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# THE PARADOX OF REALISM

Designing Virtual Reality Mechanics for  
Natural User Interfaces

Taneli Nyssönen





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# THE PARADOX OF REALISM

Designing Virtual Reality Mechanics for Natural User  
Interfaces

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Taneli Nyysönen

## University of Turku

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Faculty of Technology  
Department of Computing  
Computer Science  
Doctoral Programme in Technology

## Supervised by

---

Docent, Jouni Smed  
University of Turku  
Finland

Senior Research Fellow, Teijo Lehtonen  
University of Turku  
Finland

## Reviewed by

---

Professor, Markku Turunen  
University of Tampere  
Finland

Professor, Sian Lun Lau  
Sunway University  
Malaysia

## Opponent

---

Associate Professor, Yiyu Cai  
Nanyang Technological University  
Singapore

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*Everything stays,  
but it still changes.*

- Adventure Time

*Dedicated to Jessica, and the love of gaming.  
My sweet pareidolia..*

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## ABSTRACT

This thesis discusses the utilization of natural user interfaces in the design of virtual reality mechanics. The mechanics are inspected from the perspective of interaction fidelity of virtual interactions, usability, cyber sickness, enjoyability, and feasibility. The thesis is formed out of research outlined in five scientific articles, each exploring slightly different types of natural interaction mechanics and how they could be best utilized. The mechanics include simulating real-world activities, such as swimming and climbing, with VR controllers, hand-tracking and gesture user interfaces with one- and two-handed gestures, eye-tracking, and context-awareness utilizing subconscious biological reactions. The research questions outlined in this thesis attempt to find out how natural user interfaces could be constructed to be as usable as possible while simultaneously immersive, what kind of added benefits they can bring to the user experience, and what type of applications do they suit the best. The results show that a one-size-fits-all approach is not viable for natural virtual reality user interface design, highlighting how the differences in individuals affect the design requirements. The resulting conclusions are combined into an initial design framework for natural interfaces in virtual reality.

**KEYWORDS:** virtual reality, interaction design, mechanics, gesture, natural, user interface, eye-tracking, pulse, controller, context-awareness, cyber sickness

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## TIIVISTELMÄ

Tämä tutkielma käsittelee luonnollisten käyttöliittymien hyödyntämistä virtuaaliodellisuuden mekaniikoiden suunnittelussa. Mekaniikoita tarkastellaan virtuaalisten vuorovaikutusten uskottavuuden, käytettävyyden, kyberpahoinvoinnin, miellyttävyyden ja toteutettavuuden näkökulmista. Tutkielma koostuu viidessä tieteellisessä artikkelissa esitellyistä tutkimuksista, joissa tarkastellaan hieman erilaisia luonnollisia vuorovaikutusmekaniikoita ja niiden optimaalista hyödyntämistä. Näihin mekaniikoihin sisältyvät muun muassa tosielämän toimintojen, kuten uimisen ja kiipeämisen, simuloiminen VR-ohjaimilla, käsienseuranta ja yhden sekä kahden käden eleiden käyttöliittymät, katseenseurantamekanismit, sekä kontekstiin mukautuvuus hyödyntäen tiedostamattomia biologisia reaktioita. Tutkielman tutkimuskysymykset pyrkivät selvittämään, miten luonnollisia käyttöliittymiä voidaan suunnitella mahdollisimman käytettäviksi ja samalla immersiivisiksi, millaisia lisähyötyjä ne voivat tarjota käyttäjäkokemukseen, sekä minkä tyyppisiin sovelluksiin ne sopivat parhaiten. Tulokset osoittavat, että ”yksi koko sopii kaikille” -lähestymistapa ei sovi luonnollisten virtuaaliodellisuuskäyttöliittymien suunnitteluun, ja ne tuovat esiin, miten yksilöiden erot määrittävät suunnitteluvaatimuksia. Johtopäätökset yhdistetään alustavaan suunnittelukehikseen, joka tukee luonnollisten käyttöliittymien kehittämistä virtuaaliodellisuudessa.

ASIASANAT: virtuaaliodellisuus, vuorovaikutusmuotoilu, mekaniikat, ele, luonnollinen, käyttöliittymä, silmienseuranta, pulssi, ohjain, kontekstiin mukautuvuus, kyberpahoinvointi

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Secondly, I would like to thank my colleagues at the Mixed Reality Group who assisted in the creation of some of the article materials and initial testing validation, in addition to just being great company overall. I would like to single out some names without excessive descriptions: Thank you to Olli Heimo for the talks on the breaks and the memes (I guess I should mention ethics too), Markus Krusberg for the "artistic approach" and excellent photographic skills (there might be a butterfly in this thesis), Seppo Helle for your wisdom in usability, and Kaapo Seppälä for the business(and gaming)-oriented mind. I would also like to include our recent additions who have made the workload at the lab a lot more manageable. These people are Mirva Tapola, Joni "it just works" Rajamäki, Eero Nirhamo, and Tommi Immonen. I would also like to thank the following people at or around the Department of Computing who have been a part of this journey: Tapani Joelsson, Tuomas Mäkilä, Carolina Islas Sedano, Lauri Koivunen, Timo Vasankari, Jari Lehto, Jaakko Järvi, Natasha Skult, Tomi "bgt" Suovuo, Anne-Maarit Majanoja, Jari-Matti Mäkelä, Marko Lahti, Juuso Ryttilahti, and many others.

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the extensive amount of swimming and sauna (and other) trips that have kept me refreshed, and my mother Tuija for helping to create a strong learning foundation during my early school years that has eventually allowed me to undertake this doctoral dissertation.

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*In the beginning, were the mechanics,  
and the mechanics made the world.  
I am the mechanics.  
The mechanics are everything.  
Without mechanics, there is no interaction.  
Where the mechanics end, the world ends.  
You cannot go forward, when movement is not defined.  
Repeat.*

- adapted from *The Talos Principle* [1]

As well as people there are also other concepts that have aided me in this journey, namely video games, films, and music. The adapted quote from above is one of my favourites from *The Talos Principle*, which discusses difficult fundamental concepts such as existence and what it means to be human. Is it possible that a machine has consciousness, or are humans nothing more than highly complex machines?

I would also like to highlight here a few masterpieces that I have listened to, watched, or played through during the creation of this thesis, or just in general. I strongly believe that meaning in life can be found through creation for others. I am thankful to everyone who creates, and happy for everyone who finds enjoyment in the creations of others.

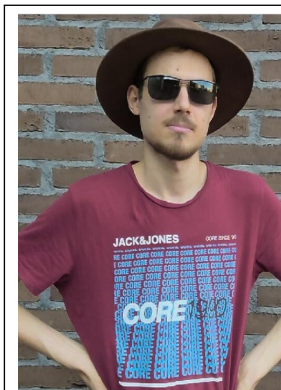
*Inspirational music:* Pareidolia, The One, Beauty of Annihilation, 115 and others by Elena Siegman and Kevin Sherwood from Call of Duty Black Ops, Scatman's World and others by Scatman John, Bad Apple, Aberraatio album by Kosovon Vanha Paska & Lökkijay, Crystallized and others by Camellia, Tikapuut Taivaaseen and others by Leevi and the Leavings, Majula theme from Dark Souls 2 by Motoi Sakuraba, Mass Effect Andromeda galaxy map theme by John Paesano, Lost by Phaxe and Morten

Granau, Red Planet Nocturne from Off-world Trading Company by Christopher Tin, Iris by Goo Goo Dolls, Want You Gone Portal 2 fanmade song by Khaff3, to name a few.

*Inspirational shows/films:* Adventure Time, Rick and Morty, Bojack Horseman, Disenchantment, The Black Adder, Forrest Gump, Arcane, Smiling Friends, Steins Gate, Higurashi, Futurama, Lord of the Rings, and many others.

*Inspirational games:* Filament, the Supraland series, Silent Hill 2 remastered, Dark Souls series, Monkey Island series, Baldur's Gate series, Songs of Conquest, Tangledeep, Strangeland, AI: the Somnium Files series, The Stanley Parable, Inscryption, Disco Elysium, Ring of Pain, Mindbug, Albion online, Call of Duty Black Ops (zombies), The Talos Principle series, Downfall, Don't Starve Together, Cyberpunk 2077, Edna and Harvey: The Breakout, The Witness, Superliminal, The Zero Escape series, Black Book, Planescape: Torment, Town of Salem, Loop Hero, Portal series, Baba Is You, Heavy Rain, Peglin, MTG Arena, Gwent, Beat Saber, Superhot, Age of Empires II, the Danganronpa series, and Badugi. At least.

May 2025  
Taneli Nyysönen



## TANELI NYYSÖNEN

Taneli Nyysönen is a Master of Interaction Design from the University of Turku. He is passionate about designing interaction mechanics for virtual and other realities, especially in relation to games. He is not your everyday author, because he is a scientist. He might also be mad, who knows? In any case, science will prevail, it always does.

俺はタネリ・ニュッソネン、狂気のマッドサイエンティストだ！

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# Abbreviations

VR	Virtual reality
HMD	Head-mounted display
UI	User interface
2D	Two-dimensional
3D	Three-dimensional
AR	Augmented reality
MR	Mixed reality
AV	Augmented virtuality
RV	Reality-Virtuality
BCI	Brain-computer interface

# List of Original Publications

This dissertation is based on the following original publications, which are referred to in the text by their Roman numerals:

- I Nyysönen, T. and Smed, J., Exploring virtual reality mechanics in puzzle design, *The Computer Games Journal* (2021), vol. 10, pp. 65-87.
- II Nyysönen, T., Helle, S., Lehtonen, T., and Smed, J., A Comparison of Gesture and Controller-based User Interfaces for 3D Design Reviews in Virtual Reality (2022), *Proceedings of the 55th Annual Hawaii International Conference on System Sciences*.
- III Nyysönen, T., Helle, S., Lehtonen, T., and Smed, J., A Comparison of One- and Two-handed Gesture User Interfaces – A Task-based Approach (2024), *Multimodal Technologies & Interaction*, 8, 10.
- IV Nyysönen, T., Blackburn, J., Lehtonen, T., and Smed, J., Eye-openness and Pulse-tracking in Virtual Reality as a Navigation Mechanic (2025), In Review.
- V Nyysönen, T., Lehtonen, T., and Smed, J., Non-conventional Virtual Reality Mechanics (2025), In Review.

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# 1 Introduction

*Virtual reality* (VR) technologies have been technically researched since the invention of the stereoscope by Sir Charles Wheatstone in 1832 [2], with the revelation that human eyes are capable of perceiving two two-dimensional (2D) images next to each other as three-dimensional (3D). The term "virtual reality" was however coined by Jaron Lanier much later in 1987 who sold the first VR products through his company VPL Research, showcasing the long journey of progress in the field [3; 4]. However, the potential of VR has been limited by the technical capabilities such as hardware and system limitations. Nowadays, major limitations include, for example, having to usually utilize inadequate controllers which can cause strain on hands or arms in prolonged use due to their weight, and which come with limited input options, buttons. Additionally, the controller-based interaction lacks realism as the desired interaction is rarely similar to the physical button press, for instance, all types of movement in VR. The methods of interaction with VR user interfaces (UIs) can also be clunky at best, as they are often modelled around pre-existing usability research used in 2D-applications due to limited 3D interaction usability knowledge [5; 6]. One specific issue is the lowered accuracy of point-and-click interaction when compared with the standardized mouse input [6].

This introductory chapter explains the history behind the technology, what VR is and what are the common properties it has. Additionally, the concept of natural interaction and its role in the context of VR is explained. Finally, we look into why natural interaction should or could be utilized in VR and define the main objectives and research questions.

## 1.1 Brief history of virtual reality

The earliest known attempts at virtual reality are believed to be 360-degree murals, also referred to as *panoramic* paintings. These murals often depict historical events, and by encompassing the viewer's entire field of vision, they can evoke a sense of actually being present at the depicted scene. An example of these is "Battle of Avay" by Pedro Américo [7] in Figure 1. The origin of the panorama dates back to 1787, patented by the Irishman Robert Barker, who described this medium as a "kind of pattern for organizing visual experience." The term "panorama," derived from the Greek words *pan* ("all") and *horama* ("view"), was also coined by Barker in the same



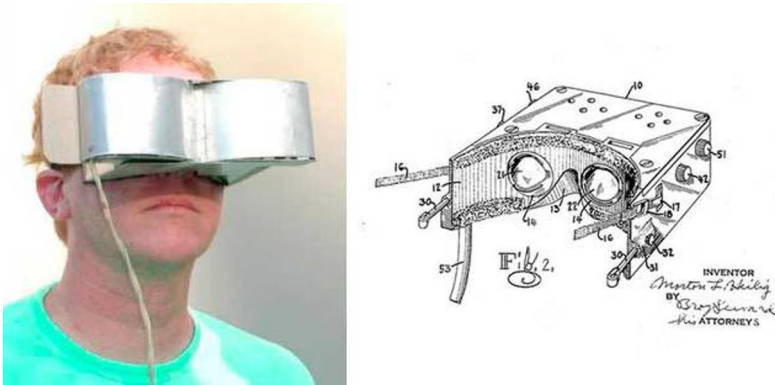
**Figure 1.** A panoramic painting of the Battle of Ayacucho from Paraguayan war in December 1868, which was fought between the forces of the Triple Alliance and the Paraguay, painted by Pedro Américo [7].

year. Barker's proposal was to exhibit a painted landscape in a 360-degree view, on a cylindrical canvas strip surrounding the viewer. He later exhibited these works in London as "The Panorama" in 1792. [8; 9; 10]

The modern resemblance of the term virtual reality started in 1838 when Sir Charles Wheatstone's research was published in the Royal College of London, demonstrating that the brain processes the different two-dimensional images from each eye into a single object of three dimensions, referred to as *stereoscopy*. Viewing two side by side stereoscopic images or photos through a *stereoscope* gave the user a sense of depth and immersion. The first stereoscope was later referred to as the Wheatstone stereoscope, and it was originally invented in 1832. The stereoscope was succeeded by the *lenticular stereoscope* (David Brewster, 1849) and later by the *View-Master* product line of stereoscopes invented by William Gruber, first of which released in 1939. [2; 11; 12; 13; 14; 15]

The potential of stereoscopy in simulation training became apparent with *Link Trainer*, the first commercial flight simulation device in the world, which was created by Edward Link in 1929. Largely used by the United States military forces at the time, these "blue boxes" trained hundreds of thousands of pilots during World War II. [16]

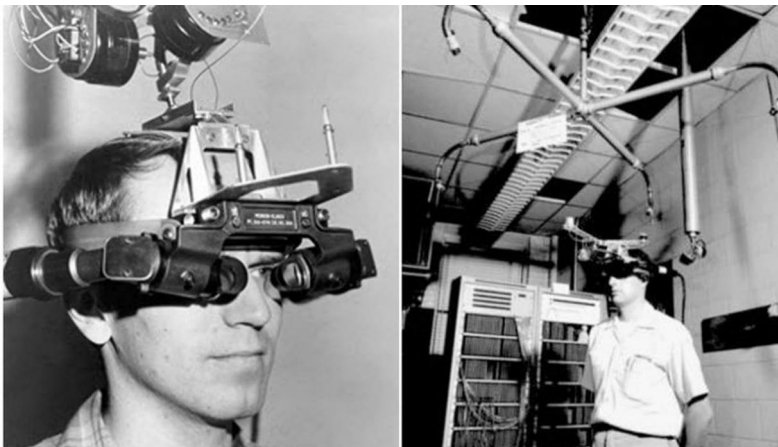
In 1957, cinematographer Morton Heilig invented the *Telesphere Mask* or *Stereoscopic Television Apparatus for Individual Use* [17] (patented in 1960), which resembled closely the likeness of modern VR headsets and is said to have been the first VR head-mounted display, see Figure 2, although it did not feature any motion tracking. He also created the *Sensorama* [18] (patented in 1962) which was a mechanical arcade-style theatre cabinet that would stimulate all the senses, not just sight and sound. It consisted of stereo speakers, a stereoscopic 3D display, fans, odor emitters and a motional chair. These inventions were early showcases of the entertainment possibilities of stereoscopy.



**Figure 2.** Morton Heilig's Telesphere Mask [17].

The first motion tracking head-mounted display the *Headsight* was invented by two Philco Corporation engineers in 1961 [19]. It allowed the user's head movements to move a remote camera, letting them inspect their surroundings quite naturally.

Ivan Sutherland's *head-mounted three-dimensional display*, jokingly named as "Sword of Damocles" due to the way it was set to hung over the user's head, was released in 1968 [20], see Figure 3. Although, the device was technically an augmented reality (AR) headset, featuring optical transparency and the graphics consisted of simple wireframe rooms.



**Figure 3.** Ivan Sutherland's head-mounted three-dimensional display [20].

In 1969, Myron Krueger developed a series of experiences which he called "artificial reality". These experiences allowed users to communicate with each other through a responsive virtual environment despite being miles apart. This technology was called *VIDEOPLACE*, and is widely referred to as the first interactive VR system, although it was technically a form of augmented reality as it did not feature a head-

mounted display. [21]

In 1987, the term virtual reality became established by Jaron Lanier, founder of the VPL Research. The VPL Research was the first company to sell VR goggles (such as EyePhone) and gloves. [3; 4] At the time, constraints such as *latency*, which in telecommunications is defined as how much time it takes for a data packet to travel from one designated point to another, were major obstacles in VR hardware development. In the context of VR, latency usually means the processing delay between the image updating and the user observing a change in the image. High latency could make systems unusable as, for example, input by the user could take too long to register for the user to react to subtle changes in the application, which could also cause VR-induced motion sickness (for definition see Section 1.4). Some advances in latency management came in 1991 when the Virtuality Group (originally named W Industries) [22; 23] launched a range of arcade games and machines which were played using VR-goggles with less than 50ms latency stereoscopic 3D visuals. Some of them were even capable of multiplayer experiences through networking.

*CAVE* or *Cave Automatic Virtual Environment* is a VR environment comprising a cube-shaped VR room or a room-scale space where the walls, floor, and ceiling serve as projection screens. It was invented in 1992 by Carolina Cruz-Neira, Daniel Sandin, and Thomas DeFanti at the University of Illinois, Chicago Electronic Visualization Laboratory. Inside the CAVE, users may wear 3D-glasses and interact using input devices such as wands, joysticks, or data gloves. [24]

In 1993, Sega announced the Sega VR headset for the Sega Genesis console at the Consumer Electronics Show. The wrap-around prototype glasses had head tracking, stereo sound and LCD screens in the visor and were aimed to be sold at a price of 200 USD. Unfortunately, the headset was never released for commercial use due to technical difficulties and remains incomplete. [25; 26]

Nintendo Virtual Boy, visualized in Figure 4, was released in 1995 and marketed as the first ever portable console capable of displaying stereoscopic “3D” graphics. However, the product failed commercially and was discontinued the following year due to complaints about its lack of colours (only black and red) which diminished its graphical outlook, high price, and comfortability being among the main complaints. The “VR” 3D effect was also seen as a hindrance rather than a perk. [27]

During the 21st century, VR development has taken giant leaps forward, major ones mentioned here, starting with the Google Street View in 2007, which consists of navigable panoramas taken from all around the globe. In 2010, Palmer Luckey designed the first prototype of the Oculus Rift, which was the first VR-headset able to produce a 90-degree field of view. The field of view in head-mounted displays is vitally important, as it determines how wide an area the eyes can see, and accounts for the peripheral vision capabilities. Before the Oculus Rift, the VR-headsets had a considerably lower field of view. Later Luckey released the Oculus Rift DK1 in 2013 [29; 30; 31].



**Figure 4.** Nintendo Virtual Boy portable “VR” console [28].

In 2013, Valve Corporation discovered and freely shared the breakthrough of low-persistence displays which made low-latency VR experiences possible. This breakthrough was used in the creation of many VR-headsets after its discovery, one being the *HTC Vive* [32; 33; 34], which Valve released together with HTC Corporation in April 2016. HTC Vive was running the *OpenVR SDK* that was released to the public in April 2015 by Valve, for developers to develop *SteamVR* games and software [35; 36]. The Oculus Rift CV1 [37] was released in 2016 as well, and it also ran on the OpenVR SDK, as the SDK was designed to also support other headsets than the ones made by its creator, Valve. These devices first featured what is called a “room-scale” tracking technology. This meant that users could freely move in the play area and their real-life movements would be reflected inside the VR. These are often referred to as the first modern, consumer-accessible VR headsets.

In December 2017, a device called *TPCAST Wireless Adapter* [38] was released for HTC Vive. TPCAST allowed users to experience VR completely wirelessly and claimed to have a sub 2 millisecond latency without affecting the image quality. Next year the HTC Vive Pro [39], an enhanced version of the HTC Vive was released in April 2018, and it featured improved resolution ( $1440 \times 1600$  pixels per eye) and came with an additional camera which allowed users to see their real-life surroundings



**Figure 5.** The Valve Index VR headset, its Knuckles-controllers, and base stations [40].

when stepping outside of the designated play area, making the device safer to use. This feature was named pass-through.

In June 2019, Valve released their first self-created VR-headset, the *Valve Index* [40], see Figure 5. The Valve Index featured vastly improved technology with an experimental up to 144Hz refresh rate and a way of partially tracking the positions of each finger without the need for gloves with its Knuckles-controllers.

In October 2019, a company called Varjo released a VR-headset, *VR-2 Pro*, which among other features claimed to feature a human-eye resolution (20/20 Eye Tracker). The headset was said to be the most advanced one on the market at the time, but it was only designed for enterprise use, having a quite steep price tag of near 6000 euros just for the headset. It was designed to function with SteamVR similar to most of the devices released at the time. [41]

In May 2019, Oculus, later acquired by Facebook which is nowadays called Meta, released the Meta Quest VR headset [42], which started the era of proper standalone VR headsets, supporting six degrees of freedom (defined in Section 1.2). The previous standalone headsets, such as the Oculus Go (released in 2018) [43], could only support the rotational tracking with three degrees of freedom. Standalone headsets are able to run VR-content without needing to be tethered to a PC, although with much lower processing power. The standalone aspect provided mobility for VR use, allowing devices to be transported and setup more easily. The mobility was also afforded due to no longer requiring external trackers to be setup in the room. The device also featured hand-tracking and partial body-tracking. An upgraded device, the Meta Quest 2, was released in 2020 [44], which featured advanced hand-tracking. Later, in year 2022, Meta released the Meta Quest Pro [45] which featured face tracking capabilities for realistic avatar expressions. A short time later in October 2023, Meta also released the Meta Quest 3 [46]. Both of these headsets were among the first to offer full color pass-through, meaning that the real world could be seen through the headset's cameras in all colors with potential virtual content displayed in it, which previously

was usually done in monochrome due to hardware limitations. These devices all ran on a custom Android-based operating system developed by Oculus (Meta Horizon OS), that was not directly compatible with OpenVR, thus applications needed to be developed separately for Meta and SteamVR devices. Another reason for separated development was the lower processing power which required computationally lighter graphical assets to be used.

Meanwhile, Microsoft had also released its Microsoft Windows Mixed Reality devices. The main reason for the platform's creation is thought to be the *Microsoft HoloLens* (released in 2016) [47], which was a mixed reality (see Section 1.2 for definition) device aimed at enterprise use. The device featured hand-tracking, gaze tracking, and voice commands to control "holograms" visible in the real world through the headset's lenses, although with a very limited field of view of around 34 degrees. An upgraded device the HoloLens 2 was released in 2019 [48]. VR headsets were also released for the ecosystem, such as the HP Reverb G2 (2020) and the HP Reverb G2 Omnicept Edition (2021) which were developed in cooperation with Hewlett-Packard Corporation [49; 50]. The G2 Omnicept Edition included eye-tracking and a pulse-sensor for advanced applications, but both of the devices lacked hand-tracking. The Windows Mixed Reality runtime that was utilized by the headsets was incompatible with Oculus and SteamVR, requiring separated development. The Windows Mixed Reality platform is set to be discontinued by November 2026 [51; 52], which will make all devices that depend on it obsolete.

When the popularity of VR increased after the commercial releases of the first consumer-headsets, such as the HTC Vive and the Oculus Rift CV1 in 2016, there eventually started to be concerns about the future of VR and AR development due to the difficulty of cross-platform development. The major issues were that developing for multiple platforms took a lot of work and the devices offered varying features with different implementations that were difficult to port from one ecosystem to another. To solve this issue, a new standard referred to as the *OpenXR*, was invented and initially released in July 2019 by the Khronos Group [53]. The goal of OpenXR was to unify the development between the different development platforms and devices, and also between VR and AR applications by providing an application programming interface that affords building applications that work across a spectrum of devices and platforms. The standard was adopted by the three largest VR platforms which were Oculus, SteamVR, and Windows Mixed Reality.

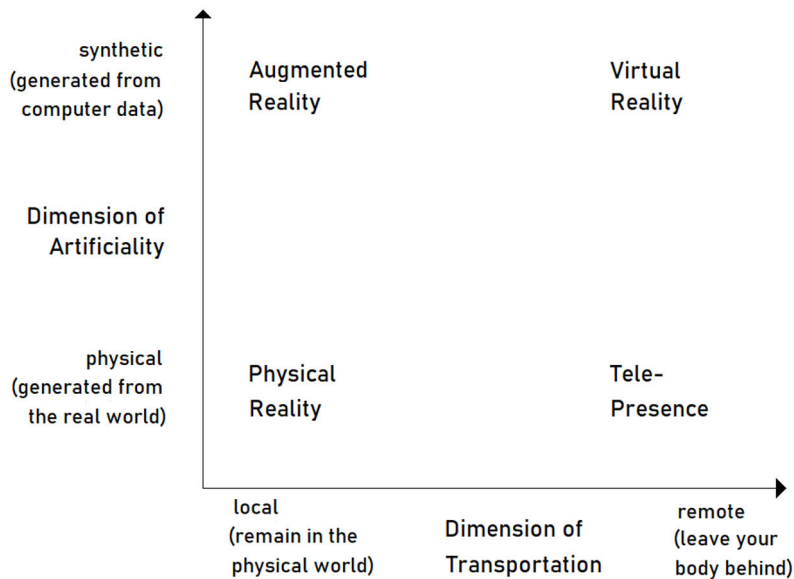
In 2023, Varjo released the XR-4 headset line, aimed at enterprise customers, with a unique feature in the XR-4 focal edition model that was a pass-through which accounted for the gaze target, changing the resolution of the real world depending on how far away objects or scenery the user was looking at. The devices worked both in VR and AR, and featured eye-tracking, but they dropped hand-tracking support in favor of controllers as it was deemed not necessary enough of a feature for enterprise use cases. [41]

In 2024, Apple released its first VR headset called the Apple Vision Pro [54], which featured hand-tracking and eye-tracking as the main input methods. It was one of the few VR headsets that did not utilize controllers at all. It remains to be seen whether controller-free approach will become the norm or if it is deemed as too impractical.

## 1.2 The basics of virtual reality

There are multiple ways to define what VR is or how it can be measured. In this section, the most common classifications are presented.

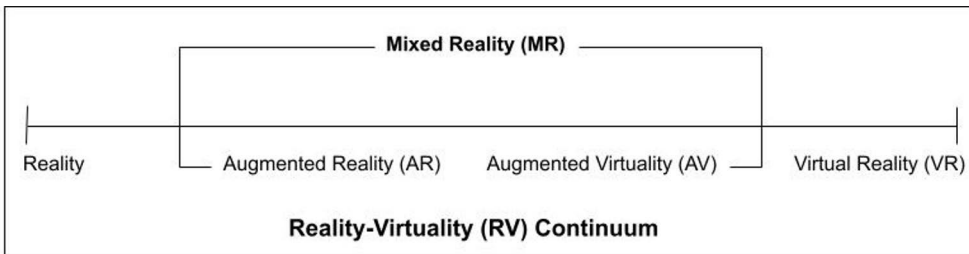
Based on the classification of shared spaces according to transportation and artificiality by Benford et al. [55], see Figure 6, VR is located in the top right corner, meaning that the user is separated from their own body and the world they are experiencing is completely synthetic. However, in terms of the dimension of spatiality [55], many physical constraints, such as height and distance remain intact.



**Figure 6.** Classification of shared spaces according to transportation and artificiality, illustrated from ([55], p. 192).

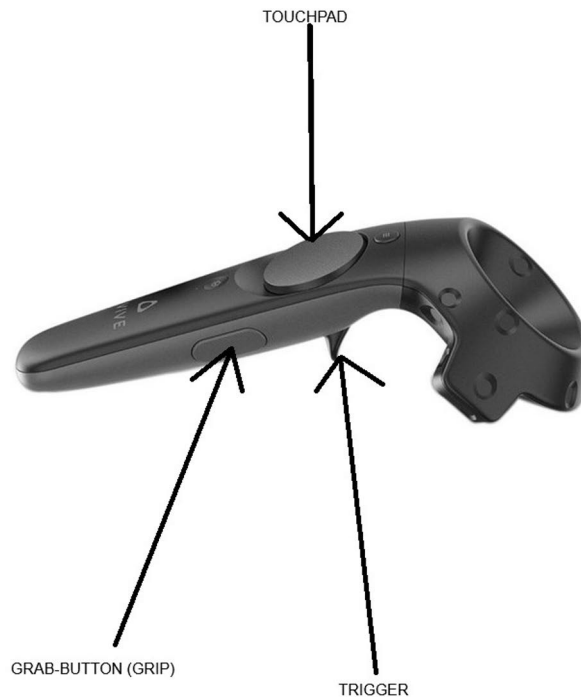
Another way to classify VR is on the reality-virtuality continuum by Milgram et al. [56], where the virtuality levels of content are compared based on augmentation, see Figure 7. On the left end of the continuum is the real world while virtual reality is at the other extreme. In the middle of these exists *mixed reality*, consisting of both *augmented reality* where virtual content augments the real world, and *augmented virtuality*, where real world content augments the virtual world.

VR systems consist of the controlling mechanics, which have traditionally been



**Figure 7.** Reality-virtuality continuum showcasing the level of augmentation of a world, illustrated from ([56], p. 283).

VR controllers, the output device referred to as the head-mounted-display (HMD) which is also known as the VR headset, and other possible space tracking apparatus such as "lighthouses", which are used to track the movement of the VR headset and control devices in room space. VR controllers contain joysticks, touchpads, or other types of omnidirectional input devices, in addition to several buttons such as the grip and trigger, for engaging in VR interactions. As an illustration, refer to Figure 8 for a HTC Vive controller and its corresponding inputs.



**Figure 8.** Depiction of a HTC Vive controller and its primary inputs [32].

A VR headset or a HMD functions as the viewpoint, allowing the user to immerse themselves in a 360-degree virtual world utilizing stereoscopy [11]. This means that

the user’s entire field of view is filled with virtual content, completely obscuring the real world. Examples of modern headsets can be seen in Figure 9, while their history is presented earlier in Section 1.1.



**(a)** The HTC Vive VR headset and its controllers [32].



**(b)** The Oculus Rift CV1 VR headset [37].

**Figure 9.** Early VR headsets.

VR enables users to physically move within the room and have this motion mirrored in the virtual environment. This phenomenon, known as *room-scale movement*, is facilitated by the headset and potential controllers being tracked in the real world in real time. The headsets contain an inertial measurement unit that uses gyroscopes and accelerometers to determine the device’s position and orientation in space. The user’s movement capabilities are referred to as *degrees of freedom*, with the options of having either three or six degrees. Three degrees refers to rotational movement only, meaning the user is able to rotate around the three axes  $x$ ,  $y$ , and  $z$  (referred to as pitch, yaw, and roll), but their movement forward and backward, left and right, or up and down in the real world cannot be detected in the virtual world. The other option, six degrees of freedom, affords movement in any direction to be translated into movement in the virtual world, meaning adding movement along the previously mentioned three axes. The ability to utilize either three or six degrees of freedom is dependent on the VR headset’s capabilities, although at the time of writing most recent headsets afford six degrees.

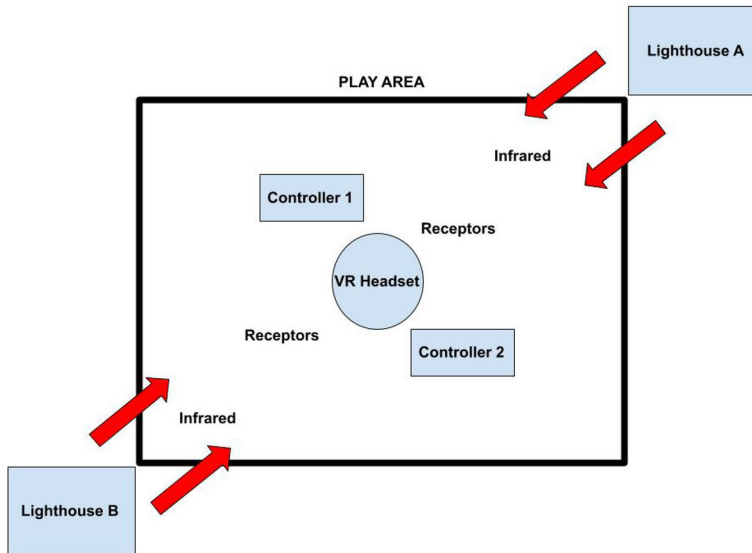
The early tracking mechanisms employed external “lighthouses” or base stations, which functioned as beacons that sent continuous infrared light and thereby helped the VR headset and its controllers to establish their position in relation to the stationary beacons via attached sensors. The most well-known example of this is the *Lighthouse*-technology created by Valve for its SteamVR VR platform [36; 57]. This practice is referred to as *outside-in tracking*, and using it limits the play area to where the infrared light from the beacons reaches which is usually a maximum of 10 square meters. While many older VR headsets, such as the Valve Index [40] and some older Varjo headsets [41] still employ outside-in tracking technology, *inside-out tracking* is currently more prevalent, and seems to have become the norm. With inside-out

tracking, multiple cameras are situated on the exterior of the VR headset, which detect changes in the surrounding environment and thereby establish the position of the headset as well as its potential peripherals. The primary advantage of inside-out tracking is that it eliminates the requirement for setting up external beacons, allowing the play area to be mobile and unrestricted to a particular room. This feature significantly improves the transportability of VR. Refer to Figure 10 for a depiction of base stations for outside-in tracking and cameras for inside-out tracking.

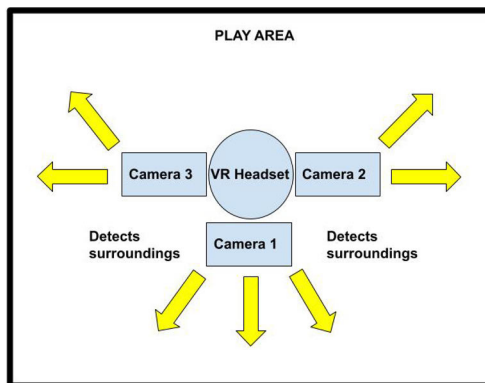
Apart from room-scale movement, the user can move using a *locomotion mechanic*. Locomotion in VR refers to artificial ways of movement, such as teleportation or joystick-directed continuous movement. Locomotion is necessary when the virtual world is larger than the room space where the user is physically in. The positions of objects in the virtual world are a physical distance away, which requires the user to move physically or use a locomotion mechanic to reach them. There exists at least the following locomotion types:

- Teleportation, which means that the user can select a position in the virtual world and be teleported there instantaneously or after a delay.
- Continuous artificial movement, which means that the user pushes a joystick or a touchpad towards a desired direction of movement. The movement direction is often determined based on the user's gaze or the direction one of the controllers is facing.
- Drag world, which is a mechanic where the user can drag themselves to any direction they choose by grabbing the virtual world and pulling their arms back and forth. This mechanic is often employed with climbing, but it can also be the sole movement mechanic if desired.
- Walking in place, a mechanic where the user's movement of the controllers and potentially legs is detected and used as a form of natural walking which does not get restricted by the boundaries of the physical space. [58; 59; 60]
- Physical treadmills, such as Virtuix Omni [61], which allow the user's walking and running to be transferred into movement in VR.
- Redirected walking, where the user walks naturally, but the virtual world is designed in a way that the user feels like they are walking in a much larger area than the physical space would allow. The effect is achieved by manipulating the virtual world in ways that cause the user to unknowingly adjust and reorient their position. [62; 63]

In essence, in VR, the user perceives the world through a VR headset, interacts with it using controllers (or even without), and their movements are monitored with the help of external beacons or internal cameras that face outward from the headset.



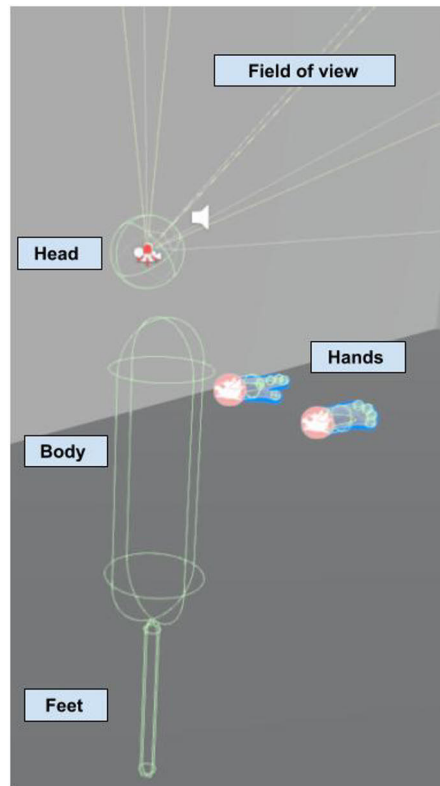
(a) Example of VR lighthouses used for outside-in tracking (as in SteamVR). The lighthouses (beacons) emit infrared light which is detected by the receptors on the VR headset and controllers. The receptors use the data to determine their pose in the play area.



(b) Example of inside-out tracking using cameras positioned in the VR headset. The cameras use mainly visible light to determine the headset's position in the room space.

**Figure 10.** Outside-in tracking versus inside-out tracking.

An example of how the user's physical appearance can be formed is presented in Figure 11. The figure depicts the user's field of view, interactors (hands as in holding controllers), and an example collider composition. Colliders are bounding boxes of various shapes that are used to detect collisions of objects with the environment and other objects.



**Figure 11.** An example user's collider composition in VR, showing head, body, feet, hands, and the field of view, originally presented in Article I.

### 1.3 The impact of user's physical properties

VR is special compared to other computer-based application types because the user's innate properties, especially their height and posture, affect the experience greatly. Differing user height can cause problems within an application if the users are, for example, required to reach into something or to grab something far away as the user's arm length determines how far they are able to reach. The user's height also determines the camera height, which will make the experience different for each user and makes them notice different areas of the virtual world more easily.

The issue can be circumvented by adjusting the height of the camera manually,

but this will lessen the immersion for the user as the floor height will no longer match the physical floor height. There can also exist multiple versions of the application, tailored for different sized individuals, but this adds development time and is not possible in shared environments. Additionally, it is possible to use other interaction mechanisms than physical grabbing or reaching to balance the user's size but this always requires compromises with immersion.

## 1.4 Cyber sickness

Cyber sickness or VR sickness refers to the symptoms experienced by people, mainly caused by visually induced experiences of self-motion, referred to as *vection* [64; 65]. Vection occurs when moving inside VR artificially (locomotion) while staying physically still, and changes in it (acceleration or deceleration) have been shown to increase sickness levels [65]. The symptoms generally include dizziness and nausea, and could even lead to vomiting. Cyber sickness is also referred to as visually induced motion sickness. Cyber sickness can be thought of as a mixture of simulator sickness [66; 67], which refers to symptoms experienced in simulators with or without actual movement of the user, and motion sickness [68], which relates to symptoms experienced when being moved by, for example, a vehicle. [69]

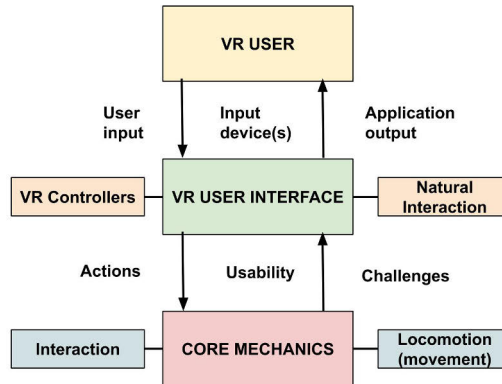
The cyber sickness is mainly generated by the user's brain not being able to process two mixed signals: one sent by the eyes that the user is moving, and another sent by the vestibular system that the user is definitely not moving. The vestibular system, located in the inner ear, refers to the sensation of our limb and skin positions and is responsible for the sensation we like to refer to as balance. The mixing of these signals is called the *sensory mismatch theory* or the *cue conflict theory* [66; 67], and it has been shown that people without a functioning inner ear do not appear to experience motion sickness. Another potential theory is the *postural instability theory* [70], where instabilities in the posture cause the sickness. A third common theory is the *poison theory* [71], which argues that the sickness is an evolutionary adaptation to being poisoned, which would cause similar visual and vestibular disturbances, with the goal of vomiting the ingested toxins out. [72; 69]

However, there can be other causes for it, some of which are discussed later in Section 2.4 in combination with means to overcome it.

## 1.5 Natural interaction

Interaction in VR happens through the core mechanics, which refers to a process where input from the user is transferred to the application as functionality (output) through the usage of some input device(s) which are accessed via a user interface (natural or otherwise). This relationship in the non-VR form is showcased in the book *Fundamentals of Game Design, Third Edition* ([73] p. 38), and Figure 12 is adapted

from it by adding some VR-specific examples.



**Figure 12.** Relationships between the user, user interface, and core mechanics in VR use. Adapted from ([73] p. 38), originally presented in Article V.

*Natural interaction* is part of a broader set of paradigms collectively known as reality-based interaction [74] or reality-based user interface systems [75]. This collection encompasses diverse interaction styles that extend beyond direct manipulation, including virtual, mixed, and augmented reality, as well as tangible interaction, ubiquitous and context-aware computing, handheld interaction, and perceptual and implicit interaction styles such as natural interaction. These paradigms leverage tacit knowledge across four main areas: fundamental physics (e.g., gravity, friction, persistence of objects, relative scale); bodily awareness (e.g., proprioception, range of motion, two-handed coordination, whole-body engagement); environmental awareness (e.g., navigation, depth perception, spatial relationships between objects); and social awareness and interpersonal skills (e.g., presence of others, verbal and nonverbal communication). [76; 77; 78; 79; 80; 81]

In general, natural interaction refers to UIs that are, in a sense, invisible. They are so innately part of us or require no effort to learn or use that they become almost like they were not there. For example, our hands are a natural interface, because when we go about our lives and use our hands for various things, we do not need to constantly concentrate on that we are using our hands. As a contrast, we would have to concentrate on using an *artificial interface* like a controller of any device.

Natural interaction in the context of this thesis mainly refers to utilizing our body's normal functions as control mechanics. This means that instead of using some devices such as controllers, we would use something that is already part of our body such as our hands or our eyes or some internal reactions such as heart rate or brain signals. As these functions are already innate to us, they should feel more natural to utilize

than any artificial interfaces, and their potential benefits and drawbacks in the context of VR are what form the central idea of this thesis.

One potential benefit of natural interaction in VR is increased immersion, as with less peripherals there is less chance to get distracted from the experience. However, it is still necessary to, in some form, wear the sensors required for detecting the natural interactors. A deeper dive into types of natural interfaces can be found in Section 2.3.

## 1.6 Reasons to utilize natural interaction

One reason for seeking highly realistic or natural VR interaction mechanics is that they could reduce the cyber sickness. My hypothesis is that the reduction of cyber sickness will happen because our brain more easily associates real-world movements (hand or other body part) with perceived movement inside a game or another application than, for example, button presses. This association can decrease the sensory mismatch between our vestibular and visual systems, and this hypothesis has been tested in this thesis. Conversely, there is some evidence that more realistic graphics could increase the cyber sickness [82], which is why only the mechanics should be realistic while the graphical level of detail should remain low to medium.

Another reason is that realism in VR, as in more natural and intuitive interaction, corresponds to immersion, which is a very important aspect for the enjoyability in VR games [83]. One way to achieve this “mechanical” realism, is to mimic the motions that the action in question (e.g., swimming) utilizes in the real world with VR controllers. Another way is to cease utilizing controllers completely, and instead use hand-tracking and gesture-based UIs for more precise action mirroring. Additionally, other tracking mechanisms such as eye-tracking and face-tracking can act as complementary mechanics in combination with either controller- or gesture-based control schemes, or even potentially as the sole mechanics in cases requiring high accessibility.

Third reason is that realistic mechanics can be more usable: they can be easier to learn as they are more intuitive by design. This can be especially true for gesture-based UIs, as learning various controller types can be time-consuming and difficult, even more so as the controller buttons are ideally not visible inside the virtual environment but are rather replaced by hand models. Thus, utilizing gestures can achieve the best result from both worlds: the immersion is preserved as the hands can still be modelled inside the virtual environment, whereas the users can see precisely what the inputs the control elements (their hands) are forming without needing to take off the headset. Furthermore, a careful UI design for the gesture controls tied to similar real-life actions can make the control scheme easy to remember and perhaps one day universal. Usability can also be enhanced via increased accessibility when utilizing mechanics that are, for example, hands-free, which can open up interaction possibilities among users with physical disabilities.

The overall usability can also be higher for natural UIs due to them possessing high *interaction fidelity* [84], which is a measurement to distinguish among natural, semi-natural, and non-natural interaction techniques, for more details see Section 2.2. According to McMahan et al., the uncanny valley, a relation between an object's degree of resemblance to a human being and the emotional response to that object, is also present in VR interaction in a way [84]. This means that users prefer to utilize low (such as a controller) or high (such as precise body or body part tracking) fidelity interaction mechanisms, whereas the moderate (e.g., a partially functional body tracking or a combination of a controller and body tracking) mechanisms suffer from the uncanny valley effect and can thus lead to the worst user performances out of the three [84]. Although, it should be noted that the familiarity with the interaction mechanism has a large impact on the performance results. All in all, the idea is that using the highest possible fidelity interaction mechanisms, the user performance and immersion levels would be the highest possible, and potentially the cyber sickness could be lowered as well.

Furthermore, in relation to technology availability and progress, accurate hand-tracking has recently become more available commercially, starting with the release of the Meta Quest 2 VR headset [85], which is utilized in the prototypes developed for Article II and III of this thesis. Moreover, gesture-based UIs are not only high-fidelity interaction mechanisms, but they are also well suited for communication purposes in virtual environments, as hand-tracking makes it possible to record and add gestures that are used in everyday conversations into virtual environments effortlessly and seamlessly. Additionally, mechanics such as pulse sensors and eye- or face-tracking are being integrated into the VR hardware to further enable monitoring user reactions with products such as the HP Reverb G2 Omnicept Edition [50]. Utilizing the reactions to adjust the experience is referred to as *context-awareness*, for more details see Section 2.3.5.

## 1.7 Objectives and Research Questions

This thesis aims to have practical and theoretical significance. The contributions of this thesis are listed below. The research questions presented are addressed throughout all the articles I-V.

- This thesis presents prototypes that utilize bodily movements and poses as parts of VR movement or interaction mechanics. The aims are to figure out potential usability and immersion benefits and disadvantages that utilizing these mechanics can bring. The major findings are aimed at other developers and researchers who can use them to develop better VR software in the future.
- The prototypes are presented as case studies and there are also considerations for what type of software various natural interfaces are suitable.

- An initial design framework for designing natural UIs in VR is presented.
- The novelty value of this research emerges from designing and evaluating experimental VR mechanics and UIs in addition to testing them within relevant use-case scenarios.

### 1.7.1 RQ1: How to design usable and immersive natural user interfaces in virtual reality?

There exists a predicament in VR software design that adding realism to increase immersion can often lower the usability unless some serious design considerations are taken into account. Examples include simulating real motion, such as walking or climbing, with controllers. This can feel more realistic, but unavoidably causes more strain for users than remaining still. Another clear example is that increasing visual fidelity, and thus immersion, can increase experienced cyber sickness levels. This is due to the brain "thinking" that the virtual world must be more real because graphical elements look more realistic, leading to higher expectations of mechanical realism as well. And thus, when mechanics are not perfectly one-to-one with the real world, sensory mismatches causing cyber sickness can occur more easily. A third example involves employing hand-tracking rather than VR controllers, as gestures offer a more intuitive means of interaction. Partially due to the fact that we are not accustomed to controlling software with gestures, there are significant reliability implications. For instance, the Midas touch problem [86], see Section 2.3.1, can result in a considerable number of unintended inputs while merely moving our hands around, which could be prevented by utilizing controllers.

### 1.7.2 RQ2: What kind of added value can natural interfaces provide in virtual reality?

Some natural interfaces (e.g., eye-tracking) can be utilized by people who are unable to use standard UIs, but this should not be the only reason to study them. The main advantage for natural VR interaction is likely enhanced immersion, as when utilizing our body more fully or at least with less peripherals, it is easier to forget that the world we are seeing is not real. Another possible advantage is that natural interaction in VR may lead to a decrease in cyber sickness. This is because such interactions might cause less cognitive confusion for the brain compared to the more standardized means of interaction.

Additionally, there exists the possibility of more versatile body utilization, which could prevent fatigue in body parts, such as arms. If easy enough to switch, some interaction methods could be interchangeable even during use. These kind of measures could be seen as early preventative design against VR-induced repetitive stress injuries.

Natural interfaces also enable easier implementation of context-awareness, which means that applications would adapt to the user instead of the usual case of vice versa.

### 1.7.3 RQ3: What type of virtual reality applications do natural interfaces suit the best?

In standard computer usage some applications, such as games, function very well when utilizing a keyboard and mouse combination while others shine with a controller. This has a lot to do with the controller type required for the application, as for example many real-time strategy games, which often require a lot of fast and precise cursor inputs, are difficult to play with most controllers, as a joystick mouse just is not fast and precise enough in comparison. Alternatively, driving games which utilize the whole 360 degrees of turning motion with the controller joystick are much better suited for controllers rather than keyboards which only feature the four arrows in most cases. Furthermore, certain games, such as fighting games can utilize combinations of button presses that are difficult with keyboard only as they are designed to work with a controller for ease of reaching many buttons simultaneously and in combinations.

Similarly, in VR, some applications benefit the most when the interactor is a standard VR controller, whereas other types of applications are hindered by their lack of functionality, immersion, or accessibility. Clear examples for controller use are applications which require extreme precision and where an unintended input can have dire consequences, such as remote surgeries. In relation to applications that benefit from natural interaction, communication-centered applications are maybe the most relevant. For example, using gestures for communications can enhance the experience greatly while there is no need to be extremely precise at all times.

## 1.8 Structure of this thesis

This doctoral thesis has the following structure. The second chapter explains the theoretical background behind the prototype design and implementation. The chapter defines important concepts for this thesis, such as the interaction fidelity of virtual interactions, the gorilla arm syndrome, and the Midas touch problem. The natural interaction mechanisms are also elaborated on in detail.

The third chapter presents the case studies. This includes a more detailed explanation of the specific mechanics utilized in each of the prototypes in this thesis. The case studies are the following:

- **Taneli Nyysönen & Jouni Smed:  
Exploring Virtual Reality Mechanics in Puzzle Design**
  - This study compares realistic and game-like controller mechanics in VR.
- **Taneli Nyysönen, Seppo Helle, Teijo Lehtonen, & Jouni Smed:  
A Comparison of Gesture and Controller-based User Interfaces for 3D Design Reviews in Virtual Reality**
  - This study compares controllers and gestures in VR for 3D design review use case.
- **Taneli Nyysönen, Seppo Helle, Teijo Lehtonen & Jouni Smed:  
A Comparison of One- and Two-handed Gesture User Interfaces – A Task-based Approach**
  - This study compares one- and two-handed gesture UIs.
- **Taneli Nyysönen, Jessica Blackburn, Teijo Lehtonen & Jouni Smed:  
Eye-openness and Pulse-tracking in Virtual Reality as a Navigation Mechanic**
  - This study utilizes eye-openness and pulse as control mechanics for navigating in VR and as forms of context-awareness.
- **Taneli Nyysönen, Teijo Lehtonen & Jouni Smed:  
Non-conventional Virtual Reality Mechanics**
  - This study combines the results from the previous studies and visualizes a design framework for natural UIs in VR.

In the fourth chapter, the major results are laid out with deliberation of their potential significance and limitations.

The results and their implications are further elaborated on in the final chapter in addition to future work considerations with concluding remarks.

## 2 Foundation

In this chapter, we look into the initial motivations to start pursuing VR mechanics design research. Afterwards, we list the metrics that are utilized to define the quality of VR interactions and define interaction fidelity. Next, the types of natural interaction in VR are presented. Then, we discuss the main challenges of designing for VR in addition to why they are important to solve. Finally, we present the main methodology of the study.

### 2.1 Initial motivation

The idea to start researching VR originated from game development, which I had been working on for several years prior to learning about VR. After learning to develop traditional games, I became interested in VR game development. At the time, the devices available were only the first HTC Vive and Oculus Rift, which lacked in resolution, comfort, and development support. There also was basically only one way of interaction, which was through the controllers. At first I found the immersion of VR astonishing, but soon after I started feeling awful as I noticed that I was extremely prone to cyber sickness. This was interesting as one of my game development partners at the time did not seem to be affected by cyber sickness at all in comparison. This was my first peek into how VR affects people differently and it made me wonder why that is and how could that be improved for the people who are prone to this feeling.

In any case, I started developing basic VR experiences using a loaned HTC Vive in the premises of the Finnish Virtual Reality Society in the Turku Game Hub HIVE, which at the time had been rather underutilized as a working space, so I had the perfect opportunity to join in. While continuing my master's studies in interaction design, I spent years learning how VR affected me by testing anything that came to my mind. I also became part of a small team of students interested in VR game development. My team and I were developing VR games for several years and during it I learned to design VR mechanics, such as creating an inventory system accessible by physical hands, swimming in VR, as well as a lot of different locomotion options. It also became clear to me what issues VR has when it comes to interaction with objects and the game world.

Later on the interest of many of the team members in the development waned but I was still keen on continuing, and as I was so interested in VR as a medium I attempted

to pursue the design of its mechanics as a PhD after completing my master's in 2020. The pursuit was successful and I started my PhD in 2021 after first publishing my master's thesis as a scientific article, which is Article I of this thesis.

## 2.2 Measuring the quality of virtual reality interaction

When it comes to determining whether a virtual interaction is "good" or "bad", there are many metrics that can be utilized, namely at least usability, immersion, physical strain, cognitive load, cyber sickness induced, and interaction fidelity. Usability describes the ease of use and intuitiveness of a system, including learning how to operate it. Immersion refers to the level of presence or mental involvement in an activity. Immersion can, for example, refer to the degree of ease of forgetting the rest of the world during an experience. Physical strain and cognitive load refer to the amount of energy expended on physical and mental activities during interaction in a system. The cyber sickness is explained in sections 1.4 and 2.4.

The other metrics named here are somewhat well-known, but interaction fidelity is a less utilized and known concept. It is defined by McMahan et al. [84] as "the objective degree of exactness with which real world actions are reproduced in an interactive system". The interaction fidelity can be analysed using its evaluation tool *Framework for Interaction Fidelity Analysis* [87] with three metrics:

- *biomechanical symmetry*, which means how well the used mechanics mirror the simulated real-world actions (e.g., hand motion exactness, haptic feedback),
- *input veracity*, which refers to the accuracy at which the interaction is captured by the input devices (e.g, latency, camera tracking radius), and
- *control symmetry*, which describes the degree of exactness with which a real-world theoretical transfer function is reproduced through interaction (e.g., handling an object with a hand-tracked hand is near identical to how one would handle a physical object, whereas using a ray going out from the user's hand or controller is not) [84].

The interaction fidelity, as described by McMahan et al. [84], is negatively impacted by the *uncanny valley* effect, which indicates that medium fidelity interaction mechanisms are less effective in terms of usability compared to both high fidelity (very realistic) and low fidelity (not realistic at all) mechanisms. Although, it should be noted that the familiarity with the interaction mechanism has a large impact on the performance results. Consequently, by definition, hyper-realistic VR mechanics must also possess high interaction fidelity.

How, then, can one achieve high interaction fidelity in VR? A straightforward example is walking. In a room-scale VR environment that does not incorporate

artificial locomotion mechanics, such as joystick-based movement, the user can physically walk within the space, which simultaneously moves their avatar in the virtual environment. This approach offers the highest interaction fidelity, as it directly mirrors real-world physical action. However, it has significant limitations when used independently, primarily because the real-world room size dictates the maximum movement range, typically only extending to ten square meters or less.

To address this limitation while maintaining high interaction fidelity, various treadmills, such as the Omni One [61], enable users to walk or run in place, thereby largely preserving the interaction fidelity. The obvious disadvantages of these systems include cost, lack of portability, and substantial space requirements. Furthermore, for safety reasons, the user must either be secured to the system using a harness or be surrounded by physical barriers, which can detract from the immersive experience.

## 2.3 Types of Natural Interaction in Virtual reality

The following sections will explain the major categories of natural interaction in VR. These include hand-tracking, eye-tracking, face tracking, brain-computer interfaces, and subconscious sensors in combination with context-awareness.

### 2.3.1 Hand-tracking and gesture-based interaction

VR features *3D user interfaces* and the terms *tangible* or *graspable* interface are mentioned frequently in related research, referring to digital interfaces which are interactable via the physical dimension in some way [76; 77; 80; 81], for example, a computer mouse using a personal computer, or VR controllers selecting something. A prime example of rather literally graspable interfaces is the *hand-tracking* mechanic. Hand-tracking means that the user's hands are tracked by some type of tracking apparatus, such as cameras or wearable tracking devices, such as gloves. Hand-tracking affords much higher interaction fidelity than using standard VR controllers, but it comes with caveats and restrictions which make it unsuitable for all scenarios.

Differences in experienced strain between controllers and hands are mainly that the controller can weigh on hands or arms, while performing gestures can cause strain in general and when repeated multiple times, although without the extra weight. For the controllability, controllers have a limited amount of buttons, whereas there are technically an infinite number of possible gestures, albeit they have to be distinct enough to not get mixed. Furthermore, controllers are an unnatural way of interacting compared to hands, but many people have a lot of experience using them to offset this, although there are many different controller types that need to be learned. Gestures are more sensitive to hand size and shape differences than controllers, and it is more difficult to check for gesture accuracy than a button press. It might also be impossible for some users to perform various gestures, for example, due to inflexibility of fingers

or previous injuries. Finally, gesture use can invoke the *Midas Touch problem* similar to eye-tracking use [86], which means that all hand movements are detected as input, rather than just the ones which are intended, causing unintentional input in a system. This basically cannot occur when using controllers due to the strong intent required to press a button.

Additionally, gesture usage can be less precise than controller usage, and this can be seen the easiest when navigating in menus. Menus are often navigated via ray-based interaction in VR, which works to a certain extent with standard controllers. However, it is very easy to accidentally move the hand and thus the interaction ray when performing a select action (often the pinch-gesture) with gestures. This issue does not manifest in the same way with controllers, as pressing a button can be done more easily with a stationary hand. Due to this issue, menus in VR that rely on hand gestures need to be made larger than traditional digital menus. Namely, the selectable areas need to be bigger so that the offset between the aimed location and the aimed location after the select gesture do not interfere with selection.

Furthermore, there is a chance for the *gorilla arm syndrome* [88], which refers to the unnatural position of our arms or hands when interacting with arms extended without any arm support that can cause discomfort and strain, often referred to as heaviness in arms. It is possible that hand-tracking use could reduce the unwanted gorilla arm syndrome by removing the controller weight. However, there is evidence to the contrary with mid-air gesture use [89], albeit clever gesture design can overcome the issue at least partially [90].

Gestures can be detected in multiple ways, but the most common ones are using cameras which detect either visible light or infrared, or by using a tracking glove of some kind. The tracking itself requires a tracking algorithm to understand the data that is captured by the sensors, and there exists a plethora of research related to designing robust hand-tracking algorithms, such as [91; 92].

Due to the hand-tracking mechanisms and algorithms being different from device to device, it is rather difficult to easily transfer gesture commands of one device to an application built for another. This issue is further exacerbated due to the lack of designated gesture libraries, e.g., what gesture to use for selection or teleporting.

Gestures can be classified into three main categories: *Temporal*, *Contextual*, and *Instruction-based*.

Temporal refers to the gestures being *static* [93] (hand stays still) or *dynamic* [94] (hand moves from one gesture state to another). Opting for static gestures is often more feasible, as dynamic gestures can be hindered by potential tracking issues and could cause unnecessary physical strain for the user, in addition to being difficult to perform for users with low hand dexterity levels. [95]

Contextual distinctions in gestures are classified into *communicative* and *manipulative* types [96].

Communicative gestures include:

- *semaphoric*, which articulate a standalone language, such as application-specific rules unrelated to any real-world languages [97; 98],
- *pantomimic*, which reflect actual concepts [96; 99],
- *iconic*, which denote existing concepts, for instance, the shape, location, or function of an object [100; 101],
- *metaphoric*, relating to abstract ideas [100],
- *symbolic*, universally recognized gestures within a society, like the thumbs-up indicating positivity in many Western cultures [96; 99],
- *modalising symbolic or speech linked*, which accompany speech, such as gesturing broadly to imply someone's size while asking about them [96; 99; 102; 103],
- *deictic*, pointing gestures [97; 99; 101],
- *gesticulation*, minor gestures that enhance speech [101; 102; 104],
- *adaptors*, involuntary gestures that relieve physical tension, like head shaking [105], and
- *Butterworth's*, indicating a momentary lapse in thought or struggle to recall a word, though the frequency of these gestures may be misrepresented [106; 94; 107].

Manipulative gestures are employed to alter the spatial properties of objects, such as changing their position or orientation [97]. These gestures may also serve communicative functions in different contexts. For instance, Article III describes a scenario where the thumb-up gesture, typically a positive signal in English-speaking cultures, is instead used to adjust speed within the application's language, thereby classifying it as both semaphoric and manipulative.

Instruction-based gestures consist of *prescribed* and *freeform* gestures. Prescribed gestures are part of a defined gesture language or library and cannot be altered by the user. They are designed to initiate a specific action without ambiguity or room for interpretation. Conversely, freeform gestures are composed of a series of smaller movements combined to form a more complex action that is subsequently recognized as a specific function. Examples of these could include drawing a shape in the air, which then leads to the creation of an object resembling the drawn shape. Alternatively, an object might be moved in space by tracing a path with one's finger. These gestures are not preset and rely on the user's discretion and creativity. [95].

Furthermore, gestures can be *unimanual* (single-handed) or *bimanual* (dual-handed). There can be many potential reasons for why a certain gesture should

be performed with just one hand or why it requires both of them. When seeking maximum immersion, gestures often try to mimic the real world actions that performing them in a VR system relates to, which means that actions which are in the real world performed with two hands require two hands also in VR. Nevertheless, this is not always possible or advised.

Bimanual gestures are useful when the required actions are very precise and mistakes could cause serious issues, such as remote medical operations using VR. Unimanuality and easier action initiation is useful for situations where multi-tasking is necessary and user errors cannot cause any real harm. Also when needing to switch between different actions rapidly it is better to utilize unimanuality in most cases. Studies related to unimanual and bimanual gestures include the work of Schäfer et al. [108], who compared the use of both one-handed and two-handed user interfaces in a teleportation-based locomotion system. Their study found that unimanual gestures were preferred due to ease of activation while bimanuality felt more reliable to those who preferred it, although the general consensus was that there was no preference. In conclusion, bimanual and unimanual gestures are useful depending on the context, and neither is necessarily better than the other.

### 2.3.2 Eye-tracking

Eye-tracking is widely recognized as a key objective measurement of usability in research, particularly when subjective measures may be misleading. In VR, eye-tracking proves especially effective by allowing simultaneous tracking of head and eye movements. This capability has been extensively utilized in virtual learning environments, establishing its value in VR usability studies [109; 110].

Eye movements typically measured by eye-tracking technology include *fixations*, where the eyes pause to focus on a particular area, and *saccades*, which are quick eye movements between points of interest. Together, fixations and saccades contribute to our overall perception and understanding, forming what are known as *scan paths*—sequences of eye movements indicative of shifts in attention and cognitive processes [111]. Furthermore, *the eye-mind hypothesis* [112] suggests that the visual information the eyes focus on is precisely what the brain processes.

In VR, eye-tracking has been explored as a method for controlling locomotion, including techniques like wink-based and gaze-based teleportation, or combining eye-tracking with electroencephalography (EEG) for gesture-initiated teleportation. However, continuous use of eye movements for control is limited by the Midas Touch problem meaning the unintentional actions triggered by natural eye movements, and the potential for visual fatigue from repeated intentional movements. Moreover, eye-tracking has shown promise in redirected walking strategies in VR, allowing users to move physically in a virtual space that appears larger than the actual physical space, with eye-tracking aiding in predicting user movement intentions with significant

accuracy. [63; 113; 114; 115; 116; 117]

Additionally, research into *eye dominance* highlights the variations in individuals' ability to use one eye over another, affecting the feasibility of eye-dependent technologies. Eye (or ocular) dominance describes the phenomenon where one eye performs better than the other in certain visual tasks. This difference is typically evaluated in three main categories: *acuity* (sharpness), *binocular rivalry* (which eye sees more often), and *sighting* or *eyedness* (eye use preference). Among these, sighting is the most frequently used method to assess eye dominance [118; 119; 120; 121]. Typically, the dominant eye, which is relied upon more, is harder or even impossible to close quickly or properly by itself, whereas the other eye closes easily. [122; 123; 118; 119; 120; 121].

Eye dominance can be either strong or weak, and in extreme cases it can render one eye almost or fully unusable if its signal processing capabilities are extremely weak. With a significant portion of the population (99 %) exhibiting a dominant right or left eye (of some degree), any eye-based technology must accommodate the inability of some users to close one of their eyes on its own [119; 124; 125].

### 2.3.3 Face-tracking

Some VR headsets, such as the Meta Quest Pro [45] are able to utilize face-tracking via a camera. The main use case at the time of writing for this is transferring user facial expressions into virtual avatars, affording more realistic interaction in a shared virtual environment. Another use case is lip-syncing of speech in the avatars. The mechanic has potential for other use cases as well, such as VR interaction, however the drawbacks for this include the difficulty of reading expressions correctly and the cost associated with that. [126; 127]

Generally speaking, a neural network is required to determine what expression a user is making. Even this can often backfire as there is so much variation among human faces that even the best AI is likely to have trouble parsing them, or at least such effort would require more power than the processors of most VR headsets and computers can provide at the moment. A recent example is a study by Zhang et al. [128] which showcases high recognition rate for emotions such as "neutral" or "happy", but highlights the inaccuracy of such models with the emotion "anger" only detected correctly around 25% of the time and being misclassified as "neutral" often. This issue would be further exacerbated with more complex emotions such as contempt versus disgust. Another issue is that "pulling faces" constantly could be rather demanding for the face muscles which are likely untrained for it among most people, in addition to the huge potential Midas Touch problem issues and the difficulty of filtering unintended facial expressions. This is why face-tracking is likely to remain a niche VR-mechanic used mainly to create more realistic avatar-based communication. [126; 127; 128]

### 2.3.4 Brain-computer interfaces

In this thesis, we have omitted all invasive sensors which require surgical interventions to install (such as electrocorticography), which could one day permanently connect our brain to a computer or a VR headset to generate input via thought only. Brain-computer interfaces (BCIs) can be classified into three groups based on the signals they measure, *Motor Imagery* (MI) [129], *Steady-State Visual-Evoked Potential* (SSVEP) [130], and *P300* [131]. MI analyses the sensorimotor electroencephalographic (EEG) patterns generated when a user imagines a specific movement, thus it can be used for a variety of tasks, although it requires a pre-analysis phase for the computer to learn user-specific patterns. SSVEP refers to the EEG response occurring when perceiving a visual stimulus flickering at a constant frequency, and it can be modulated based on where the user is fixating their attention. P300 is a positive waveform which occurs a short time (around 300ms) after a rare and relevant stimulus. [129; 131; 130; 132]

Examples of BCIs in VR use (and in general) are often related to a medical purpose among people with a disability, for example, in stroke rehabilitation using on-skin electrodes [133; 134]. Furthermore, virtual environments are seen as a cost-effective testing ground to BCIs before a real-world application. When it comes to the usability of BCIs in VR in comparison to more standardized input systems, there are major points of weakness. First, the mapping of the mental state of the user to a BCI should afford the user a lot of commands in the application, as there are many different aspects that need to be controlled in standard VR applications, such as movement, object interaction, menus etc. This is a challenge, as usually the BCIs are only capable to recognize a very limited amount of mental states, affording very few actions to the user, although the MI approach can overcome this with pre-training. Second, the mental state to command mapping should be intuitive and efficient, without straining the user too much when performed. This can also be difficult due to the low amount of mental states recognized, as well as the difficulty in achieving them consistently by the user. Additionally, there is still the rather large potential for misclassification of the user's intent. [132; 135]

There have been some attempts to utilize BCIs as a locomotion control in VR, such as self-paced exploration using MI where the user imagines taking steps etc. to move through a virtual environment with some success in laboratory environments, but to transfer this functionality to widespread usage will require some time still [136; 137].

### 2.3.5 Subconscious sensors and context-awareness

Subconscious reactions that happen in the human body can be useful when there is a need to measure the experience in non-verbal ways. This is especially useful when performance is not accurate enough of a measurement to determine usability. A

common example is heart rate which, while possible to be influenced in minor ways through, for example, breathing speed, is a general indicator for stress in humans (although not in all situations). Higher stress, achieved by activities such as exercise, will increase the pulse, while lower stress, for example, resting or sleeping, will decrease it. This effect has been studied multiple times, although often utilizing heart rate variability, which does not have a clear relationship with heart rate itself [138; 139; 140; 141]. There are also some indications that higher stress decreases performance, which means that keeping the stress (pulse) lower could lead to increased task performance [142; 143; 144].

Utilizing pulse as a mechanic, such as is done in the study of Article IV for movement speed, is a form of *context-awareness* in VR applications. The goal of context-awareness is to tailor each experience based on individual needs and restrictions using non-verbal cues to automatically detect the optimal settings for any given time. Furthermore, context-awareness is not limited to just users' traits but it can also encompass situational features of devices or even the environment. Examples include weather conditions and location, thus location-based applications are a prime example of utilizing context-awareness.

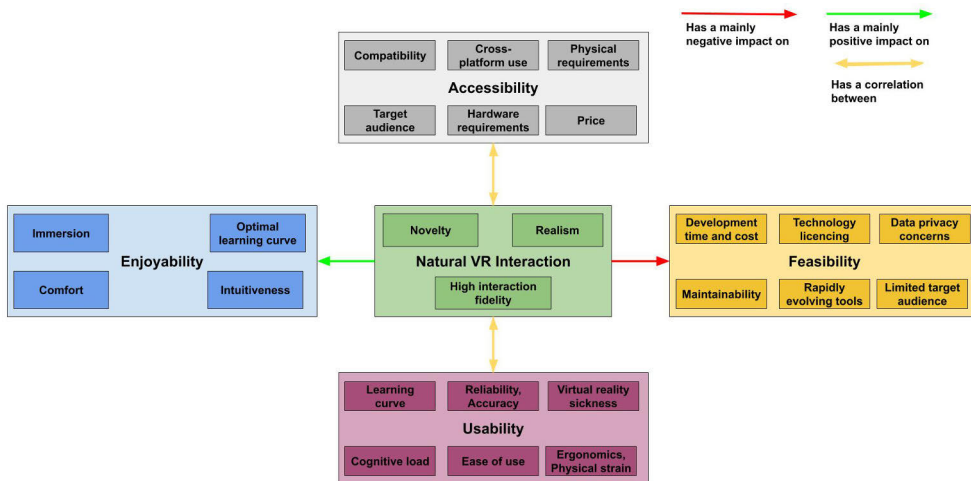
Other subconscious reactions than pulse have also been measured in VR applications, but their use as a mechanic is very low to nonexistent. An example for a slightly mechanic-based purpose is *ManySense VR*, a Unity-based [145] software which attempts to synchronize user's avatar with their actions via the help of eye and face tracking, electroencephalogram, pulse, respiration, and galvanic skin response [146]. These reactions are certainly interesting, but the main difficulty is that the research surrounding their interpretation is lacking, thus making the utilization of them as mechanics difficult.

Furthermore, there are some devices which are capable of measuring many of the signals simultaneously, such as *Galea* [147], which is a BCI integrated into a VR HMD (Varjo Aero or Varjo XR-3 [41]), that includes EEG (brain activity), PPG (pulse), EMG (muscle motor sensor), EDA (sweat sensor), and eye-tracking. These types of devices can be used, for example, for locomotion with face muscle movements or to detect the user's fatigue levels based on sweat output, offering a new world of interaction possibilities for VR.

## 2.4 Design challenges of virtual reality

There are various challenges when designing mechanics for VR, and more so when utilizing natural interaction. Figure 13 that was originally presented in Article V presents an overview of the primary concerns involved in the development or use of natural user interfaces. This can be thought of as an initial design framework for natural VR mechanics.

When looking at the design challenges of VR, the first obvious challenge is the



**Figure 13.** Graph showcasing various relationships that need to be taken into account when developing natural interaction for VR, originally presented in Article V. It is an initial design framework for natural VR mechanics.

cyber sickness. The main reason is related to our proprioception system, which refers to the sense of our limb positions and self-movement, determined by our muscles and joints. If there is a mismatch with how our body *feels* and our brain thinks we *should feel*, things start to go wrong. This is why cyber sickness is usually caused by artificial movement within VR that does not match up with how our brains anticipate our body to move simultaneously, resulting into nausea, dizziness, or even vomiting. The symptoms are seemingly largely dependent on the individual, and aspects such as prior proneness to motion sickness in vehicles or sea sickness could have a relationship with cyber sickness susceptibility. As a personal observation, motion sickness can occur in moving land vehicles when trying to focus one’s vision on something other than the road, such as reading, while experiencing movement in a sea vessel causes no sickness at all. This highlights that the reasons for why the sickness happens in some cases but not in others are rather a mystery. Furthermore, the onset of cyber sickness seems to be dependent on personal traits such as age, gender, and physical and emotional condition. In general, older users seem to suffer from higher levels of cyber sickness than younger ones, potentially due to the decreased ability to control their bodies. There exists some research showing that women can suffer from more extreme cyber-sickness than men, but not all studies found any differences. Additionally, poor body awareness can increase the onset of cyber sickness, and so can strong negative emotions, such as anxiety. [148; 72; 69]

Some design solutions for this challenge are avoiding moving the camera without initiation by the user, minimizing the input lag, and depth of field blurring or blacking out the user’s field of view when necessary, for example, during teleportation transi-

tions. Blacking out or reducing the user's view, usually from the peripheral vision areas, is called *vignette*, and using it can aid the brain to adjust, but it could also do the opposite [149; 150]. Additionally, it is possible to ease the confusion caused to the player's brain by visualising the movement in the air using "speed stripes", which the brain might understand as the environment being the one which is moving, not the user. [69]

Technical reasons for cyber sickness can include using VR with inadequate optimizing of 3D models that makes applications too heavy to load causing latency, insufficient hardware that is unable to render VR at high enough frequency (at least 90Hz), setup issues such as inter-pupillary distance measurement being set inadequately, display type, resolution, or the headset being too tight or not tight enough. Inter-pupillary distance refers to how far away from each other one's eyes are, and having this distance set wrong in the headset's lens can cause distortion issues quickly. [69]

However, these are not the only causes of cyber sickness, all causes are not necessarily even known, but there are indications that visual fidelity of the world can impact the onset of cyber sickness [151; 152; 153]. This is mostly seen as that if the world is very high resolution in graphical quality, it could result into more cyber sickness than a low-resolution world. The reason for this is likely that when the world looks more real, the brain anticipates that the mechanics in it must be more realistic as well. This then amplifies the feeling of sensory mismatch if the brain sees motion that is not felt by the body. Conversely, a very low-resolution world could make the brain "think" that the world is not real so the mechanics are allowed to be less realistic too. Although, the science around the topic is not unanimous, there clearly seems to be a link with movement visualizing ability and cyber sickness. This manifests with the visually induced experiences of self-motion in VR, referred to as vection [64; 65], causing cyber sickness when the user notices their movement more. This means that if the world has just plain colours as floors or walls, it is difficult to distinguish movement, and thus cyber sickness occurs less. However, if the environment is very detailed, it is easy to notice movement, and cyber sickness occurs more. Furthermore, changing the movement speed causes more cyber sickness than having a static speed [65]. However, it has been noted that the presence of vection is not necessary for the onset of cyber sickness [154]. [69]

In any scenario, the solution cannot simply be to create all VR environments as dull and low-resolution, forcing users' brains to lower their expectations for realism and reducing the visibility of movement to eliminate cyber sickness. Such an approach would significantly undermine the primary appeal of VR: immersion. The ideal VR world should feel like a real world, the user should forget that they are in an artificial space, but doing that causes cyber sickness for some users if anything other than physical movement is employed in the application. Thus, the only solution that is left, is the mechanics, namely the movement mechanic (locomotion) itself. In general, it is

thought that using teleportation as the sole movement mechanic will prevent most of cyber sickness from occurring, but this is not necessarily the case. The differences in the perceived location before and after the teleport can still confuse the brain and cause cyber sickness even though it might be milder. There are also different types of teleportation and the question whether the user's view should be darkened (using vignette) during the teleport or not and for how long duration. One of the motivations for this thesis was to see if natural interaction, where the user's body is more involved in the locomotion, could reduce the onset of cyber sickness. The evaluation of this is difficult, as not everyone is prone to cyber sickness, and it is somewhat difficult to predict who will be if the user is already not aware of it themselves. Secondly, many first time VR users will experience a degree of cyber sickness, but for some it goes away with experience, for others, like myself, it seemingly never goes completely away.

Another aspect is the physical and mental comfort: wearing a VR headset for a long time or sometimes even a short time can become very painful for the head, which takes away from the experience. This includes the strain felt on hands and arms when holding controllers. The comfort issues are also especially noticeable when trying to either type text or select elements in VR, which can be rather frustrating experiences with controllers, and not necessarily easy utilizing other interaction methods either. Apart from strain, the accuracy of ray interaction using controllers is also intermediate at best when compared to more standardized interaction methods, such as utilizing a computer mouse, due to the difficulty of holding a controller in the same place in the air for a long time or even momentarily in cases [6].

Strain can also be mental, which is often referred to as *cognitive load*. In simple terms, it means that something non-automatic happens in the mind, which causes the consumption of mental resources [155; 156]. Cognitive load can be extraneous (i.e., poor instructional design), germane (i.e., learners' problem-solving activities), combination of both, or intrinsic (related to the material only, such as interaction mechanisms) [157; 155]. Knowledge about cognitive load for a given system is important to ensure that system demands do not exceed the information processing capabilities of the user, which are subjectively limited [158; 159]. In other words, if a system is too difficult (subjectively) to utilize, a processing overload can happen, which contributes to decrements in the user performance. However, too simple systems would cause learner's working memory to be sub-challenged by a too low intrinsic load, resulting into no learning outcomes other than further schema automation [160]. For example, frustration caused by the inaccuracy of VR interaction mechanisms can be a cause for increased cognitive load.

Third aspect is the user boundary control which refers to the ability of the user to always walk or move around in the room space independent of potential virtual walls around or above them. This makes it challenging to try to simulate small spaces where the user would be crawling or crouched. In VR it is not feasible to force the

user to be in a certain physical position by the world design only. This is in contrast to standard applications or games where the user's camera will be locked to where the designer wants it to be. Due to this, another method is required. For example, if the user cannot be forced to crouch, then the game mechanics can be designed in such a way that progressing in the game is impossible without crouching. This is an indirect way of "forcing" the user to crouch.

This issue is further exacerbated by the height differences of the users: features such as obstacles in the virtual environment may be perfectly scaled for some users yet completely unreachable for others. The height difference can be just general height or the differences in the lengths of arms and legs which will impact a person's ability to reach, especially when utilizing climbing as a mechanic. Some solutions for this include building multiple versions of an application for people of different height or designing everything so that the shortest person will be able to complete it, which of course will make the experience worse for the taller people. Alternatively the user's height could be fixed which would result into the position of the "virtual legs" no longer matching the physical floor. However, this can lead to decreased immersion and potentially reduce the amount of viable mechanics that can be utilized.

Feasibility is another challenge, as the tools that are used for VR development evolve quickly, and specialized mechanics are only available using specific devices, which might become unsupported in the near future. For example, entire VR platforms can be disbanded, such as what will happen to the Windows Mixed Reality system in 2026 [51; 52], leaving the devices and potential device-dependent mechanics obsolete. This makes developing novel natural interaction mechanics for VR risky, as the specialized device cost increases development budget requirements, while the target audience for such devices is often limited and might suddenly decrease, leading to negative payoffs. Furthermore, certain mechanics, such as eye-tracking, often require licenses to get access to the raw data, which can prove costly and sometimes impossible. Without unobstructed access to the data some mechanics cannot even be created. It is also time-consuming to train developers to understand how these devices work, and same goes for instructing users. [161]

Another issue with feasibility relates to the data privacy concerns, which gathering physical data can cause. There are bureaucratic issues, such as the General Data Protection Regulation [162] in the EU, which might prevent collection of certain data for mechanics creation or at least make the process of obtaining such data more difficult. Additionally, there are ethical concerns with how this data is utilized if obtained, as some entities could use the highly personal access to human functions for extrinsic goals, such as targeted advertising or insurance cost determining. Utilizing certain data for research purposes could also discover underlying serious and less serious medical conditions in test users, which would be a violation of the users' privacy as well as lead to moral dilemmas about disclosing such information. [163; 164]

Accessibility is both a challenge and an advantage of natural VR interaction. The advantageous part is that certain natural interaction mechanics can help users who are unable to interact in standardized manner to part-take in VR. One potential example for this is the eye-openness based UI in Article IV. One challenge is that many of the natural interaction mechanics require certain physical capabilities, which then reduces the amount of users that can utilize them. Another factor that reduces accessibility is that devices which feature capabilities for natural interaction are often expensive, and thus inaccessible to many. The distribution of these devices might even be restricted to an extent. The devices might also require a powerful personal computer to run on, which is also costly. Furthermore, the mechanics are often linked to the devices they are created for, which makes sharing VR applications across different VR ecosystems difficult or impossible, which can make cross-platform online experiences challenging. [165; 166]

In relation to enjoyability, the main strength of natural VR interaction is increased immersion, which is achieved by making the UIs more intuitive and less visible to the user. Simulating real-world actions can also be made in a more realistic way, which further increases user engagement. Ideally, utilizing natural interactors such as one's own hands could also afford a better, potentially optimal, learning curve in comparison to artificial UIs. This is due to our inherent skills with such interactors, although in many cases this requires an adjusting period. It is also likely that a natural UI is more comfortable to use than more standardized UIs due to the lack of as many external devices, such as handheld controllers.

## 2.5 Methodology

The main idea was to create software artifacts with practical use case potential, and to test them in relevant contexts. The main formal methodology that was followed was *Design Science Research Methodology for Information Systems Research* (DSRM) by Peffers et al. [167]. The methodology is used for research which results in IT artifacts that are intended for solving identified organizational problems. The methodology consists of the following phases [167; 168; 169]:

- Identify a problem
- Define objectives
- Design and develop
- Demonstrate the artifact
- Evaluate performance
- Communication

The studies in the thesis followed the aforementioned structure, with some design iterations added based on initial user testing. Each created artifact was evaluated based on self-designed questionnaires, which utilized Likert-scales [170] to gauge the usability of the various natural interaction mechanics used in the artifacts. Standardized questionnaires such as the NASA Task Load Index (NASA TLX) [171], System Usability Scale (SUS) [172], and the Simulator Sickness Questionnaire (SSQ) [173] were considered but not deemed suitable for the studies. The reasons for the NASA TLX were that there was no need to assess the specific load caused by tasks such as avoiding an obstacle but rather the general controls, whereas SUS, while potentially applicable, looks at system usability in a rather holistic manner, which is a too broad view for the aims of this thesis. Although, there are some elements similar to the questions in SUS adapted into the self-created questionnaires. The reason to exclude the SSQ was that it is not in the scope of this thesis to thoroughly investigate what type of cyber sickness occurred but rather to see if it occurred at all or not and at what frequency. It is also potentially difficult for the test users to specifically identify the types of cyber sickness they encountered to make the SSQ useful enough. Additionally, the studies did not seek balanced samples where users prone to cyber sickness would be present in equal numbers to those who are less prone, making the comparison less reliable in any case. Furthermore, the level of interaction fidelity (see sections 1.6 and 2.2) in the mechanics was evaluated and its impact on the results contemplated.

For in-depth analysis, where deemed necessary, t-tests (or Student's t-tests) [174] were utilized for testing statistical significance in the data. When comparing test user groups, such as males and females, independent two-sample t-tests were utilized. Normal distribution of the data was tested with a Shapiro-Wilk test [175] using significance level of 0.05, and the assumption about equal variances was made using a Levene's test [176] with the same significance level. The t-tests were calculated using an alpha of 0.05 (95% significance level). In cases where the data was not normally distributed or the participant amount in a user category was too low, the means, standard deviations, and any potential qualitative data were utilized solely. In general, qualitative data such as observations were used to pinpoint the major findings in the created artifacts.

## 3 Practical Application

The following sections provide an in-depth explanation of the VR mechanics used in the articles comprising this thesis. The presentations are arranged chronologically, with more recent articles displaying some lessons about VR mechanics design that have been discovered in the earlier articles. All of the prototypes have been developed utilizing the Unity game engine [145], while the VR headset used differs from prototype to prototype.

### 3.1 Article I

The purpose of Article I was to assess the preference between game-like and realistic VR mechanics, while also addressing usability factors. Three mechanics were evaluated: swimming, crawling in combination with climbing, and discovering hidden objects within other virtual objects. The primary objective was to examine puzzle game mechanics in VR, featuring two types for each mechanic. The more realistic versions demanded greater physical engagement from users or involved employing the 360-degree camera view of VR for a more authentic hide-and-seek puzzle experience than conventional camera controls allowed. The game-like versions of the puzzles utilized more standardized button-pressing and hide-and-seek design based on standard camera controls. The test was conducted using the HTC Vive VR headset [32]. The article was published in *The Computer Games Journal* in January 2021.

Each of the puzzle types had their own objective measurements, which are described in the corresponding sections below. The subjective data was queried from the users via a questionnaire and it consisted mainly about questions related to immersion and usability differences between the two mechanic types in each of the three puzzles. Additionally, the study aimed to understand the links between a user's skill in a certain real-world skill and how that compares to skill in VR. In this article, comparisons were drawn between real-world swimming, diving, climbing, and general athleticness. Furthermore, the order in which the participants tested each mechanic and each version of a mechanic was taken into account by randomizing them and including the potential impact in the analysis of the results.

## Button pressing versus moving controllers

One simple example about realism in VR is whether to have the user to just press buttons on the controllers while the location of the controllers does not matter, or to require the user to complete certain motion that mimics the performed action via the controllers. This concept manifested mainly with the swimming mechanic.

In the realistic version, users were required to move their hands in a swimming-like motion while climbing in the water with lessened gravity, creating the sensation of water physics. In the game-like mechanic, swimming functioned via button pressing, and controller moving was not necessary. The game-like mechanic also featured the teleportation mechanic.

The main objective of the swimming (or diving) puzzle was to find a hidden path in low-lighting water environment by exploring and lighting up areas with lanterns found underwater while being careful not to run out of air.

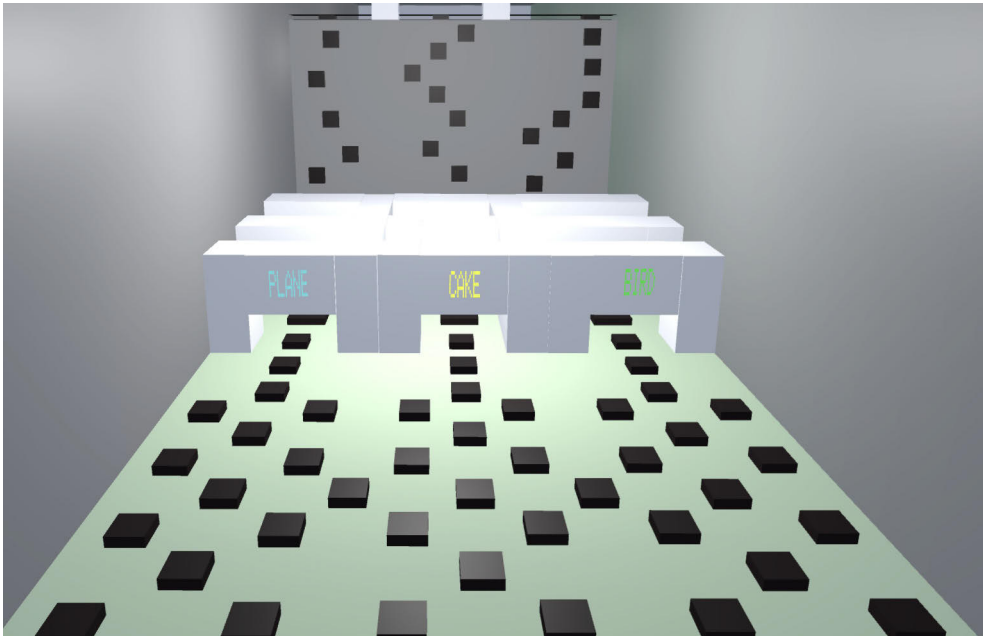
The main objective measurements in the study were the completion time and the amount of drownings. The only penalty from drowning was that it took longer to complete the puzzle, but the users were, in general, trying to avoid it. The metrics aim to assess both the usability and difficulty level of the puzzles.

## Attempting to force user pose

The second mechanic explored in the study presented in Article I was climbing and crawling. At the time VR had solutions for climbing already in different forms but crawling was, and still is, a difficult mechanic to create realistically. The main issue with crawling stems from the inability to force the user to stay in a crawling position as there is not much that the developer can do to make sure that the user is actually crawling. Furthermore, if the user should choose to stand up during a section where they are supposed to be crawling and end up inside a ceiling, there is no way to return them to their crawling position either.

The study's idea was to attempt to force the crawling by not allowing the user to move forward without being in the correct position. This was achieved with the realistic mechanic having climbable panels on the floor, with which the user needed to drag themselves forward, thus "crawling" potentially, see Figure 14 for reference. The game-like mechanic afforded standard joystick-based locomotion and required the user to physically crouch when going through low tunnel environments.

The mechanic for climbing was simply an ease in the holding while climbing, meaning in the realistic version the user needed to hold the grab-button while climbing on panels laid out on the side of walls, releasing the button with one hand when reaching for the next panel, similar to real climbing, affording falling down due to user error. For the game-like mechanic, the panel attaching functioned as a toggle, so holding the button down was not required, making the process significantly easier.



**Figure 14.** Showcase of the panels on the floor and walls which were used to simulate realistic crawling and climbing in the study presented in Article I.

The puzzle level consisted of three sections, each with three tunnels. The entrances of the tunnels were labeled with words. Passing through a tunnel entrance would lock the player to that tunnel path and play a sound corresponding to the path. The sound was required to be used as a hint for the next word selection in the next path choice. After completing the three choices correctly, the user would finish the puzzle. Choosing incorrectly teleported them back to the beginning. The first path did not have a hint preceding it; therefore, it was always correct. Thus, the total amount of possible paths was nine.

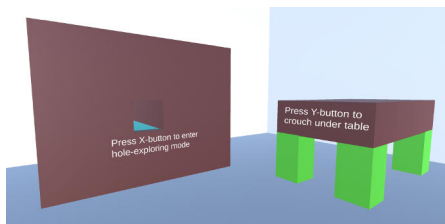
The objective metrics gathered from the puzzle were the completion time and the number of resets required by the user. Resets refers to the number of wrong path combinations the user attempted.

## Camera model benefits of VR for realistic puzzle design

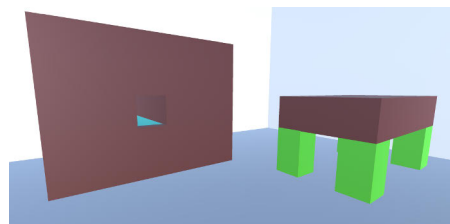
The third mechanic explored in the study of Article I was related to finding objects that are hidden inside other objects. This relates to the usage of the user-directed camera in VR (camera is or follows the headset), which is one of the most distinct differences between VR and standard digital applications. Namely, the player no longer plays as a character, but they rather are the character inside the virtual world. This means of course that additional considerations have to be included, such as player height

and posture, but it also allows the developers to spend less time with camera control design.

The benefits of the camera model apart from design ease include additional immersion and high level of interaction fidelity, but it also affords specific design paths to take place. The idea in the study was that unlike in standard applications with strictly planned camera control at all times, in VR the user can move the camera basically wherever their head fits, allowing the utilization of the full space of, for example, a room for hiding items. The idea stipulates that if one was to hide items in a standard digital puzzle game, then the implemented camera controls would reveal the possible hiding locations, thus giving hints about where the items are hidden just based on the knowledge that the camera was not able to see somewhere. As an example, see Figure 15, originally presented in Article V.



**(a)** In a non-VR application the user would be indicated whether it is possible to explore a hole in a wall or crouch under a table.



**(b)** In a VR application there is no need to give the user hints about possible camera movements due to the VR's inherent physical camera control.

**Figure 15.** Non-VR versus VR camera model example, originally presented in Article V.

The same does not work in VR due to the inherent camera control, which means that, for example, seeing a set of holes in a wall could mean that in any of them there might be something hidden, whereas in a standard game the player could consider their height and disregard some of them without exploration. This becomes even more pronounced when adding small "tunnels" inside holes that are in other objects, as tested in the study. This means that in VR it is possible to put one's head through a hole, then twist the head sideways and in an angle to locate a hidden item. The same action in a standard game would be indicated to the player to be either not possible or possible long before considering if an item is hidden there. Consequently, the implementation of a specific camera model will indicate that there is a reason for that camera model, meaning that at least *something* is hidden so that all of the camera model's features need to be utilized (at least in general, as otherwise features of camera model are implemented and thus development time is used without a purpose other than to confuse the player). Due to this difference, the VR camera model is very interesting, and hide and seek -type puzzles can feel more rewarding to both design

and take part in.

In the puzzle, the user was confined into a rather small space with walls on all four sides and a ceiling. The task was to find two key items hidden somewhere in the room. The space contained boxes and other shapes; some had holes in them. To aid the user, there were a few hints scattered around the space. A hint indicated the location of one of the key items. The user was able to move through the space using joystick-based locomotion, and the objects were climbable for maximum exploration possibilities.

In the game-like version, the key items were both visible on top of a surface, and there was no need to go inside objects to find them. The realistic version featured more advanced hiding locations, one of which required the user to enter a hole and twist their head inside it to find the hidden item.

The only objective measurement from this mechanic was the completion time, and whether the user gave up the search or not. Subjective measurements included the "surprise factor", which measured how surprised the users were when discovering one of the keys, and which hinted at the hideout difficulty level and the seeking enjoyment level.

## Main findings

The findings presented in the Article I show that the realistic mechanics were more enjoyable overall and especially to the users who had a lot of previous gaming experience, while the game-like versions appealed to the more casual gamer participants. Furthermore, the hardcore gamers enjoyed even the game-like versions more than the casual gamers. However, the impact of previous VR experience was rather mixed overall, which means that experience with a medium does not necessarily indicate mechanics preference. Additionally, there was a somewhat clear social desirability bias [177] toward familiarity with the testing supervisor, which seemingly increased enjoyability ratings. Furthermore, users provided indications of the Dunning-Kruger [178] effect, as they rated puzzles to be easier than their actual performance implied. The puzzle type testing order did not have impact on the enjoyment results but the version order of each mechanic did. The result showed that testing a version first was a lot more difficult, meaning worse performance, but also more enjoyable than testing the version as second. However, the enjoyability result was only replicated with the swimming and climbing and crawling puzzle types.

The main takeaway of the swimming puzzle is that button pressing can be easier to grasp for novice users, while with experience more realism can be preferred even though it would require more effort. Furthermore, the swimming puzzle indicated that real-life abilities similar to the mechanics in VR (swimming and diving) can impact the enjoyment levels. This was shown as increased enjoyment in the more realistic versions and decreased enjoyment in the game-like versions for users with

high perceived real-life skill. As a more general rule, there should always be a consideration whether button pressing is "adequate enough" form of interaction and if the task at hand requires more immersive controls or not. For games, immersion is often sought after, but in case of, for example, work applications it might reduce usability with little benefit. Furthermore, in relation to the climbing and crawling, the test served as an interesting look into forcing user position and pose in VR, showing that it is somewhat possible to utilize mechanics design to limit user movements without physical intervention. This type of mechanic would score high interaction fidelity, but it is worth questioning how enjoyable it is to mimic the physical world completely, considering comfort and strain especially. Additionally, often the user is willing to suspend their disbelief and will obey the instructions of the application without explicitly forcing their hand. However, unlike with swimming or diving, the perceived real-life climbing ability did not have a clear impact on the enjoyment levels. Although, the result should be taken cautiously as there were some issues with the puzzle design which manifested via over-representation of test users selecting a specific path out of the options. This was likely to do with the other paths not having a clear enough connection between the displayed words and the sounds that were played.

As for the seeking and finding puzzle, the main measurable aspect was the surprise factor which indicated how much the user anticipated to find one of the key items from a given location, thus describing the success level of the hideout design. The surprise factor was considerably higher for the more realistic puzzle hiding locations utilizing the VR camera model fully. Even though otherwise there were not many conceivable differences between the versions, the result suggests that the hideout design worked as intended for the most part.

## 3.2 Article II

After drawing comparisons between more and less realistic controller-based interaction in the study presented in Article I, there was a need to dig deeper into the possibilities of VR mechanics. Hand-tracking (see Section 2.3.1) using the Meta Quest 2 VR headset [44] had recently become available to the general public, which afforded us to expand our experiments outside of controller use. Additionally, the project Sustainable Shipbuilding Concepts [179] that the research team was part of became useful to the goals of the research, as recruiting test users from real companies helped to test natural interaction possibilities in a different setting than teaching or entertainment environment. Furthermore, the companies were able to supply us with test users already familiar with controller-based VR, which afforded the perfect opportunity to test how natural interaction with hands would compare in a real setting to controllers. The article was published in the Proceedings of the 55th Annual Hawaii International Conference on System Sciences in January 2022.

This scenario, comparing controller -and gesture-based interaction, was tested and presented in Article II with a prototype and a use case of 3D design review. The main idea was to compare an existing 3D design review program called CTRL Elements [180] to a custom made prototype utilizing hand-tracking and gestures. To maximize validity, the environments that the interfaces were tested in were as identical as possible and the mechanics functioned similarly design-wise despite their interactors obviously being different. The testing of the application was partially conducted using project partners who had interest in potentially utilizing 3D design review applications in VR for work purposes. The total amount of test users was 20, and the test users were divided into four categories based on their origins: university staff, students, VR developers, and company representatives.

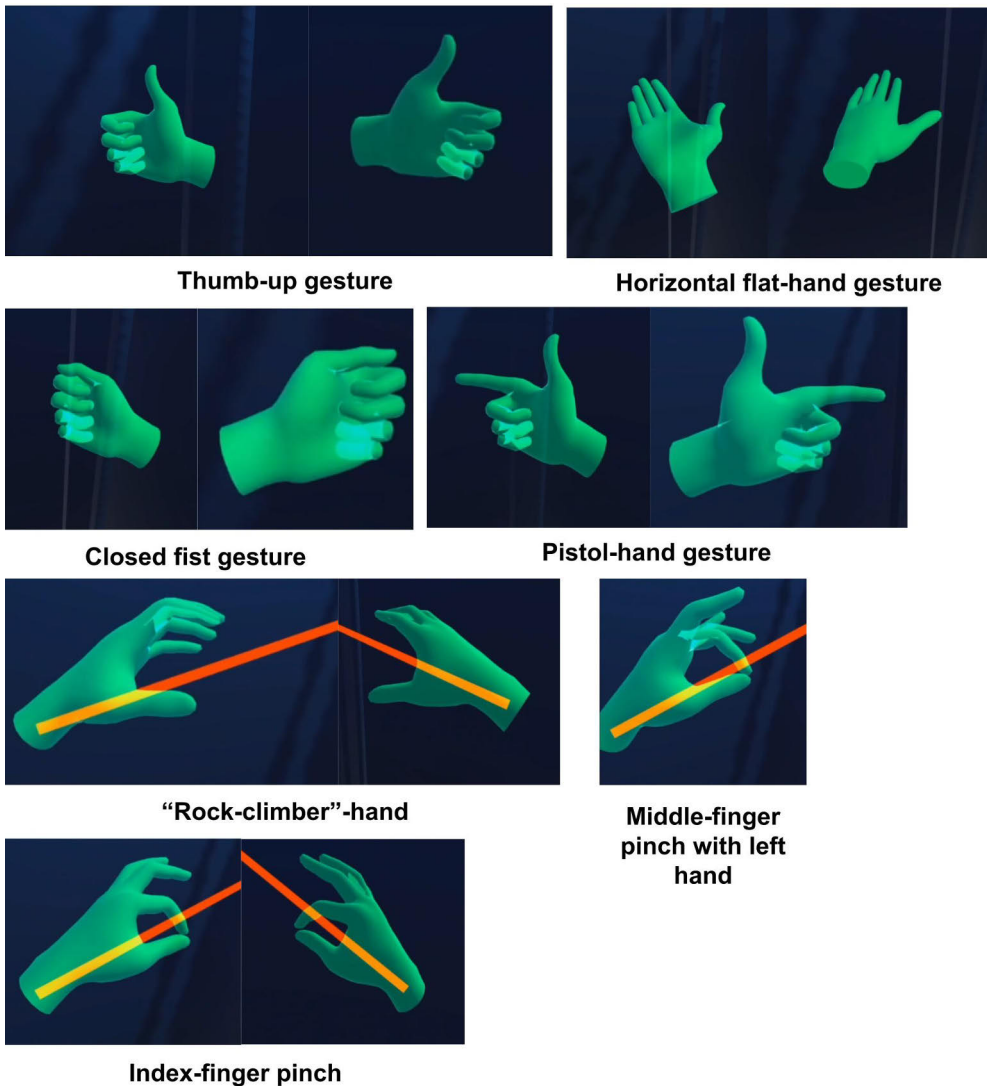
The main mechanics included the ability to utilize a menu that was positioned near the user's left wrist to spawn 3D models into the VR scene, in addition to near-omnidirectional movement controls (reversing was not possible) and teleportation. The menu was activated and utilized via the use of gestures and ray interaction. The menu afforded moving, rotating, and scaling the 3D models and they could also be deleted or selected from the scene. Test users also had the option to enable or disable artificial gravity. The utilized gestures can be seen in Figure 16.

The test structure was freeform, meaning the test users were allowed to test all of the mechanics in their own pace and finish when they felt ready. The testing supervisor was present to ascertain that all participants tested all of the mechanics. Due to the freeform nature, there were no objective measurements in this study, but rather the subjective ratings of usability, immersion, gesture use preference, cyber sickness and physical strain of the experience were utilized solely. There were some issues with the recognition of certain gestures and certain hand types. These issues were learned from and improved upon in Article III, which continues on gesture usage analysis.

## Main findings

In general, the gesture UI was rated to be less usable than the controllers, but it was perceived as more immersive. The main reasons for the lower usability ratings were that some gestures were experienced as unintuitive while there was also a lot of involuntary gesture activation happening. The main unintuitive gesture was the "pistol-hand", which was utilized for turning. It was seen as unintuitive, because the finger was pointing towards the opposite direction in relation to the turning itself. This was an important lesson in gesture design, which showed that gestures should be designed so that if they control a movement, then any pointing aspect of the gesture should be aligned with the movement as well.

The involuntary gesture activation was experienced by most users to some extent, which was to be expected, as the interface design was rather experimental and novel. However, there were some clear outliers among the gestures. The main one being



**Figure 16.** A showcase of the gesture design utilized in Article II.

the "thumb up" gesture, which was very difficult to distinguish from the "closed fist" gesture, especially for the left hand. The "thumb up" gesture was utilized for forward movement and using both thumbs would double the movement speed. This issue with the recognition caused instead the menu to become active and hinder the user's view when trying to double the movement speed. The main issue lies in the similarity between the two gestures. When viewed by the headset cameras from certain angles, the thumb-up can appear very closely like a closed fist. Furthermore, the right hand index finger pinch gesture was recognized incorrectly as the closed fist gesture at times, although the reason for it was that the gesture evaluation code

afforded recognizing a pinch type gesture simultaneously than other gestures, which is not very advisable design, and it was later rectified.

The main lesson to learn from the gesture design is that gestures should always be distinct enough from each other, as otherwise there will be involuntary overlap in the activation and thus the behaviour of the controls can feel unpredictable. Furthermore, gestures that were more natural and easier to form, such as closed fist, were preferred by the test users. Whereas, very seldom utilized gestures, such as a middle finger pinch, were disliked. This result emphasizes the need to at least bind the more commonly required functionality to familiar gestures and leave the novel less familiar gestures for edge case scenarios or enable them only for more experienced gesture users.

The test was also attempting to evaluate whether there would be any differences in cyber sickness and strain based on the interaction mechanism. Due to the short duration of the test and that the test users did not experience clear amounts of cyber sickness or strain during the test, it is difficult to draw any conclusions about the interactor's impact on those metrics.

In general, the user familiarity with an interaction mechanism, such as controllers, also plays a large role on the enjoyability and usability ratings of such medium. This is why controllers, which are familiar interactors for most users, usually come on top when compared with something completely novel such as hand gestures. Otherwise, it was identified that it is difficult to design gestures when there are no widely accepted gesture libraries defining what gesture should be forward movement or what gesture should be teleport etc. For controllers there is a lot more prior knowledge on what button usually does what and thus the design of those controls is easier. Aside from hand ergonomics differences, which are difficult to determine, gesture usage at least lacks the possibility for haptic feedback, which controllers possess. Furthermore, controllers have a rather limited amount of buttons in them whereas there is technically an infinite amount of different gestures and gesture combinations that could be utilized, although prior noted limitations apply.

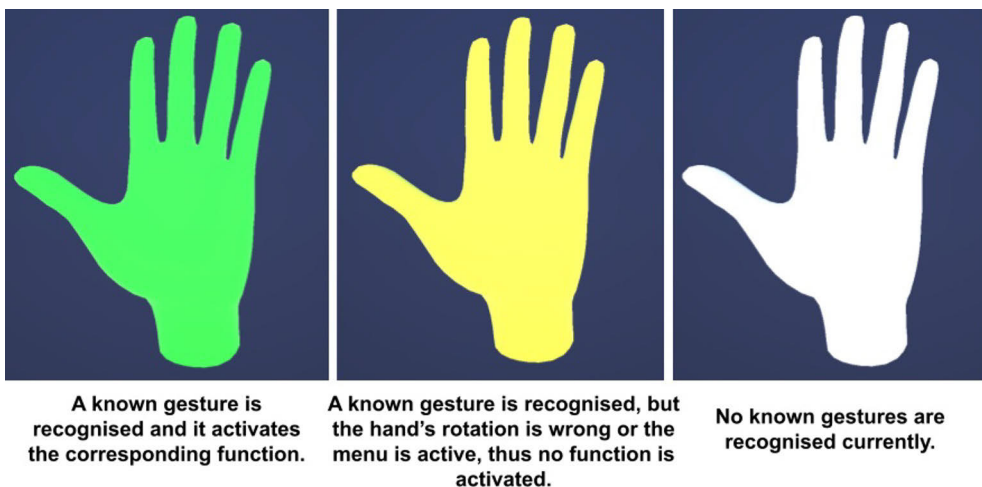
### 3.3 Article III

After the initial gesture UI design presented in Article II, we moved on to refine and redesign gesture use based on what was learned during the Article II. This was necessary, as there were some identified areas of improvement in the design of the prior interface based on the user testing. The idea was to improve the existing gesture UI, and to expand the study by creating two competing UIs for one-handed (unimanual) and two-handed (bimanual) use. The development and testing continued with the Meta Quest 2 VR headset [44]. The article was published in the *Multimodal Technologies and Interaction* journal in January 2024.

The main idea with the unimanual UI is that if only one hand is necessary to

activate an action, then it is simpler and more rapid to initiate actions and thus achieve the desired functionality. It is also possible to activate two different actions with either hand, such as moving forward and up simultaneously. This approach is thought to cause a rather high amount of involuntary gesture activation in addition to having a large potential for the Midas Touch problem occurring, see Section 2.3.1. The bimanual UI focuses on reliability at the cost of action speed, which should lead to reduced Midas Touch problem occurrence. It also does not afford multitasking unlike the unimanual interface because both hands are required to initiate an action.

The test was structured into 13 tasks that introduced each of the mechanics one by one, and tested with 25 test users. Furthermore, the communication about the gesture recognition state to the user was enhanced via the addition of a color code system, see Figure 17. This system shows unrecognized hand states as white, whereas recognized and active states are green. Yellow states are utilized in case the hand is in a position that would activate a gesture action, but either the angle is incorrect or something in the system prevents the action from activating, such as the menu being currently open. The usability of the various gesture mechanics was evaluated based on user feedback and performance. The system also features extensive logging of the test data, calculating the amounts for gesture initiations, gesture deactivations, and user actions, in addition to durations for how long a given gesture was active, and completion times. These metrics were all calculated on a task-by-task basis and in total. The test users were also divided into groups based on personal differences such as previous experience in VR, gender, and age group. The users were randomly allocated to test either the unimanual or bimanual UI first, which was done to account for the order effect.



**Figure 17.** Gesture recognition color scheme in Article III.

The 13 tasks involved setting up the VR headset, learning how to move forward,

up, down, backwards and turn using the gesture mechanics, in addition to teleportation, bringing up and closing a menu, and learning how to use the menu via ray interaction. The menu was utilized to spawn 3D models into the test scene and change their coordinates in position, orientation and scale. Additionally, it was possible to take control over the models and move and rotate them in real-time using gesture controls. Completing the tasks took around 30 minutes to one and a half hours depending on the test user skill and the main goal was to ascertain that every user understood what they were doing instead of just trying to brute force through the tasks.

The gestures were rather well explored at this point, although there was no definitive best design by any means. However, our future interests involved moving towards studies with even less common forms of interaction, which was made possible by the ever-evolving VR hardware landscape. This work started in the study presented in Article IV via leaving out hands as interactors altogether.

## Main findings

The main result was that the unimanual UI was largely preferred by users. This was due to that, even though the bimanual UI was deemed more reliable, the unimanual interface afforded faster actions and easier activation. It also seemed that it was more difficult to learn to utilize the bimanual UI than the unimanual one, but this issue might rectify itself with prolonged use. It also seemed that the longer and more complicated tasks 10 to 12 that were related to controlling 3D models via gestures were a lot slower with the bimanual UI. This is likely related to the difficulty of activating many actions and swapping between them. The quickest and likely easiest was Task 4, which was about moving downwards.

Furthermore, it seemed that the feature of the unimanual interface to afford multiple actions simultaneously was severely underutilized. One reason for this could be that none of the tasks specifically required two actions to be combined despite it being possible. So it is difficult to draw conclusions of the usefulness of multitasking in gesture UIs based on this article alone. In addition, there was a preference for right-hand usage in the unimanual UI, which could indicate that dominant hand is preferred in single-hand gestures, as the sample was mainly right-handed.

Another factor that had impact on the version preference was the testing order. This means that testing a version first reduced the preference of that version, likely due to the unfamiliarity with gesture controls making the tasks more difficult. Whereas the version that was tested second was already more familiar because of the first tested interface and thus it felt easier and more comfortable to utilize.

The study helped to understand a lot about gesture design because many gestures were difficult to explain to the test users in written form and even via a video displaying the gesture inside the application. The reason for this was that the gestures do not have well-known names in our society, so the names were needed to be made up, and

especially translating them in both Finnish and English was very challenging. Due to this, it would be important to always visualize the gesture in front of the user, because just describing it or seeing it in 2D screen is clearly not enough to convey how the gesture actually is formed. Furthermore, the study supported the finding from article 2 that middle finger pinching is a lot less intuitive and easy than index finger pinching. So that probably should be utilized in gesture UIs.

In terms of movement mechanics, while this version included backwards movement via a gesture command, unlike article II, it was severely underutilized. One reason for this could be that moving backwards just is not something that humans naturally do that much in the real world when exploring areas. The mechanic was also only required in one of the tasks, which likely impacted its utilization rate. This showcases that when the interaction mechanism is rather realistic, then the mechanics that it embodies should also be to avoid further sensory conflicts. Although, in this study, the only outcome was that one mechanic was barely utilized. In other studies or use cases it could lead to more noticeable usability consequences.

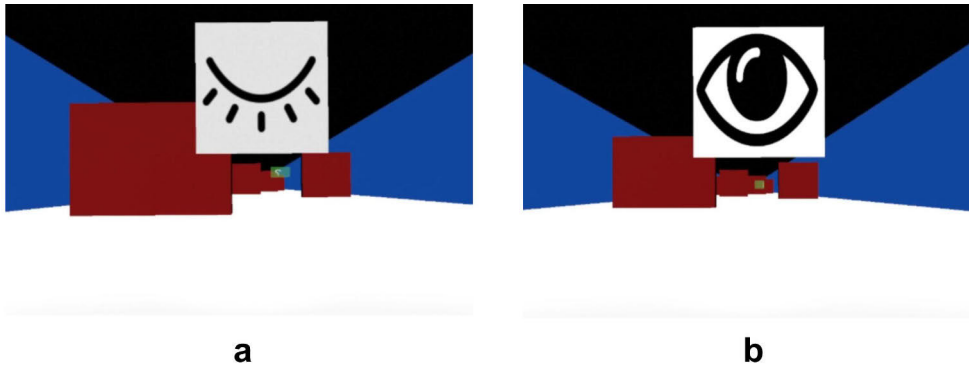
The study also attempted to evaluate whether utilizing gestures could reduce the potential cyber sickness that is caused by artificial locomotion. But as four users out of 25 became so nauseous that they had to quit the test with one user even vomiting during it, it is safe to say that gesture usage at least does not completely remove the possibility of cyber sickness occurring.

### 3.4 Article IV

In this article, the idea was to study a lot less conventional VR mechanics than in the previous articles. The main mechanic was eye-tracking (see Section 2.3.2), but instead of tracking where a user is looking, which is the most common way to utilize it, the idea was to test whether just measuring eyes being open or closed could be used as a means to control VR locomotion. Additionally, the concept of context-awareness (see Section 2.3.5) became relevant, which means that the applications could adapt to the users based on their subconscious biological traits and signals. A main use case for this would be to increase or decrease control mechanic complexity based on determining how well the user is understanding the mechanics they are using. The mechanic chosen to accompany eye-openness tracking was heart rate. The main idea was that increased heart rate would indicate increased stress levels and thus potentially mean that the user requires easier time with the mechanics whereas a lower pulse would mean that the user is ready for new challenges. The device utilized in the study was the HP Reverb G2 Omnicept Edition [50]. The article is currently under review.

The study consisted of an obstacle course, which the user needed to complete four times with changing control mechanics. The idea in the first two mechanics was that the user would control the movement direction with a sideways strafe based on the eye-openness, whereas the movement speed would be determined based on the pulse

compared to the individual baseline of that user which was measured previously. This functioned so that having one eye closed would strafe the user to either left or right based on the currently active mechanic. The currently active mechanic was indicated to the test users when the mechanic was changed via eye imagery, see Figure 18. The other two mechanics utilized the more conventional head turning to determine the movement direction while eye-openness was utilized to either double or halve the speed of movement, which was done by holding either eye closed.

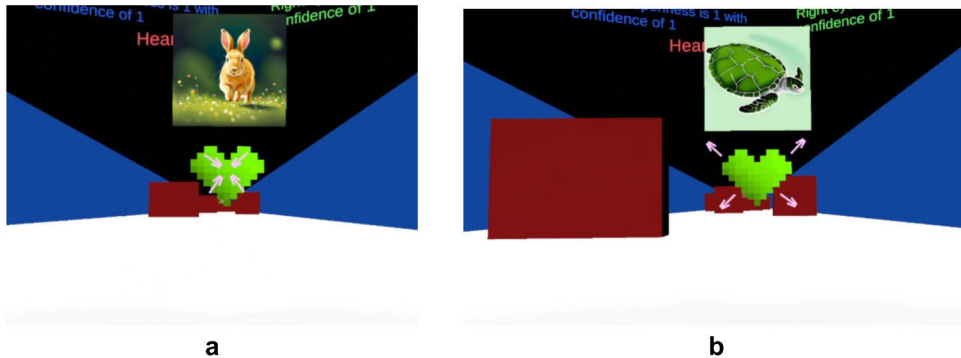


**Figure 18.** The eye-based strafing mechanic was indicated to the test users with the above images in Article IV. The closed eye (a) means that strafing happens towards the eye that is currently closed, if the other is open, and vice versa for (b).

The individual heart rate baseline was measured with a practice obstacle course, which contained some static wall obstacles that the user needed to dodge using their eye-openness, while the pulse did not impact the speed yet. The main obstacle course contained similar wall obstacles and some of them were moving as well, in addition to narrow paths with the possibility to fall down to see the level of control the users had over the mechanics. It was also evaluating whether the change in graphical fidelity, lighting or other visual elements impact the stress levels and thus the pulse. In practice this functioned so that at first the course did not contain any textures, but the obstacles and the floor and walls were just plain solid colors and then later on all those aspects were given textures which made it easier for the user to visualize their movement speed. The underlying premise was that providing users with clearer visibility of their perceived movement would, under typical VR usage, increase the likelihood of experiencing cyber sickness (refer to Sections 1.4 and 2.4). Consequently, it became relevant to investigate whether the implementation of eye-based and pulse-related movement mechanics could mitigate or prevent the occurrence of such symptoms.

Additionally, the course utilized moving obstacles, darkness, transparent floors, and artificial falling in order to increase the stress levels in users and this way increase the heart rate as well to see how the correlation between the movement speed and heart rate would impact the experience. The heart rate changes were indicated to the user with imagery, as seen in Figure 19. The color of the heart depicted the intensity

of the change in pulse in beats per minute (bpm) since last measurement, while either inwards or outwards facing arrows showed the direction of the change. The movement speed change was communicated via a picture of a rabbit (speed increases) or a tortoise (speed decreases).



**Figure 19.** The speed changing was indicated to the test users via a picture of a rabbit for speed increases (a) or a tortoise for speed decreases (b) in Article IV. Additionally, the change in the user's heart rate was shown as an image of a heart with arrows facing in for decreasing rate (a) or outwards for increasing rate (b). The color of the heart indicated the scale of the change in bpm (green < 5, yellow 5-10, red > 10).

Another important topic to consider is eye dominance (see Section 2.3.2), which impacts the mechanics design greatly. Strong eye dominance is usually characterized by the inability to close the dominant eye on its own, or at least closing it is a lot more difficult than closing the other eye. Due to this, it was not enough to build a mechanic that afforded moving left or right with a specific eye, as some users would then only be able to move to one direction, not both, rendering the system useless to them. This is why a mechanic to switch the active eye controlling was developed which could be activated using a wink of certain length with either eye. This way even the users with high or strong eye dominance could strafe left and right via just using one of their eyes. As an additional bonus, the mechanic would now also function for users who only possess one eye.

All in all, the idea with the mechanic was to test both the context-awareness, that is the heart rate could be utilized to tone down or increase the movement speed based on how the user is currently feeling, and to see whether eye-openness would be deemed usable enough mechanic for VR locomotion. While the mechanics have obvious implications among physically disabled users, for example, affording paralyzed people who cannot move their head at all but still retain functionality in their eyes to use them, the main idea is to test whether these kind of mechanics could be used by everyone. They offer potential temporary substitutes for hand-based interaction, which could then afford resting one's hands during the day, which could prevent many issues such as repetitive stress injuries caused by hand movement.

The objective measurements included the completion time of the obstacle courses and each part of them separately, eye blink amount, blink speed, blink frequency based on obstacle course part, pulse changes and the speed of the pulse change. Additionally, whether the test users were able to collect some or all of the three collectibles in each course, and whether their collecting improved in subsequent obstacle courses was noted. Subjective measurements included obstacle course part preference, eye usage preference, immersion, cyber sickness, and usability of the mechanics. Furthermore, users were asked to evaluate whether the pulse-based movement speed impacted their experience.

## Main findings

The results showed promise for eye-openness-based locomotion as test users got rather accustomed to using it. The main caveat was the eye-mechanic switching designed for strong eye dominance, which activated frequently accidentally. In any case, while the eye-based strafing was learned somewhat well and it was not hated by the users, the more conventional head-turning-based movement directing was still greatly favored in the test results. Furthermore, utilizing eye-openness for movement speed adjusting could be potentially useful, but in the test it was mainly preferred as a speed halving mechanic rather than speed doubling. This was due to the movement speed in general being deemed too low, which caused most test users to hold one eye closed almost all the time when it doubled the speed, and very rarely when it halved the speed. The preference was explained by realizing that holding one eye closed for extended periods (constant throttling) leads to user discomfort, while occasional eye closures (seldom braking) do not. The result indicates that eye-openness might be more usable when used in moderation.

For the heart rate based context-awareness though, it was firstly difficult to evoke changes in the heart rate for the users and secondly even more difficult to make the users notice these changes despite the provided visual feedback. Furthermore, inquiring about the usefulness of the pulse-based mechanics, most of the test users did not feel that they added much value to the experiment. The pulse measuring was further hampered with the inaccuracy of the tracker and the fact that it sometimes lost the tracking completely.

## 3.5 Article V

The final article was written as a book chapter and its main idea was to apply the results of the articles I-IV and condense them into a more approachable form for the wider audience. Additionally, it included a literature review discussing the previous research in the field in comparison to the findings presented in the articles. The potential future of natural interaction was also discussed there by comparing what

has been achieved now to concepts such as accessibility, cost, and social standards of interaction.

In general, the chapter encompasses the previous findings of articles I-IV and makes a conclusion about what the main benefits and disadvantages of utilizing natural VR interaction are or could be. The result is an initial design framework for natural VR mechanics. The framework considers the advantages, such as increased usability, immersion, feasibility, and enjoyability, against the disadvantages, which are decreases in these aspects. The major parts of the framework are presented earlier in Section 2.4 and the framework can be seen there in Figure 13.

### 3.6 Summary

Overall the different mechanics utilized gave a lot of information about the use of natural interfaces in VR. The main results and topics of each of the articles in this thesis are summarized in the Table 1.

Article	Topic	Main result
I	Realistic versus game-like controller mechanics	Realism was more enjoyable for users experienced in gaming while game-likeness is better for the less experienced.
II	Gestures versus controllers	Gestures were less usable but more immersive. Gesture design is challenging and subjective.
III	One- and two-handed gestures	One-handed gestures were preferred, likely due to ease and speed of forming. Two-handed gestures are slower but cause less errors.
IV	Eye-openness, pulse, and context-awareness	Usability of eye-openness seems promising, while eye dominance impacts a lot. Pulse changes are difficult to detect by users, so context-awareness using them is hard to assess.
V	Framework for natural interaction design in VR	Natural interaction design has to account for enjoyability, feasibility, usability, and accessibility. Natural interaction usually increases enjoyability at the cost of feasibility, with impact on usability and accessibility.

**Table 1.** Main results of the articles summarized.

## 4 Results and Analysis

In this chapter, we will revisit the original research questions and examine the findings about them based on the conducted studies. The detailed results for each study can be accessed at the end of the dissertation.

### 4.1 RQ1: How to design usable and immersive natural user interfaces in virtual reality?

One common theme in all studies included in this dissertation is that the design should be user-centric. This means taking into account a user's personal qualities to create the best natural UI for them. According to results presented in Article I, a user's previous experience with an activity simulated in VR can affect its learnability and enjoyment level. Mechanics should be designed differently for users with varying levels of experience in VR or specific control mechanics. The key point is that a one-size-fits-all approach does not apply. This approach is, however, difficult to implement due to users being inadequate at estimating their own skill levels before taking a test or often inadequately so afterward as well. To put in other words, the Dunning-Kruger effect [178] applies also here: users often believe their skills are higher than in reality.

Results of Article II support the hypothesis that prior familiarity with control mechanics significantly impacts the usability. This is why mechanics that are unfamiliar, such as hand-tracking and gesture UIs, can be challenging to learn at first. However, there are signs that, given sufficient time and sophisticated design, they could become usable enough. This is further emphasized by gestures being rated as more immersive than controllers, acting as a source of increased enjoyment for basically every user that tested them. An important design lesson learned from the study related to gestures is that the easiest gestures to form should correspond to the most frequently used actions, while less commonly used gestures can be more complex to prevent accidental activation. Another lesson is that it is important that gestures are distinct enough from one another to avoid excessive overlap. This approach maximizes their usability by avoiding unintended activations and command mismatches.

In articles II and III, the aforementioned one-size-does-not-fit-all became more apparent. Individuals possess varying hand sizes and shapes, as well as differing abilities to twist their fingers. Consequently, creating a single gesture UI without

any variations is not an optimal solution for everyone. The best option would be to organize extensive user testing and designate a set of gestures that work effectively for most people. Then, provide users with the ability to assign specific gestures for various inputs. An alternative method would be to allow users to record their own gestures upon initiating use of an application. However, the caveat for this approach is the time required, and users would need to memorize the gestures they have set up. This issue is raised in Article III concerning the naming of gestures for effective understanding by users during the learning process. Notably, many of the gestures exhibit a challenge in terms of being named sensibly. When teaching gestures, those that are not already widely used in society can be rather challenging to name intuitively. For instance, the gesture "flat hand with fingers facing forward" comes across as somewhat obscure. To resolve this, the gesture image or 3D representation ought to be presented to the user concurrently with its name, as different users may interpret various gestures from the same description. Additionally, the long description length can also make them hard to comprehend.

It is also important that the mechanics, such as gestures, fit into the culture of the target audience. This means that designing, for example, a gesture UI with gestures that are deemed offensive in a culture might make members of that culture resent learning the UI or be unwilling to utilize some parts of it. Additional consideration should be given to the ease of activating mechanics based on the target user's goals. These goals may include simplicity (or speed), allowing for the most actions in a given time frame with the capability to perform multiple actions simultaneously, or reliability, ensuring no mistakes or errors in command interpretation. This was experimented within the study presented in Article III when comparing gesture usage between one-handed (unimanual) and two-handed (bimanual) systems. The results showed that unimanual gestures afford *simplicity* in terms of action activation, resulting into more rapid functionality. However, they are more prone to user errors and the Midas Touch problem. Additionally, when the gesture controls function with just one hand, the other hand can rest during actions or perform another function, affording multi-tasking. An example of multi-tasking would be using the left hand to move forward while simultaneously moving up with the right hand. The bimanual gestures were shown to afford *control* over the interaction at a higher degree than unimanual gestures do. The main advantage is easier avoidance of the Midas Touch problem due to actions only activating when both hands are in a specified pose. Naturally, this causes the activation of actions to be slower and more cumbersome and there is no option for multi-tasking or resting the other hand while performing actions with the other. Furthermore, users can have differences in the dexterity levels between their hands and in some cases one of the hands can be unable to function at all. The results suggest that unimanuality might be preferred at least initially, meaning when tested before the bimanual system, by users due to its simplicity. However, bimanuality shows promise after prolonged use of hand-tracking, meaning when

tested after testing the unimanual system. The result highlights the importance of version order comparisons in testing natural interfaces.

Article IV continued to utilize user-centric design, even though the interaction mechanics were significantly altered from the previous designs to utilize eye-tracking and pulse. It demonstrated that eye usage varies among individuals, primarily because of eye dominance, a factor that should be considered when creating eye-based UIs. The study demonstrated that catering to all users, including those with specific needs, such as strong eye dominance, resulted in a preferred interface for the users with specific needs. Consequently, these added features hindered users who did not need them. The solution for the problem would be to allow users to choose from the settings which option they prefer, although it is difficult to make this decision prior to testing, as novel mechanics are always unfamiliar to users. Additionally, people have many innate features that they are not aware of.

A design feature that could enhance the usability and immersion of users is context-awareness. Instead of creating an application based solely on known or estimated user traits before use, the application would also analyze how the user interacts with the content within it. This adjustment would be made using some form of biological signal believed to be related to some important trait such as stress. Article IV employed heart rate monitoring as a method for assessing the user's proficiency with the control mechanisms. The main finding was that users find it challenging to assess the effectiveness of context-awareness as these signals are intended to go mainly unnoticed by the user. The main advantage would be that their experience is modified before they become aware that such adjustments are necessary. This makes it challenging to determine if context-aware mechanics enhance or reduce usability or if they were merely poorly designed, with regards to the optimal ranges of mechanics that they regulate being initially sub-optimal. The example provided in Article IV demonstrated the adaptation of movement speed, which was influenced by the user's heart rate. It is challenging to determine if the adjusting range for movement speed was sub-optimal (or it likely was sub-optimal for some users and optimal for others) or if users failed to recognize the correlation between their pulse and the enhanced or diminished experience resulting from the modification. Thus, it is rather impossible to determine the effectiveness of context-awareness based on Article IV alone.

However, what is clear is that any natural mechanics are not optimal for all users simultaneously, indicating that context-awareness could be beneficial. This is particularly relevant to cyber sickness, which unfortunately drastically affects users who are susceptible to it. It could be that certain natural interaction mechanisms are less susceptible to cyber sickness than others, but there is a lot of research required to determine which ones they are or what is the order of susceptibility. Therefore, it is essential to investigate potential solutions for it, and mechanics design is a promising area to explore. The eye-openness and pulse-based locomotion system in Article IV did not appear to cause major cyber sickness, so it is a good starting point, but in all

of the studies presented in this dissertation the major limitation is that the sample size was rather small, which makes it difficult to draw generalized conclusions. However, while solutions to design problems require a lot of users and many different testing scenarios, finding the issues is not as difficult even with smaller studies. This is why it is vital to test even unlikely usable mechanics, as they could give out hints on to the wider issues of natural VR interaction.

Then there is also the topic of strain. Using a mechanic that requires more body parts will, in most cases, be more strenuous than a mechanic that requires fewer body parts. Using hardware that weighs something to control aspects of an application can often cause strain during prolonged use compared to not having to do so. An easy comparison is gestures and controllers, as was done in Article II, with the assumption that controller weight is a negative in most cases. Then again, having a physical handheld object that requires distinct actions to activate commands can provide reliability, which some users prefer even at the cost of more strain. Furthermore, the strain can also be mental, as in cognitive load, which was explored mainly in Article IV. Even though measuring cognitive load is difficult, as it is highly subjective, and the study did not provide clear answers about whether it increased or decreased based on the mechanics used, it is important to understand that doing anything that requires the brain to process something non-automatically will use mental resources and thus affect a system's usability. The main solutions to minimizing cognitive load are clear and concise tutorials that allow users to test the mechanics in a controlled environment before the actual test, as well as trying to design the systems robustly enough so that there are no excessive learning curves.

Article V offers a combination of the aforementioned conclusions and sheds light on how technology will continue to shape and influence VR interaction design paradigms. Furthermore, it helped to identify other means of interaction not explored in this dissertation, such as brain-computer interfaces, which could aid in the design challenges faces by the technology. The resulting initial design framework for natural interface design for VR was constructed with the help of the results obtained in this dissertation, and it will hopefully prove beneficial for further research.

## 4.2 RQ2: What kind of added value can natural interfaces provide in virtual reality?

The main added value from natural interfaces is increased immersion and that is often the first starting point for why these mechanics are researched. This is showcased by the mechanics in the study presented in Article I, which attempted to simulate real-life activities in VR, namely swimming, climbing and crawling, which are somewhat difficult to accurately replicate. Similarly the gesture use in Article II and Article III is intended to increase immersion as having controllers, which is the standard approach, will remind the users that they are in fact in an artificial world, but having

the freedom to use their hands makes it easier to suspend their disbelief and fully immerse themselves in the virtual world.

Another benefit is accessibility, as not everyone is able to use standard controllers for interaction. That is why exploring other means of interaction using different body parts will make VR interaction possible for more people. The focus of the studied mechanics was not on accessibility, yet it is clear that they have implications for physically disabled users. Namely, the eye-based mechanics in Article IV afford hands-free interaction with partial possibility of not having to move one's head, which would be suitable for even most paralyzed people.

Furthermore, as mentioned in Section 4.1, natural interfaces have the potential to alleviate strain experienced by hands or arms. The default way of reduction is related to reducing the weight that body parts need to handle by removing controllers and also by transferring some of the strain from one body part to another, such as utilizing eye-tracking and hand-tracking in combination. The main issue with this is that some body parts are more prone to strain than others, requiring users to adjust before realizing potential benefits.

Another point is the cyber sickness, which could potentially be alleviated by having a stronger connection between one's body movements and the movement that occurs in VR. It is unclear whether natural UIs reduce cyber sickness or not. However, users in the studies did not seem to experience that natural interfaces would accelerate the onset of cyber sickness, at least, but they did suffer from it in some cases. Furthermore, in Article IV, where artificial movement was controlled by eye-openness and pulse, there were no major occurrences of cyber sickness. However, we must remember that the sample size was rather small. Still, this dissertation gives hope that mechanics could play a crucial role in reducing or eliminating cyber sickness in the future.

Finally, it is possible that natural interfaces could even improve the general usability in VR applications, due to their potential learnability. Furthermore, this could be a major advantage gained from the use of even more sophisticated interaction methods such as brain-computer interfaces, as mentioned in Article V.

### 4.3 RQ3: What type of virtual reality applications do natural interfaces suit the best?

This dissertation explores natural interface use in both work and entertainment application design, although the tested applications were not utilized in real working conditions for a very long time, nor were they published for the wider audience. This limits the conclusions that can be drawn from their suitability to application types.

What was learned is that the target audience for work applications, as in companies, are in general potentially more resistant to changes in their work habits than the target audience in the entertainment sector. This was mainly discovered during the project

work related to Article II, when VR was introduced to companies in the shipbuilding industry as a new visualisation tool. This proved bureaucratic and slow, and the employees using the new devices were required to be trained extensively to utilize the technology, and explained why they should. Additionally, employee motivation to test new ideas is not necessarily always there, as this increases their workload in comparison to just staying with the old system and learned ways. Their motivation is also to earn a living, which is always a priority compared to personal interest, which leads to users that are not that enthusiastic about a technology being used as test subjects. This obviously has an impact on subjective questionnaire results. Furthermore, for the company there is a risk in cost of the technology and staff training, which means that the new addition should be able to be proven prior receiving much interest from the company leadership. Another issue is the network setup, which is often highly restricted in company environments which handle trade secrets. This leads to the need for connecting to private secure networks, which adds to development time when utilizing VR in multi-user environments and communication purposes, which was the idea in the Sustainable Shipbuilding Concepts -project utilizing the CTRL Elements software. These issues hinder the ability of VR and especially more experimental VR mechanics such as natural interfaces to be adopted by companies, as often the benefits cannot be proven beforehand, and will even in best case scenarios take a long time to manifest.

Furthermore, the testing conducted in the study presented in Article II gave valuable insight into the reception of a natural interaction mechanic (hand-tracking) from different user types. The developers appreciated and disliked different features than the novice users or company representatives, highlighting again the subjective needs of users.

For the entertainment sector, the users that are enthusiastic about VR and natural mechanics have in most cases likely purchased the devices already out of personal interest and need no persuasion to test them. This means that novel VR mechanics are likely to be better received for those audiences, as there is no requirement to prove their usefulness beforehand. The market sentiment is not directly tested in the dissertation, but Article I evaluates the experience of a VR puzzle game and the authors have experience in VR game development and the game market. To obtain more data on natural mechanic reception, the applications developed in the dissertation would have to be publicly distributed, but the assumption is that entertainment-sector target audience contains users which accept lesser usability in favor of increased immersion. This is also what the testing of the applications used in the Articles I-IV has pointed towards.

Overall, these factors mean that VR applications catering for the work sector need to be a lot more refined and targeted and often they need to communicate with the target audience directly in order to have the functionality that is required, for information security already. Another factor is the sometimes difficult hierarchy

structures in companies which make it so that adopting new technology can take a long time and also, the users of it can be often less experienced with VR than when catering for the entertainment sector.

In general, for work applications, usability is key and immersion comes second, while for entertainment applications, it can even be the other way around. There is also the fact that it is rather costly for companies to adopt new working techniques and buy new hardware for VR. This means that if an application or a mechanic is to be introduced into a company, then it really needs to work near flawlessly as otherwise it will be rejected very quickly. This is why very experimental natural interface might not necessarily be the best suited for work applications or at least there needs to be options to utilize the more common interaction methods as well.

Furthermore, there is the aspect of reliability in tracking mechanisms, which makes it so that applications that require extreme precision might be better off utilizing non-natural interfaces, at least until the tracking accuracy of natural interfaces becomes sufficient. For example, similar to Article IV, it might be interesting to utilize pulse as a mechanic for adjusting movement speed in some entertainment applications, but due to its reliability errors, such as sometimes randomly losing tracking for several seconds, it would not be the best idea to utilize it for, for example, remote surgeries in VR.

## 4.4 Limitations

The major limitation of all of the studies presented in this dissertation was the rather modest sample size of around 20-25 test users per study. This limitation is difficult to avoid due to time constraints and the inability to offer monetary compensation to test users, meaning relying on the volunteers. Furthermore, there was a bias on the test user background as convenience sampling was mainly utilized, meaning the test users were often from the Finnish society and a majority of them were in some way affiliated with the University of Turku or one of the researchers. Additionally, the hardware that were used in the studies occasionally did not function perfectly and also had some accuracy limitations which reduced the reliability of their data. This was mitigated by careful logging of the events that happened during the user testing by utilizing video, sound, and view recording of the test users in addition to in-application logs.

There are also some identified reliability issues in test user reported results in general, such as cognitive biases, including Dunning-Kruger effect [178], demand characteristics [181], and social desirability bias [177]. These issues decrease the reliability of the self-reported data, which is why any conclusions are drawn only with the support of objective measurements and observations.

## 5 Conclusion

In this thesis we reviewed several natural interaction mechanisms in VR. The mechanics included controller usage, comparing controllers to gestures, designing gesture user interfaces in general and for unimanual and bimanual use, and experimenting with eye-tracking and eye-openness in addition to context-awareness utilizing heart rate. The mechanics are analyzed through the lens of interaction fidelity of virtual interactions.

The results highlighted many unique design challenges in these mechanics and offered potential solutions while acknowledging the limitations. Namely the main result is centered around the idea that natural VR mechanics need to be designed with different user types in mind, creating variations for users that lack abilities or have different goals with the application. It is also possible that natural mechanics could reduce cyber sickness, but there were no clear confirmations related to this in the studies. It is also difficult to evaluate the usefulness of a new mechanic due to familiarity bias with the pre-existing commonly used mechanics, and lack of comparisons with similar mechanics already used elsewhere. Furthermore, the accessibility of the novel mechanics due to cost, physical requirements, or distribution chain priorities leaves still a lot to be desired.

After all is said and done, we can see that the problem of usable natural VR interfaces is anything but simple. Not only it is rather difficult and expensive to acquire hardware that is capable of tracking some natural human phenomena, but due to the low user base of these devices and the fact that most potential test users are completely inexperienced in utilizing these mechanics, it is extremely difficult to evaluate whether these user interfaces could be usable or more usable than any of the alternatives. This is further exacerbated by the fact that there are few other design solutions to compare with when utilizing the most unfamiliar mechanics. When we take into account the highly user-centric requirements the problem becomes extremely challenging.

Considering these design and other challenges, we can see that adding realism into VR experiences is truly a paradox: enhancements in one area of the user experience usually cause deterioration in another, either objectively or at least subjectively. And when taking into account that the incentives to develop these systems have a rather warped nature due to potential target audience limitations, technology costs and accessibility, in addition to high potential for future obsolescence, the paradox is

complete.

What can be said though is that gesture usage, at least in a limited format, seems to be here to stay for VR interaction. Especially gestures and hand-tracking might suit entertainment applications aiming for maximized immersion, whereas for professional use cases they could be too unreliable. An example of this is seen with the Varjo company giving up hand-tracking in their latest 2023 headsets, which are aimed at enterprise customers. Similarly eye-tracking, at least when used to operate menus, seems to be a promising use case when looking at the latest hardware, such as the Apple Vision Pro. Whether these two mechanics will be robust enough on their own remains to be seen, with the future hopes being projected towards the use of brain-computer interfaces, which would afford a much more customizable and at least physically less strenuous way of interaction.

In the future my hopes include to be able to research brain-computer interfaces and to see whether they would offer solutions for the many design challenges of VR interaction. Undoubtedly they will come with a set of challenges of their own and the hardware development might take several years still to become more available to even researchers. Although, considering the rapid speed of development in the recent years, right now is a very exciting time to research the many possibilities of VR.

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