioceptive interactions in VR applications and the potential for HCI solutions designed to utilize proprioception more cognitively.

Conclusion

The examination revealed that VR has long been established as a research platform for studies of physical movement and proprioception. While this exploration is conducted through a video game, which is inherently proprioceptive, the more conscious use of proprioception explored in this thesis is largely absent from the video gaming domain. The difference between this thesis and past studies in the proprioceptive aspect of video games demonstrates its potential to contribute to the understanding of proprioceptive HCI, which has shown a range of benefits for VR applications. And the explored interactions need to be designed to compensate for the mutable inaccuracy in proprioceptively perceived hand-position estimation.

Methodologies

The research purpose of this project is to explore different proprioceptive VR hand interactions and gain insights about the experimented interactions. To achieve the research objective, different proprioceptive VR activities were developed, and test participants were recruited for test sessions where the VR software will automatically collect test data, and test notes can be taken from participants' feedback and observing participants' behaviors. Some of the test sessions may also have optional surveys or questionnaires as additional channels for tester feedback.

Before the start of the project, a simple prototype VR activity was developed to test and confirm the viability of using proprioception to perceive and interact with the VR environment without any visual information of one's body.

To provide a relaxed, low-stakes testing environment and minimize test participants' pressure, the VR interactions will be presented as different activities in a VR video game. The initial concepting stage of the project includes two main parts: the design concept for the various types of proprioceptive interactions as game mechanics, and the narrative concept to put all the game mechanics together as a coherent experience. A design document was created to include these concepts, and it will be continuously updated as the project progresses. The design document will serve as the development guidance and provide references when the project is being worked on.

After the initial concepting stage, a plan is laid out for the content and features that will be included within the scope of this research project (the initial concept included content and features beyond the research scope). After the prototype of each feature and content piece (proprioceptive VR activities) is developed, playtests are hosted to test one or more of these individual features/activities or test an entire segment of the VR game.

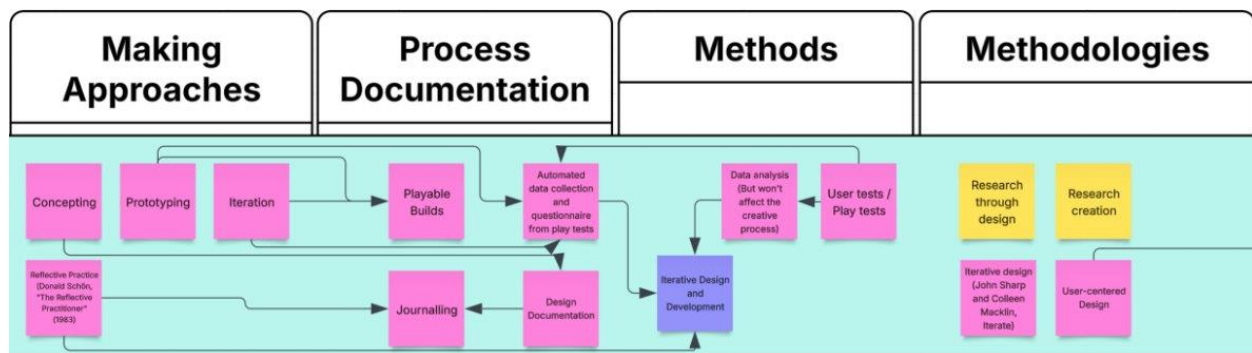
Three main categories of data will be collected from each playtest session: quantitative data automatically collected by the test software, and qualitative data that includes tester feedback through direct interview or questionnaire and notes about testers' behaviors through observation. The data will be used for the following purposes:

- Quantitative data will be used to give context for some of the implemented features.
- Qualitative data from the observation notes and tester feedback will be used to analyze learning and interaction difficulty, whether the activity served its planned purpose, and the consistency of performing the activity.

After analyzing the data, the design of the activities will be iterated based on the reflection of the analysis. The evaluation focuses on identifying patterns in user performance,

learning difficulty, and interaction consistency across iterative prototypes, allowing design insights to emerge through comparison between activities. Then, new iterations will be implemented and tested to generate more data and guide further iterations, creating an iterative design loop until each activity can consistently serve its purpose. It is also possible to add or remove individual activities to improve the flow of the full gameplay experience. The design document will also be updated to reflect the changes made to the activities.

In summary, this research-creation project starts with an initial conceiving stage and is followed by iterative design through prototyping and reflecting the data gathered through playtest sessions of the prototype builds.



The research-creation process

An accompanying design document will be updated based on the iterative design and guide the prototype development.

Design and Development Process

Overview of the prototype development

This chapter will cover the parts of the project's development process relevant to the thesis's topic. Begun several years before the start of the thesis, although this project did not have research purposes initially, the early concepts and prototypes are crucial to its subsequent development. Therefore, the insights and development process of these early prototypes will be included in this chapter.

The chapter will be structured into segments covering the design and development processes for each phase of the project, with each segment accompanied by insights from that phase.

Phase 1: Proof of concept for proprioceptive VR hand interactions

The initial project concept can be summarized into one sentence: make a VR game where the player can't see any representation of their hands. To test whether this premise can support gameplay that feels different from VR games with visible player hands, two early prototype activities were developed and tested with the HTC VIVE VR system.

The first activity involves punching boxes flying towards the player. This activity is designed to draw from similar VR games, such as *Audioshield* (Fitterer, 2016), but without any visual of the player's hands/arms.



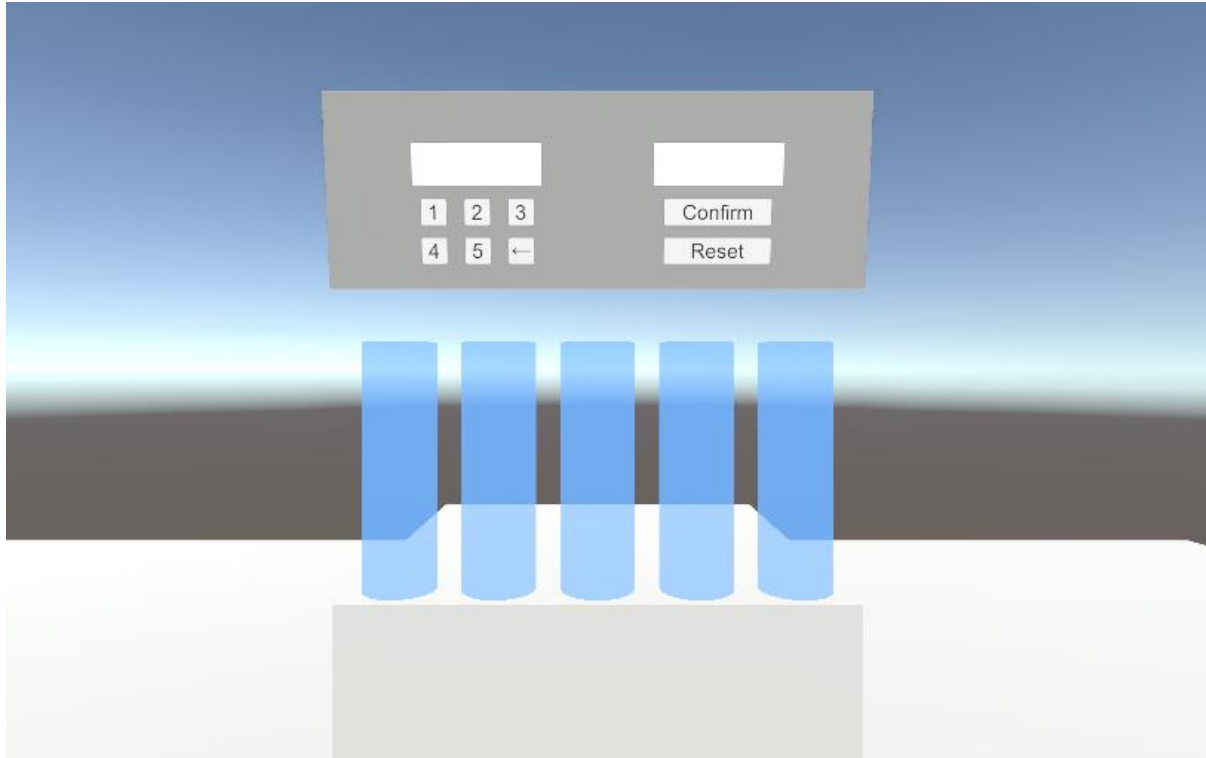
Audioshield: the player holds a shield in each hand and tries to block incoming projectiles.

Having played *Audioshield* before, the gameplay of “punching boxes with invisible hands” didn’t feel much different. A closer examination of the mechanics behind “punching boxes” revealed that visual confirmation of the hands’ location is not critically required for hitting a visual object with the hands. To “punch a box” in VR is essentially reaching one’s hand toward a visually perceived position - a case of direct hand-eye coordination. In this case, the first-hand information about the performed proprioceptive task is acquired through vision, and proprioception is used to subconsciously guide the hand movement.

Further critical analysis of this finding led to another insight: to create importance for obscuring the visual of the hands’ location, positional information must not be perceived by other senses.

Based on this analysis, another activity was developed in the early exploration of the project in an attempt to make external information (as opposed to information about the body itself) perceived by proprioception instead of vision. This activity has the player try to find the correct password. The password is 5 digits, and each digit must be from the numbers 1-5 with no repetition. In addition, 5 identical cylinders are visually presented, and each is “filled” from bottom to top with invisible volume. The fill amount ranges from 1/5 to 5/5 of the cylinder height, and each cylinder’s fill amount corresponds to the password digit it represents.

To find the correct password, the player must put their invisible hand inside the cylinders. When the hands are moving inside the invisible volume, the VR motion controller held in the hand will send haptic feedback. The player needs to sense the volume by feeling where their hands are through proprioception.



The top is the keypad to enter the password, and the bottom is the 5 cylinders with invisible filling

In this activity, the obscuration of the player's hands' visual representation and the visual of the cylinder's filled volume led the player to perceive the invisible volume through positional information gained from moving hands around and proprioceptively feel their relative position to the body. This experience is similar to trying to find something on the nightstand in the dark, but in this case, everything except the object on the nightstand is still visible.

The experience from this activity verified the early analysis and became the foundation for the project's design concept and development. Further research on the mechanics behind the experience of "feeling the hands' position" revealed the concept of "proprioception," which will be the main theme of this thesis.

When conducting the initial literature review, a publication on proprioception suggested that proprioception is largely subconscious and does not typically require directed attention (this subconscious nature is also brought up in Swink's (2008) book *Game Feel*). But in some cases, humans do have conscious access to proprioceptive sensory information (Tuthill and Azim 2018). This finding provided research grounding for the differences in the two prototype activities' experiences, where "punching boxes with invisible hands" can be categorized as subconscious proprioception and "feeling invisible volumes' sizes with invisible hands" as conscious proprioception.

Insights:

To create importance for obscuring the visual of the hands' location, positional information must not be perceived by other senses (in this project's case, positional information should only be perceived by proprioception). The second prototype activity demonstrated that external positional information can be perceived by conscious proprioception.

Phase 2: Assessing the importance of a proprioception calibration system

The literature review of papers on human proprioception revealed potential inaccuracies in proprioception-based sensing of limb position. A 1991 study re-examined the hypothesis that proprioceptively perceived limb position drifts during visual occlusion and showed clear evidence of a drift in perceived limb position towards the body during visual occlusion (Wann and Ibrahim 1992). A journal published in 2018 also noted that proprioceptive signalling is not immutable and that its effect on motor output can vary dramatically (Tuthill and Azim 2018). This knowledge indicates that when moving one's hands, the perceived movement may differ from the actual movement. In relation to the context of this project as a VR video game, a 2020 paper found that HMD (head-mounted display) delivered VR has particular visuo-proprioceptive features that can disrupt proprioception in adults (Valori et al. 2020).

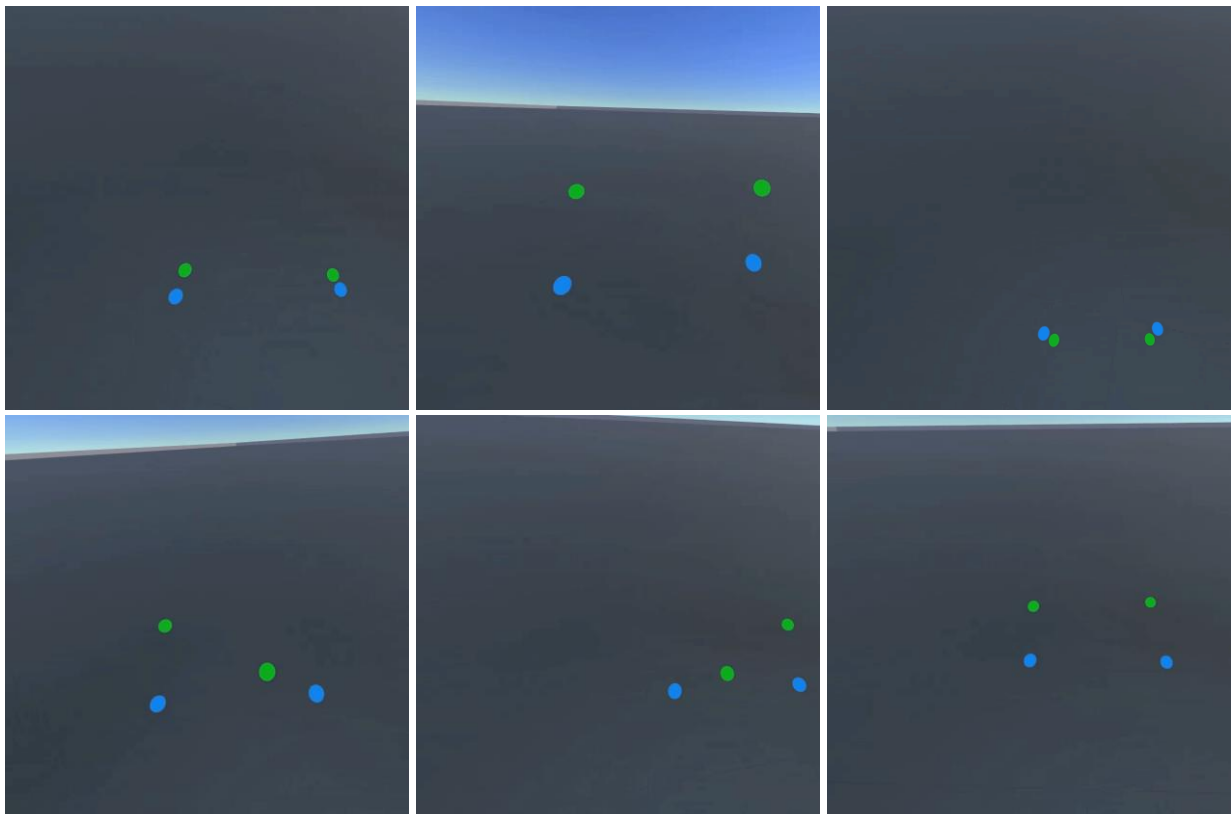
To minimize proprioceptive inaccuracy suggested by the literature review, assistive features need to be designed and developed for the project. However, one essence of the video game medium is the emphasis on the player's skill. Giving the example of a first-person shooter game where the player aims at targets with an input device, the aiming accuracy can vary among players. Although some modern games have implemented aim assist to help players aim at targets, many games in this genre make the player rely purely on their skill. Because of this project's context as a video game, it is reasonable not to provide assistance for proprioception accuracy and expect the players to improve their skills through gameplay. However, a "proprioception calibration" solution is still proposed and developed to gather test data and provide insights into the thesis topic.

The calibration solution has two main components: the first component gathers calibration data by making the player perform simple tasks, and the second component uses a simple algorithm to calibrate the player's hands' virtual position in VR to the player's perceived hand position.

In the first component, visual targets with pre-defined positions relative to the player's body are shown sequentially, and the player is asked to stand straight and reach their left or right hand toward the visual targets as if they are grabbing the target at the center of their

hands. There are 6 targets for each hand, placed at the top, bottom, left, right, close, and far points relative to the body. When the player confirms the calibration of a target point by pressing the “trigger” button on the held motion controller, the reaching hand’s position relative to the target is saved. After finishing the calibration sequence, a total of 12 pairs of target and hand position relative to that target will be generated to be used by the second component’s calibration algorithm.

In the second component, each set of the 6 target points creates a “calibration volume” for each of the player’s hands. When the player moves their hands around, a simple algorithm will apply a calculated “calibration vector” based on the hand’s proximity to each of the 6 points. When the player reaches out their hand towards a target and saves the hand’s relative position (to the target), the visual target represents the perceived hand position, and the saved relative position is the deviation between the player’s hand’s actual position and the perceived hand position. The algorithm calculates the aggregated “calibration vector” based on the assumption that the closer the hand is toward a target point, the more weight the deviation at that point should be applied.



Screenshots of the calibration system demo, blue spheres are the hands' actual position, and green spheres are the calibrated (perceived) hands' position. (Video [link](#))

An initial user test consisted of 7 participants collected calibration data for all 12 points (6 per hand) for each participant. And the data shows variation in proprioceptive inaccuracy, supporting the findings from the literature review.

In the span of this thesis, a total of 21 unique participants (including the initial test) had their hand proprioception accuracy tested, and 12 of them also had their accuracy tested again after applying the calibration solution. The natural proprioceptive inaccuracy of the 21 participants is displayed in chart A, and the comparison of the calibrated proprioception accuracy for the 12 participants is displayed in chart B.

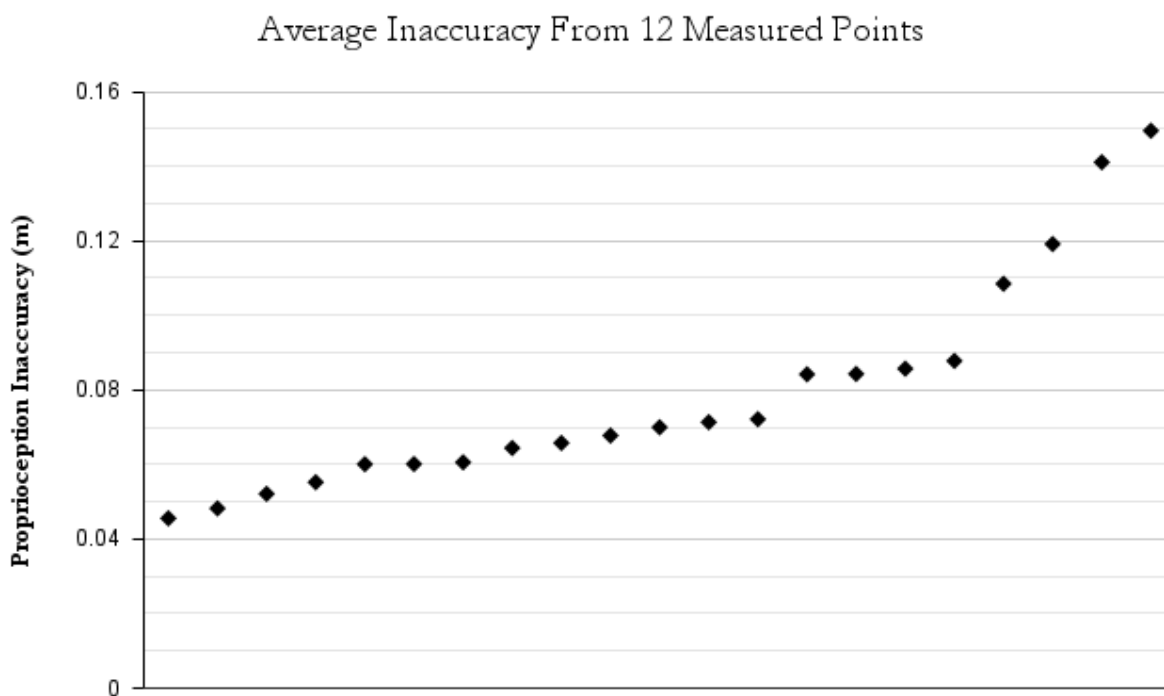


Chart A

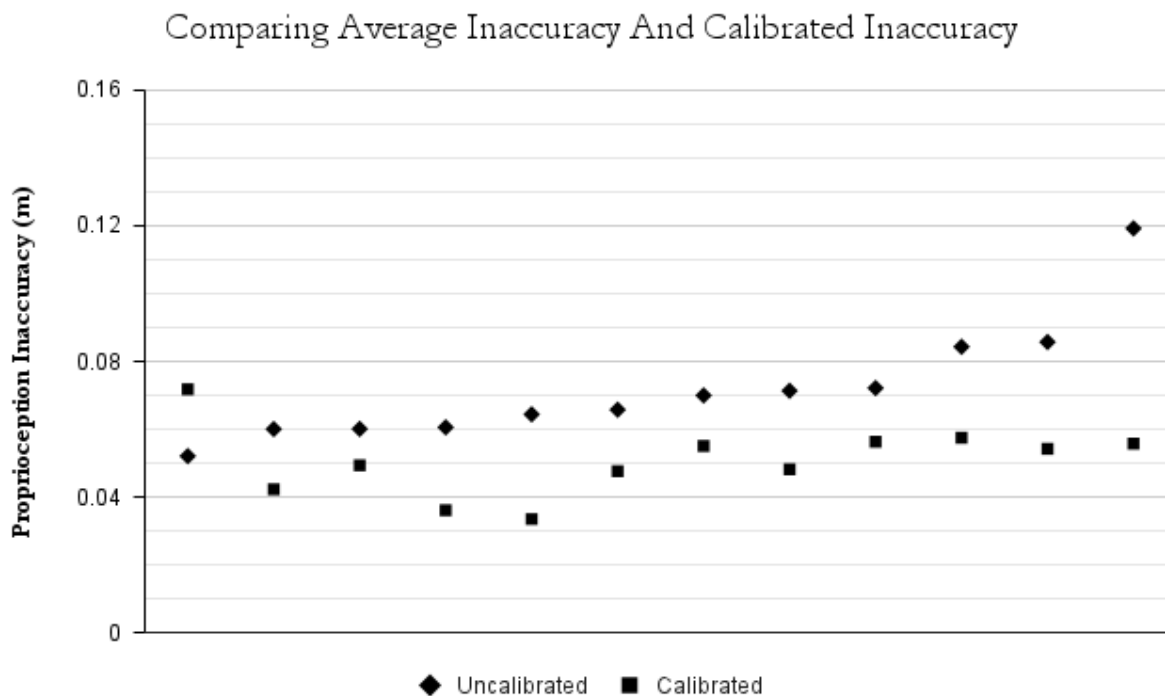


Chart B

Chart A showed that even the lowest hand proprioception inaccuracy is greater than 4 centimeters and ranges up to 15 centimeters. This means that the discrepancy in hand proprioceptive inaccuracy can be more than 10 centimeters, and such a discrepancy can make it more difficult to design proprioceptive VR HCI for a large audience.

When the calibration solution is applied, as shown in chart B, all but 1 participant had their hand proprioception accuracy improved, with the least accurate individual (at around 12 centimeters) receiving the most improvement. What's more important is that this simple solution reduced the inaccuracy discrepancy from more than 8 centimeters (the number in chart A is not used because the participants with the least and most inaccurate hand proprioception did not test again with the calibration solution enabled) down to less than 4 centimeters, which is more than one fold in reduction. Being able to compensate for the extreme outliers means it can be easier for VR HCI designers to cater to the public.

Another point that needs to be addressed from chart B is that the only participant with reduced proprioceptive accuracy after applying the calibration is also the one with the lowest inaccuracy without it. To better understand this, future studies are needed to specifically look at the effect of such calibration solutions on people with more accurate proprioception.

Insights:

The literature review revealed inaccuracy in human proprioception and is supported by user test results. Although proprioceptive inaccuracy may be acceptable in non-serious activities such as video games, minimizing the inaccuracy will make practical proprioceptive applications more reliable. When a simple calibration system is applied, the calibrated proprioception can be more accurate than natural proprioception.

Phase 3: Playtesting simple proprioceptive VR hand-based activities

Before starting phase 2, the password activity from phase 1 was developed into a more comprehensive experience for demo purposes. The 5 cylinders were reduced to 4 invisible cuboids aligned inside a visible “keyhole”. The player needs to reach their hand inside the keyhole to feel the height of each cuboid and make a key that matches the shape of the 4 cuboids.

This “lockpicking” demo was tested by a few participants on separate occasions, and each test session was observed to gather information on player experiences. Both the testers’ feedback and observation showed that the demo is too difficult for people with no experience of proprioceptive VR interactions. Compared to the password activity, the clear visual cue of 5 cylinders was reduced to a single keyhole in the lockpicking demo. And when the player’s hand is inside the keyhole, they not only need to feel the height of each cuboid but also need to aim their hand in the same azimuth direction as the keyhole and perceive each cuboid’s depth position in the keyhole.

A crucial piece of feedback from one of the testers suggested that instead of immediately presenting inexperienced players with a challenge, the game can ease them in with simple activities. After phase 2, a few basic activities were proposed, and 3 of them were developed initially.

The first activity consists of a holographic-looking cuboid placed horizontally, and the player needs to feel the amount of invisible volume in it with their hand, then use a visual UI slider to input how much they think the invisible volume fills the cuboid. The invisible volume inside the cuboid is filled from the left end towards the right end, and when the player’s hand is moving inside the invisible volume, the VR controller held in their hand will send haptics to relay this information.



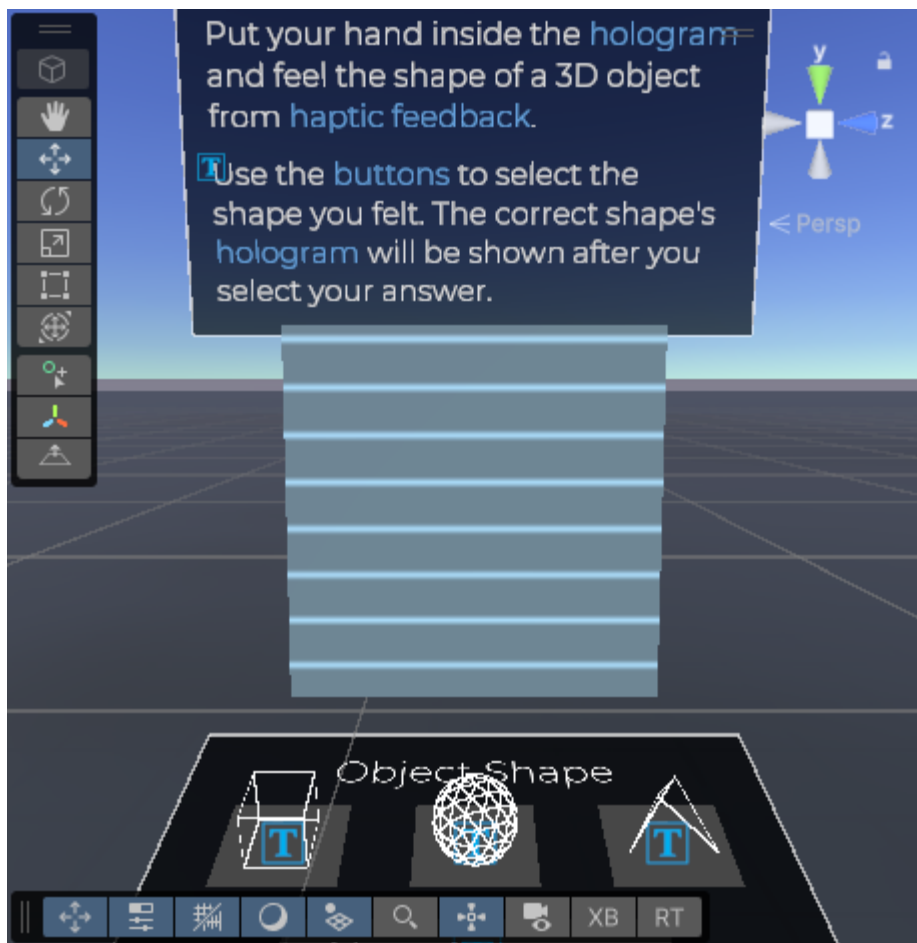
Screenshot of the first activity

The second activity consists of a cuboid with a random number of invisible spheres inside, and the player needs to feel and count how many spheres there are, then use a visual UI slider to input the number of counted spheres. Similar to the first activity, the VR controller in the player's hand will send haptic feedback when the hand moves inside an invisible sphere.



Screenshot of the second activity

The third activity consists of a cuboid with an invisible 3D shape inside it. The 3D shape can be either a cube, a sphere or a tetrahedron, and the player needs to proprioceptively feel the shape, then use visual UI buttons to select which shape they think it is.



Screenshot of the third activity

The first playtest on these three activities did not give much information on how quickly the players can learn and complete the activities successfully, because most of the players encountered significant difficulty when trying to interact with the visual UI. Initially, the UI's interaction area was limited to the exact size of the visual elements, and there was no indication of whether the player's hand was moving closer to the UI elements. Even though the UI elements are visible, the players struggled to use their invisible hand to "touch" the UI elements in VR. After the first playtest, the interaction area was increased by more than 10 times, and visual transitions were added to indicate if the player's hand is moving closer towards the UI elements without direct visual representations of the player's hand's position. This version was tested by a few individuals in separate sessions, and all of them could consistently use the visual UI to complete the activities. From these test sessions, the first activity was the easiest to complete successfully, while some testers excelled at the second, and others at the third.

Later, a fourth activity was developed to replace the third. In this activity, the player has to place one hand inside a holographic-looking sphere. When the hand is inside the sphere, a

stick will attach to the hand and become invisible. Then, the player needs to keep the hand inside the sphere and turn it horizontally as if they are pointing the invisible stick left to right. The arc shown in the screenshot marks the range of horizontal angle where the player may receive haptic feedback from the controller when turning their hand. Similar to the first activity, the haptic feedback will start from the left side of the arc and stop at an angle within the arc. The player must feel how much the hand turned from left to right and use the input slider to submit their answer.



Screenshot of the fourth activity

This change was led by two main reasons: first, all three initial activities are testing the player's ability to gain positional information through their proprioception. By exchanging one of them with an activity that requires the player to gain directional information, the player can practice more varied use of their proprioception. Secondly, the fourth activity is mechanically more similar to one of the planned activities in phase 4, and can act as a steppingstone towards the more complex version in phase 4.

Due to the lack of step-by-step instructions for the activities and the difficulty in using the initial implementation of the visual UI without any visual hand representation, test participants were unable to get or submit the correct answer. But after understanding the

activity objectives and getting used to using the improved UI, most of the test participants can submit the correct answer, demonstrating proprioception's capability to perceive external information.

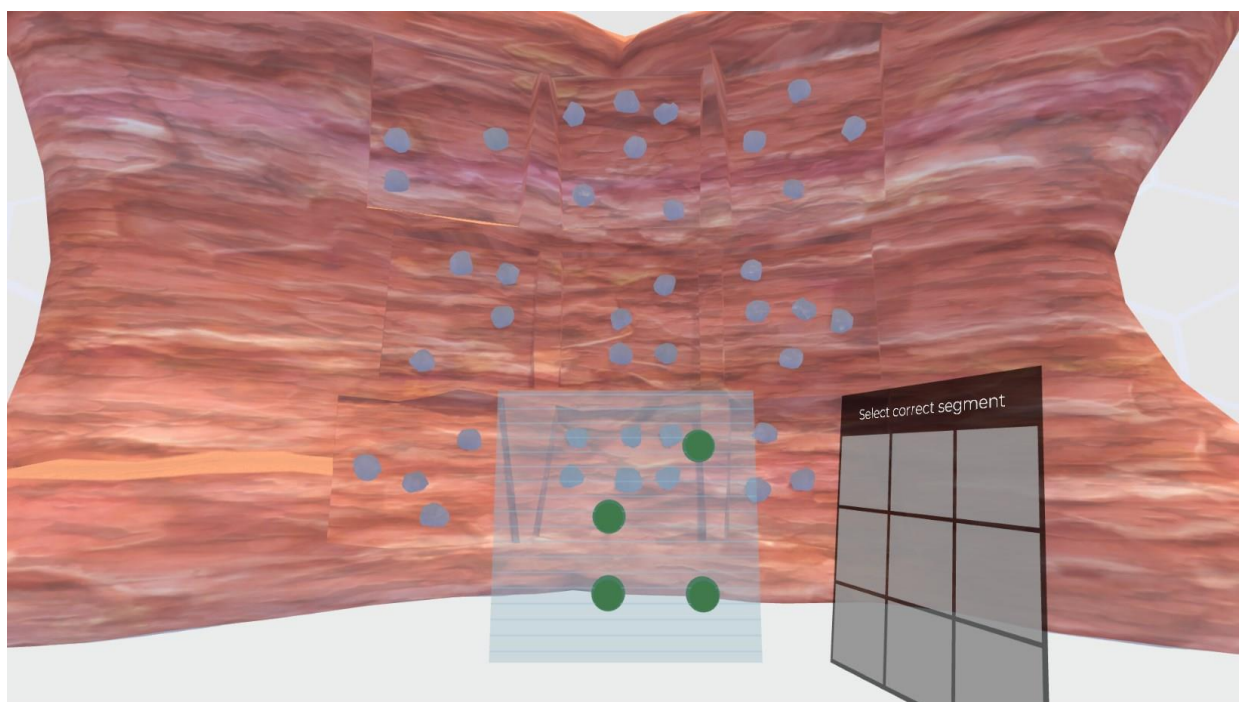
Insights:

It is possible to design VR HCI where external information can be correctly perceived through proprioception. For individuals without prior proprioceptive VR experiences, introducing simple proprioceptive VR activities will help them build more confidence. Even when interacting with visual VR objects, obscuring the hand position can cause significant difficulty for consistent UI experiences.

Phase 4: Playtesting more complex proprioceptive VR hand-based activities

The last phase consists of three main activities, with the second and third having two different “modes” with some mechanical variations. Different from the activities in phase 3, where external information is perceived by proprioception, phase 4's second and third activities' information will be acquired through vision. However, the activities will not involve direct target-reaching hand-eye coordination.

The first activity involves a structure similar to a climbing wall. The wall is divided into 9 sections, with each section being able to display randomized points (every section's point pattern will be unique).

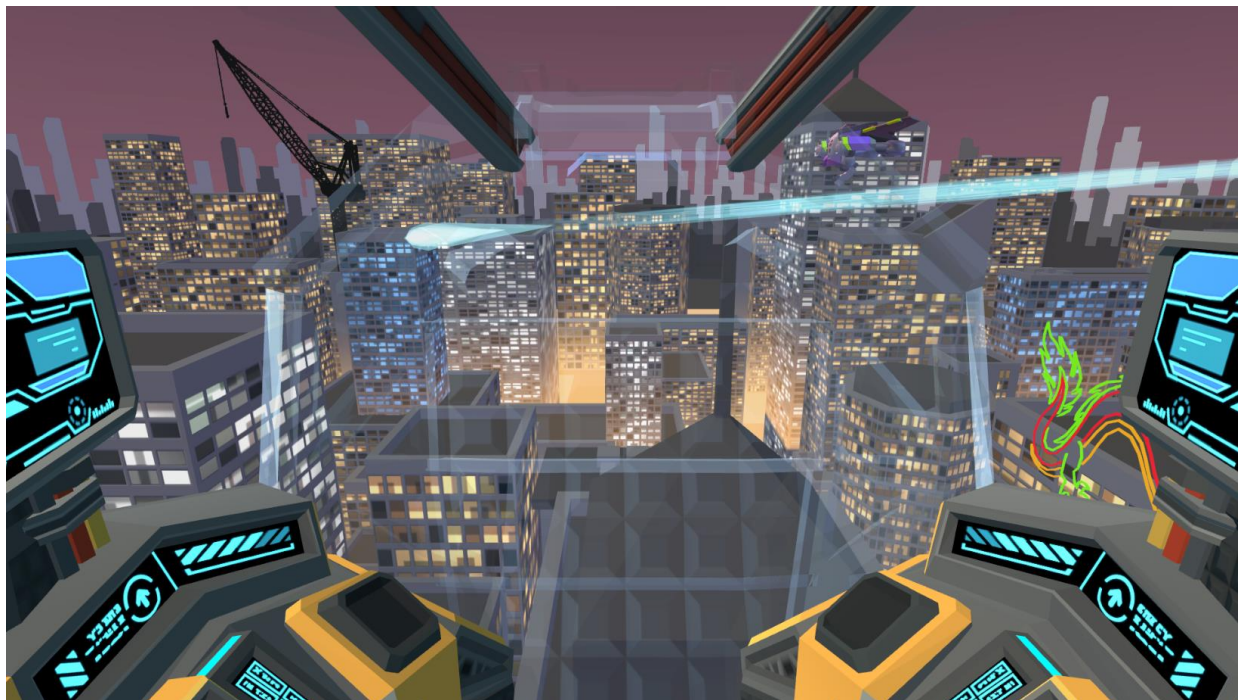


“Climbing wall” activity

The player is positioned in front of the climbing wall at a distance facing it, so the wall sections and the points within them are clearly visible to the player. Also placed in front of the player within hand reach is a holographic-looking panel. Within the panel, invisible spheres will be placed to match 1 randomly selected wall segment's point pattern (in the screenshot, the green points in the panel matched with the center section; green points are not visible to the player). The player is instructed to move their hands inside the panel, and the VR controller will send haptic feedback when the hands are moving inside the invisible spheres. The player will perceive their hand position through proprioception, thus acquiring positional information about the invisible spheres when informed by the controller's haptic feedback when the hand moves inside one. After the player is confident that they've got all the invisible sphere's position, they can use the UI panel on the right to select which wall segment's point pattern match with the invisible sphere's pattern on the panel.

Despite the similarity between the "climbing wall" activity and the second activity (counting invisible spheres in a volume) from phase 3, test participants showed a higher success rate of performing the climbing wall objective. Analyzing this behavior leads to two hypotheses: first, the invisible spheres are spread across a larger volume, reducing the probability of confusing one sphere with another. Second, the climbing wall provided visual information for possible point positions in the panel. Based on the second hypothesis, it can be further hypothesized that visually perceived positional information can aid proprioceptive VR HCI even when the visual information is not directly mapped to the proprioceptive information in the VR environment.

The second activity is similar to a "shooting range" where the player needs to pick up a virtually depicted pistol and aim and "shoot" at a target point.



“Shooting range” activity

The player is instructed to move a hand towards the pistol while maintaining the hand orientation as if the hand is grabbing the pistol. When the player’s hand reaches a certain distance from the pistol, the pistol will be automatically “snapped” onto the hand and turn invisible. To “fire” the pistol, the player needs to press the trigger button on the VR controller held in the hand that the pistol snaps onto, and a blue line will briefly appear to indicate the shot path. The player can “test fire” and see if the blue line points in the expected direction, and can drop and regrab the pistol if they want to adjust the pistol’s orientation in their hand.

After the player is satisfied with the shooting direction, they can use the visual UI on the left to start a game. A white sphere will appear at a random position within a defined area, and the player needs to try to aim the invisible pistol at the sphere by proprioceptively feeling where the hand with the pistol is aiming. After the player fires a shot, the sphere will move to another random position regardless of whether the shot hits it or not.

As mentioned in phase 4’s introduction, this activity does not involve direct target-reaching hand-eye coordination. Instead, this activity is target-pointing - the player is trying to proprioceptively point an invisible pistol directly at a visual target. To further increase the role of proprioception in this activity, a variation of this activity is introduced and can be switched to after the player hits the target at least once in the initial setup.

In the initial setup, the player’s view perspective in the VR environment is first-person, meaning that they are looking at the virtual space from their eyes’ position and angle.

Therefore, when they try to point the pistol at the target, they are pointing directly at where the eyes are looking. To further isolate the proprioceptive aspect of the target-pointing action, the visually perceived aim direction from the pistol to the target needs to be internalized as abstract information, so that proprioception will guide the hand to point the pistol in a desired direction instead of the look direction.

Based on this analysis, several third-person viewing perspectives were added to the variation of the “shooting range” activity. The first one is a “top-down” perspective where the player’s viewing point is moved to the top of the shooting range activity’s setup and looking down at the VR environment. The other two perspectives are viewing the shooting range from the left and right sides. The player is informed that although their point of view is changed, their virtual body in the VR environment (invisible to the player) will still fire the pistol from the position in the initial setup. To put it another way, when the perspective is shifted into third-person, the player will imagine watching themselves performing the action (without seeing their virtual body) from a position away from their own body.

When playing this variation of the shooting range activity, the player’s perspective will be randomly changed between the original (the first-person perspective) and one of the three third-person points of view every few seconds. If the player is switched to the top-down perspective, the player must visually perceive the horizontal direction they need to aim at the target, then proprioceptively aim the pistol at the perceived direction. For viewing from the left or right side, the player will instead visually perceive and proprioceptively aim along the vertical direction.

Compared to the initial setup, where only first-person target-pointing is involved, test participants missed more shots in the variation mode. However, participants’ performance was not random, and performance improvement was observed after the participants got more practice. This observation demonstrated that proprioception is reliable at performing hand-based target-pointing interaction even when the desired hand-pointing direction is not spatially aligned with the look direction.

The third activity is themed as a “sword dojo”, and the player needs to pick up and slash a virtually depicted one-handed sword at a cylindrical bar. Similar to the shooting range activity, the sword will become invisible when it is attached to one of the player’s hands. By attaching an invisible object that sticks out from the hand, this activity mainly explores how an extension of a limb can be proprioceptively perceived.



“Sword dojo” activity

The first variation of the sword dojo activity requires the player to swing the sword to hit a random segment (the segment’s length is fixed and is marked with blue color as shown in the screenshot) of the target bar. After starting the activity or being hit by the sword, the target bar will move to a random position within a defined volume and will randomly rotate to an angle around the vector pointing towards the player. From observing test participants performing the activity, two common behavior patterns were discovered.

First, when swinging the sword towards the target, test participants usually stop the swing before the sword hits the target. After being instructed to swing the sword further, test participants were able to hit the target more frequently. Second, when test participants failed to hit the designated target bar segment, they showed greater confusion or frustration compared to failing previous activities.

When asked for feedback about this activity, one test participant gave a crucial insight. The participant pointed out that when swinging the invisible sword, the proprioceptively perceived sword orientation may drift towards the arm’s swinging path. This key discovery can help explain both aforementioned behavior patterns (although there might be other undiscovered causes). When the player grabs the sword, the sword is attached to the hand at an angle leaning upward towards the player when the player straightens their arm forward. This means that, when the player swings the arm towards the target, they may stop the swing when the arm is pointing at the target because the sword is perceived to align with the arm’s direction by proprioception, and the sword’s actual motion will stop

before reaching the target because it is at an angle with the arm's direction. Similarly, when the player swings towards the designated target bar segment, the sword might lean sideways from the arm's direction, thus missing the segment's span.

For the second variation, instead of hitting the sword within a specific segment on the target bar, the player is instructed to hit the target bar with a designated segment of the sword blade (the segment's position will randomly change after each hit). To inform the player of the designated blade segment, a visual copy of the sword is displayed at a distance from the player, with the segment marked in blue (in the screenshot, the segment is marked in green instead). Different from the first variation, where the player is tested with proprioceptively moving a limb extension in a certain direction, the second variation tests the player's proprioception to perceive the length of the limb extension.

Compared to the first variation, test participants had a higher success rate at hitting the target with the designated blade segment. This observation indicates that for an invisible, virtual limb extension, proprioception can perceive its length better than its orientation.

Insights

Exploring more complex proprioceptive activities that combine proprioceptively and visually perceived information has demonstrated that visual information can guide proprioceptive action even when the visual information is not used for direct hand-eye coordination. When limb extensions are no longer visually perceptible, they can still be perceived proprioceptively, but proprioceptive accuracy may vary depending on the interaction.

Summary

Developing and reflecting on the 4 prototype phases has revealed several insights about hand-based proprioceptive VR HCI. In the next chapter, further analysis will be made about the insights from the prototype and the findings from the iteration of design elements not specific to the explored proprioceptive activities, which will help generate potential guidelines for VR HCI design.

Conclusion

Discussion

To better format the findings of the prototype exploration, this section will be split into segments, each led by a guideline for proprioceptive VR HCI design, followed by the analysis of relevant insights. Due to the limited scope of this exploratory thesis, it is important to acknowledge that the guidelines are merely suggestive and should only serve as design references instead of universal rules for software designers and HCI researchers. Examples will be given based on a selection of the guidelines to help VR HCI designers contextualize these guidelines.

1 Consider user proprioception as a reliable sense for user's information acquisition

In the VR space, the range and dimension of user interaction expanded beyond 2D visual interfaces. As mentioned in the literature review, a previous research on a proprioceptive VR HCI solution demonstrated the reliability of proprioceptive UI positioned outside of VR users' field of view (Streli et al. 2023). Insights from phase 3 of the exploration also showed that VR users can perceive external information through proprioception. By expanding the UI space beyond the range of vision, VR HCI designers can deliver information through additional proprioceptive channels.

2 Use visual information to help guide proprioceptive interaction

As demonstrated in the "climbing wall" activity, supplementary visual information can improve the performance of proprioceptive tasks in VR without undermining proprioceptive mechanics themselves. The limited exploration is insufficient to indicate any requirement for the placement of the visual elements in the VR space, as long as they are visible during the proprioceptive activity.

3 Implement calibration solutions to increase proprioceptive accuracy

Past proprioception-related research and test data from phase 2 of the exploration have both revealed proprioception's limited accuracy when perceiving positional information, while the last activity in phase 3 and the "shooting range" activity revealed the proprioceptive inaccuracy in perceiving directional information and performing target-pointing tasks. Data from phase 2 that compares the test participants' target-reaching accuracy before and after applying the implemented calibration solution revealed increased accuracy for proprioceptive point-reaching tasks and reduced discrepancy in individual performances. From these findings, it is reasonable to hypothesize that

directional inaccuracy in proprioception can also be calibrated to improve the overall consistency of proprioceptive VR HCI.

4 Account for ambiguity in proprioceptive interaction

Despite the advancement in movement-tracking technology, proprioceptive VR HCI shares similar ambiguousness with movement-based games developed for the early motion-input systems, as proprioception now becomes the “sensor” that generates “messy data”. Therefore, designing proprioceptive VR HCI can refer to the movement-based game design guidelines from Isbister and Mueller’s (2014). In addition, previous HCI research has also highlighted the potential of ambiguity to contribute to an engaging experience by giving the user opportunities to “fill the gaps” (Isbister and Mueller 2014).

5 Experiment with interactions involving limb extensions that are not constantly visible

Test participants’ performance in the “sword dojo” activity showed the reliability of proprioceptive VR interactions based on virtual limb extensions. Upon given initial visual information about the limb extension, the extension can be perceived by proprioception and interact with elements in the VR environment that are out of reach for the virtual body. By adding UI elements that are further away from the user, the total UI space will be expanded to better leverage VR’s spatial aspect.

Design Applications

Building off these guidelines, the following examples are offered as to how a developer might apply this knowledge in practice¹. In VR applications, Proprioceptive UI can be used to aid pointer-based menu navigation or expand 2D (two-dimensional) GUI (graphical user interface) interaction space to the depth dimension. When navigating small graphical menu elements, a proprioceptive representation of the graphical menu can be used instead of the visual pointer. As the user interacts with the proprioceptive menu, the graphical menu can visually reflect the user’s interaction to provide clarity. The proprioceptive menu can occupy a large amount of space to help mitigate users’ proprioceptive ambiguity. When managing multiple application windows in a VR operating system, a proprioceptive window-arrangement system can let the user arrange the windows in a 3D space instead of a 2D plane. When stacking windows in the depth direction, the proprioceptive system can tell the user about the number of stacked windows in a row. If the arrangement system runs out of space within the user’s area of

¹ These examples only serve as references for implementing the guidelines. No test was conducted to evaluate their performance.

reach, the user can manage out-of-reach windows with proprioceptive interactors extended from the hands.

Future Direction

This thesis project explored several proprioceptive hand interactions in VR, and the generated insights give directions to future studies.

As mentioned in phase 2's discussion, the test participant with the most accurate proprioception showed reduced accuracy after the calibration solution was enabled. This needs to be further studied to understand proprioception calibration algorithms' effect on the proprioceptive accuracy for people with more accurate proprioception. The calibration algorithm implemented in this study is also very rigid and rudimentary, and does nothing to address the "proprioceptive drift" discovered in the early study (Wann and Ibrahim 1992) mentioned in the literature review. Despite the simplicity of this implementation, it greatly improved test participants' target-reaching accuracy, which demonstrated the need for more sophisticated calibration systems to improve the reliability of proprioceptive VR HCI. As mentioned in the third guideline's discussion, proprioception accuracy can vary when perceiving direction. This observation points to the future development of directional proprioception-calibration algorithms.

Test participants' different rates of success in the "counting object" activity (the second activity in phase 3) and the "climbing wall" activity (in phase 4) indicated difficulties in perceiving proprioceptive information within smaller spaces. To help design more reliable proprioceptive VR HCI, further studies should be conducted to measure the effective "spatial resolution" of proprioception (the minimum positional and directional differences that can be perceived by proprioception).

Although the thesis only explored proprioceptive HCI in VR, proprioceptive interactions similar to those in this thesis can be studied in AR HCI research. Both VR and AR share the same aspect of having a virtual 3D environment, and can benefit from more spatial-oriented UI designs.

The insights from this thesis are focused on VR HCI design for video games and general consumer software, but proprioceptive VR interactions can be studied in the context of medical research and expressional art. Proprioception is still a relatively underexplored sense. As VR technology develops and becomes more commonly used, it is necessary to further study proprioceptive interactions to help design reliable proprioception-oriented VR HCI for VR experiences that can further utilize the 3D interaction space.

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Appendix

A. Additional files

Thesis defence presentation

Installation package of the thesis project for Meta Quest 3