BRNO UNIVERSITY OF TECHNOLOGY
VYSOKÉ UČENÍ TECHNICKÉ V BRNĚ

FACULTY OF INFORMATION TECHNOLOGY
FAKULTA INFORMAČNÍCH TECHNOLOGIÍ

DEPARTMENT OF COMPUTER GRAPHICS AND MULTIMEDIA
ÚSTAV POČÍTAČOVÉ GRAFIKY A MULTIMÉDIÍ

EVALUATING THE IMPACT OF ENVIRONMENTAL LEVEL OF DETAIL IN VIRTUAL REALITY IN THE CONTEXT OF USER REACTIONS

VYHODNOCENÍ VLIVU ÚROVNĚ DETAILU PROSTŘEDÍ VIRTUÁLNÍ REALITY NA REAKCE UŽIVATELŮ

BACHELOR'S THESIS
BAKALÁŘSKÁ PRÁCE

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BRNO 2026

BRNO UNIVERSITY OF TECHNOLOGY FACULTY OF INFORMATION TECHNOLOGY

Bachelor's Thesis Assignment

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Programme:	Information Technology	
Title:	**Evaluating the impact of environmental level of detail in virtual reality in the context of user reactions**	
Category:	Computer Graphics	
Academic year:	2025/26	

Assignment:

1. Familiarize yourself with the topic of creating 3D models and scenes for applications in virtual reality.
2. Analyze various optimizations of 3D models for devices with no performance-heavy graphics card, i.e. Adreno 740.
3. Design and implement a scenario in at least 3 levels of detail using the Unity framework for Oculus Quest 2/3.
4. Evaluate the implemented scenarios in an adequate user study using collected biosignals in the real operation of a virtual reality headset.
5. Create a concise poster presenting the thesis, its goals and results.

Literature:

- Slater, M. (2018), Immersion and the illusion of presence in virtual reality. Br J Psychol, 109: 431-433. https://doi.org/10.1111/bjop.12305.
- Weech S, Kenny S and Barnett-Cowan M (2019) Presence and Cybersickness in Virtual Reality Are Negatively Related: A Review. *Front. Psychol.* 10:158. doi: 10.3389/fpsyg.2019.00158.
- Yanfang Luo, Seungjun Ahn, Ali Abbas, JoonOh Seo, Seung Hyun Cha, Jung In Kim (2023), Investigating the impact of scenario and interaction fidelity on training experience when designing immersive virtual reality-based construction safety training. Developments in the Built Environment, Volume 16. ISSN 2666-1659. https://doi.org/10.1016/j.dibe.2023.100223.
- Další literární prameny související s Level of Detail s virtální realitou

Requirements for the semestral defence:

- Assignment points 1-3

Detailed formal requirements can be found at https://www.fit.vut.cz/study/theses/

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Beginning of work:	1.11.2025
Submission deadline:	13.5.2026
Approval date:	7.11.2025

Abstract

This thesis investigates the effect of environmental level of detail (LOD) on subjective presence, cybersickness, and physiological response in virtual reality. Three virtual park environments (Abstract, Low-poly, and Realistic), sharing an identical spatial layout, were designed around a biofeedback fountain, whose jet height was modulated in real time by the participant's heart rate variability. A within-subjects user study with 24 participants evaluated user reactions during periods of free exploration and a structured paced breathing exercise. Results indicate a significant but non-linear effect of LOD on subjective presence. Spatial presence and perceived realism decreased significantly when transitioning from the Realistic to either stylised condition, while the Low-poly and Abstract scenes were largely indistinguishable. Involvement showed a non-monotonic pattern, suggesting that radically abstract environments can elicit curiosity-driven engagement that partially offsets reduced visual fidelity. No significant effect of LOD was observed on cybersickness or mean heart rate, confirming that the biofeedback mechanism remains robust across substantial variations in visual style. These findings suggest that while transitioning from realistic to stylised rendering carries a perceptual cost, further detail reductions within the stylised range leave most dimensions of user reaction largely unchanged.

Abstrakt

Tato práce zkoumá vliv úrovně detailu prostředí (LOD) na subjektivní pocit přítomnosti, kybernetickou nevolnost a fyziologickou odezvu ve virtuální realitě. Byly navrženy a vyhodnoceny tři scény virtuálního parku (abstraktní, low-poly a realistická) se shodným prostorovým uspořádáním, obsahující fontánu s biologickou zpětnou vazbou řízenou v reálném čase variabilitou srdeční frekvence účastníka. Ve vnitrosubjektové studii s 24 účastníky byly sledovány reakce uživatelů během volného průzkumu a strukturovaného dechového cvičení. Výsledky naznačují signifikantní, avšak nelineární vliv úrovně detailu na subjektivní pocit přítomnosti. Prostorová přítomnost a vnímaný realismus významně poklesly při přechodu z realistické do stylizovaných podmínek, zatímco low-poly a abstraktní scéna se od sebe výrazně nelišily. Míra vtažení vykazovala nemonotónní průběh, což naznačuje, že i abstraktní prostředí mohou díky své neobvyklosti vzbudit zvědavost a kompenzovat tak nižší kvalitu zobrazení. U kybernetické nevolnosti ani srdeční frekvence nebyl zjištěn žádný signifikantní vliv LOD, což potvrzuje, že mechanismus biologické zpětné vazby je odolný vůči změnám vizuálního stylu. Tato zjištění ukazují, že ačkoliv má přechod od realistického ke stylizovanému zobrazení znatelný dopad na uživatelské vnímání, další snižování detailů v rámci stylizovaného spektra již sledované aspekty uživatelské zkušenosti významně neovlivňuje.

Keywords

virtual reality, level of detail, presence, cybersickness, biofeedback, heart rate, Meta Quest, IPQ, VRSQ, within-subjects design, Project Ekhi

Klíčová slova

virtuální realita, úroveň detailu, pocit přítomnosti, kybernetická nevolnost, biologická zpětná vazba, srdeční frekvence, Meta Quest, IPQ, VRSQ, vnitrosubjektový design, projekt Ekhi

Reference

CHROMÝ, Ondřej Jakub. *Evaluating the impact of environmental level of detail in virtual reality in the context of user reactions.* Brno, 2026. Bachelor's thesis. Brno University of Technology, Faculty of Information Technology. Supervisor Ing. Tomáš Švec,

Rozšířený abstrakt

Jednou z klíčových výzev při vývoji aplikací pro virtuální realitu je otázka, jaká úroveň detailu virtuálního prostředí je dostatečná k dosažení přesvědčivého uživatelského prožitku. Obecně se předpokládá, že vyšší úroveň detailu zlepšuje pocit přítomnosti, zároveň však výrazně zvyšuje náklady na vývoj, tvorbu assetů a požadavky na hardware. Pro nasazení na standalone VR headsety využívané v klinickém nebo výzkumném kontextu je proto prakticky relevantní otázka, kde začínají platit klesající výnosy z investice do úrovně detailu.

Tato práce zkoumá, zda nižší úroveň detailu virtuálního prostředí může být dostačující k navození smysluplného pocitu přítomnosti ve virtuální realitě, a snaží se identifikovat bod, od nějž začínají redukce úrovně detailu prostředí způsobovat měřitelný pokles kvality uživatelského prožitku. Práce se zaměřuje na tři dimenze výsledků: subjektivní pocit přítomnosti, kybernetickou nevolnost a fyziologickou odezvu měřenou prostřednictvím tepové frekvence. Studie je součástí projektu Ekhi, rámce vyvinutého ve spolupráci mezi Fakultou informačních technologií Vysokého učení technického v Brně a Psychiatrickou klinikou Fakultní nemocnice Brno.

Za účelem experimentálního hodnocení byly implementovány tři virtuální prostředí v Unity: Abstraktní scéna složená z primitivních geometrických tvarů, Low-poly scéna využívající stylizované nízko-polygonální assety a Realistická scéna s detailními, naturalistickými assety. Všechny tři scény sdílejí identické prostorové uspořádání – park s fontánou řízenou biologickou odezvou, jejíž výška vodního paprsku je modulována v reálném čase na základě variability srdeční frekvence účastníka. Napříč scénami byly záměrně zachovány konstantní proměnné: rozmístění objektů, směr osvětlení, přítomnost stínů i zvukový design.

Uživatelská studie byla navržena jako vnitrosubjektová studie s latinským čtvercem jako schématem vyvažování pořadí. Zúčastnilo se jí čtyřiadvacet účastníků, každá scéna trvala přesně pět minut. Subjektivní míra přítomnosti byla měřena pomocí Igroup Presence Questionnaire (IPQ), kybernetická nevolnost pomocí Virtual Reality Sickness Questionnaire (VRSQ) a fyziologická odezva pomocí hrudního snímače Garmin HRM-Dual přes Bluetooth Low Energy.

Statistická analýza neprokázala žádný významný vliv úrovně detailu na skóre VRSQ ani na průměrnou tepovou frekvenci, všechna tři prostředí byla dobře snášena a mechanismus biologické odezvy fungoval konzistentně napříč podmínkami. U subjektivní přítomnosti výsledky odhalily statisticky významný, avšak nelineární vliv. Realistická scéna dosahovala konzistentně nejvyšších skóre na všech subškálách IPQ. Prostorová přítomnost a zažitý realismus se statisticky lišily mezi Realistickou a oběma stylizovanými podmínkami, zatímco Nízko-polygonální a Abstraktní scény se vzájemně nelišily. Obecná přítomnost poklesla významně pouze při extrémním kontrastu Realistická–Abstraktní. Nízko-polygonální scéna si udržela úroveň statisticky srovnatelnou s oběma krajními podmínkami.

Celkově výsledky naznačují nelineární vztah mezi úrovní detailu prostředí a pocitem přítomnosti: přechod od realistického k jakémukoli stylizovanému vykreslování s sebou nese měřitelný perceptuální náklad, avšak další redukce detailu nad rámec jasně nerealistického prahu již nepřináší proporcionálně horší uživatelský prožitek. Kybernetická nevolnost a průměrná tepová frekvence byly robustní vůči úrovni detailu. Mezi limitace patří vzorek s převahou mladých mužů, vypnutý anti-aliasing jako potenciální matoucí proměnná a omezená zobecnitelnost výsledků na jiné typy prostředí.

Evaluating the impact of environmental level of detail in virtual reality in the context of user reactions

Declaration

I hereby declare that I have prepared this bachelor's thesis independently under the supervision of Ing. Tomáš Švec. Additional information was provided to me by Mgr. Martin Páleník and Ing. MichalMatýšek. I have listed all literary references, publications, and other sources from which I have drawn. For the linguistic revision of the technical report and assistance in developing utility scripts, the Claude AI tool (model Claude Sonnet 4.6, Anthropic) was used.

. . . . . .
Ondřej Jakub Chromý
May 12, 2026

Acknowledgements

I would like to thank my supervisor Ing. Tomáš Švec for his guidance and valuable feedback throughout the development of this thesis. I would also like to express my gratitude to Mgr. Martin Páleník and Ing. Michal Matýšek for their assistance and insights regarding the integration with Project Ekhi.

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Chapter 1

Introduction

One of the central challenges in developing virtual reality applications is determining what level of environmental detail is sufficient to achieve a meaningful user experience. Higher visual fidelity is generally assumed to improve immersion and presence, yet it also increases development cost, asset creation time, and hardware demands considerably. For resource-constrained deployments – such as standalone VR headsets used in clinical or research settings – understanding where diminishing returns begin is therefore a practically relevant question.

This thesis investigates whether a lower level of environmental detail can be sufficient to induce a meaningful sense of presence in virtual reality, and seeks to identify the point at which reductions in visual fidelity begin to produce a perceptible decline in user experience. The work addresses three outcome dimensions: subjective presence (Section 2.5), cybersickness (Section 2.6), and physiological response measured via heart rate.

The study is conducted as part of **Project Ekhi**, a collaborative research and development framework between the Faculty of Information Technology, Brno University of Technology, and the University Hospital Brno, Department of Psychiatry. Project Ekhi provides the technical infrastructure for running virtual reality sessions with real-time biosignal monitoring, which forms the foundation of the user study in this thesis. An overview of the framework is provided in Section 3.1.

Three virtual park environments (hereafter referred to as scenes, following Unity terminology) were designed and implemented in the Unity game engine, each representing a distinct level of visual fidelity: an **Abstract** scene composed of primitive geometric shapes, a **Low-poly** scene using stylised low-polygon assets, and a **Realistic** scene using detailed, naturalistic assets. The design philosophy and rationale for these levels are described in Chapter 4. All three environments share an identical spatial layout and are built around a biofeedback fountain whose jet height is modulated in real time by the participant's heart rate variability – a design requirement driven by their intended secondary use as therapeutic environments within Project Ekhi.

The three scenes were evaluated in a within-subjects user study with 24 participants using the Meta Quest 2 head-mounted display. Presence was assessed with the Igroup Presence Questionnaire (IPQ), cybersickness with the Virtual Reality Sickness Questionnaire (VRSQ), and physiological response via mean heart rate recorded using the Garmin HRM-Dual chest strap. The full study methodology is described in Chapter 6.

Chapter 2

Theoretical Background

In order to draw meaningful conclusions from the user study, it is essential to first establish a clear conceptual and theoretical foundation. This chapter defines the key terms and concepts that are essential for understanding the scope and methodology of this thesis.

2.1 Virtual reality

Virtual reality (VR) is a technology that enables users to experience and interact with computer-generated environments through multisensory stimulation. Immersive VR is commonly delivered through head-mounted displays – wearable devices positioned in front of the eyes and integrated with motion tracking [14]. Standalone VR headsets represent a self-contained variant of such devices, combining displays, sensors, and onboard computing into a single unit.

2.2 Biofeedback

Biofeedback is a self-regulation technique in which individuals learn to voluntarily influence physiological processes that are not ordinarily under conscious control. Using specialised sensors, physiological signals are converted into real-time visual or auditory cues, enabling the individual to observe and modulate their own physiology. Heart rate variability is among the signals commonly monitored in this way, particularly when the goal is to reduce sympathetic arousal and promote a relaxation response [5].

2.3 Level of detail

In this thesis, the term *level of detail* (LOD) refers specifically to the overall richness and completeness of the virtual environment. This should not be confused with the concept of dynamic level of detail, which concerns the adaptive simplification of individual 3D objects based on factors such as distance or computational constraints.

2.4 Immersion

Immersion describes the objective technical capabilities of a VR system – such as display fidelity, tracking latency, field of view, and stereoscopy – that provide a convincing and

continuous sensory environment, enabling partial disconnection from the physical world [12]. In modern virtual reality, the primary factor contributing to technological immersion is the manner in which visual information is delivered [14].

2.5 Presence

Presence is the subjective psychological experience of "being there" in the virtual environment – the user's sense of actually residing in the virtual space rather than the physical one [22].

An ideal virtual reality environment would deliver maximal immersion, giving users the sensation of being fully present in either real or imagined worlds. While immersion alone can create a sense of presence, body-related illusions, which depend on our physical connection to the world, demand higher levels of sensorimotor coordination [14].

Slater [19] further distinguishes two orthogonal components underlying this experience:

Place illusion is the subjective sensation of actually being in a real place – the qualitative feeling of "being there" – despite the participant's awareness that they are not. It is shaped by the range of sensorimotor interactions the VR system supports.

Plausibility illusion is the illusion that the depicted scenario is actually occurring, determined by the degree to which the system produces events that directly relate to the participant and the overall credibility of the scenario relative to expectations – despite the participant's full awareness that the events are not real.

2.6 Cybersickness

Cybersickness is an adverse effect of virtual reality exposure commonly described as visually induced motion sickness [17]. The most frequent and predominant theoretical framework suggests that it arises from a sensory conflict between the visual and vestibular systems: in a VR environment the visual system perceives self-motion while the vestibular system registers no corresponding physical movement, creating a mismatch that produces symptoms including nausea, disorientation, and oculomotor discomfort [7].

Chapter 3

The Ekhi Framework and Target Platform

This chapter introduces Project Ekhi – the framework used to deliver and supervise the virtual reality sessions – and describes the target hardware platform.

3.1 Project Ekhi Overview

Project Ekhi is a framework developed through a collaboration between the Faculty of Information Technology of Brno University of Technology, which is responsible for research and development, and the University Hospital Brno, Department of Psychiatry, which provides medical and research supervision [4]. The framework is designed to guide patients and study participants through interactive experiences in virtual reality, with applications in both therapeutic and experimental contexts.

The framework consists of two integrated components. The first is an application running on a standalone VR headset worn by the participant. The application renders the virtual environment and handles all interaction, including teleportation-based navigation and real-time response to biosignals. The second component is a web-based supervisor dashboard running on a separate device, typically a laptop or tablet operated by the researcher or therapist. Through the dashboard, the supervisor can monitor the session in real time, observe the participant's current position and view within the virtual environment, and adjust session parameters as needed.

Ekhi also integrates biofeedback via heart rate monitoring. Heart rate data is sampled periodically from a chest-worn sensor and transmitted to the application wirelessly. A proprietary algorithm, developed in cooperation between FIT BUT and the Faculty of Medicine of Masaryk University, processes the incoming heart rate signal and drives a parameter that controls an element of the virtual scene. The processed signal is simultaneously displayed on the supervisor dashboard, providing real-time physiological feedback to the operator. The internal workings of the algorithm are not disclosed in this thesis due to a non-disclosure agreement; the relevant interface is a single output value proportional to heart rate variability that is mapped to the fountain spray height parameter at runtime.

This thesis extends the Ekhi framework by contributing three virtual environments corresponding to three levels of environmental detail. These scenes were integrated into the existing framework infrastructure, reusing the biofeedback pipeline, the session scheduler,

and the supervisor dashboard without modification. In addition, the rendering pipeline was configured and optimised for the target hardware described in Section 3.2.

3.2 Target Platform

Project Ekhi is developed using **Unity** and the **OpenXR** standard. While this underlying architecture allows for broad cross-platform deployment, the specific target platform for this thesis is the **Meta Quest 2**, a standalone Android-based VR headset. A comprehensive breakdown of the technologies and tools used during the project's development is provided in Chapter 5.

The headset is powered by the Qualcomm Snapdragon XR2 Gen 1 system-on-chip, which integrates an Adreno 650 GPU [9]. While functioning as a standalone device eliminates the need for an external computer or tethering, it inherently limits the computational and memory resources available for rendering when compared to a PC VR system.

The study was originally designed to run on the **Meta Quest 3**, which offers more capable computational hardware, as well as improved display resolution and pancake lenses compared to the Meta Quest 2. However, during development, the Garmin HRM-Dual heart rate sensor ceased to connect to the Meta Quest 3 unit via Bluetooth following a system software update, preventing the reception of biofeedback data. Because no hardware fault was identified on either device and the root cause could not be resolved, all 24 participant sessions were subsequently conducted on the Meta Quest 2, where the sensor connection remained stable throughout the study.

Chapter 4

Scene Design

This chapter describes the three scenes designed for the user study: the rationale and theme selection, the design philosophy and specific definitions for each level of detail, the variables that were controlled across all three scenes to isolate the effect of LOD, and a visual comparison of the assets used.

4.1 Scene theme and layout

The scene was designed with a dual purpose in mind. The primary goal is to serve as a controlled experimental stimulus for this user study. The secondary goal is to provide a reusable biofeedback environment suitable for therapeutic use in a clinical psychiatric setting, in line with the broader aims of Project Ekhi.

The virtual environment for the user study is a **park scene** centred on a biofeedback controlled fountain. A park was selected as a familiar, nature-based setting to provide a relaxing, neutral environment for participants.

The scene occupies an area of approximately 50 m $\times$ 50 m, providing sufficient space for free exploration and natural movement while remaining compact enough to encourage participants to traverse the full extent of the environment. The terrain is flat throughout. Two opposing corners serve as entry points, while the remaining corners each contain a distinct functional zone: one features a fountain flanked by benches, and the other contains a pair of picnic tables, each accompanied by two benches, forming a casual seating area. The central area consists predominantly of open grass, enabling an unobstructed line of sight across the scene. Distributed throughout the environment are trees, bushes, benches, lamp posts, and waste bins, which collectively contribute to the visual complexity of the scene.

4.2 Theoretical LOD Conceptualisation

When designing virtual environments across multiple levels of detail, we can conceptualise visual fidelity as a continuous spectrum rather than a set of discrete steps. At one end of such a slider, a scene is reduced to its bare essentials – only the information strictly necessary to convey its structure and purpose. At the other end, it is indistinguishable from the real world. Dragging this slider from lowest to highest would progressively affect:

- **Mesh complexity** – the geometric detail of objects in the scene (polygon count)

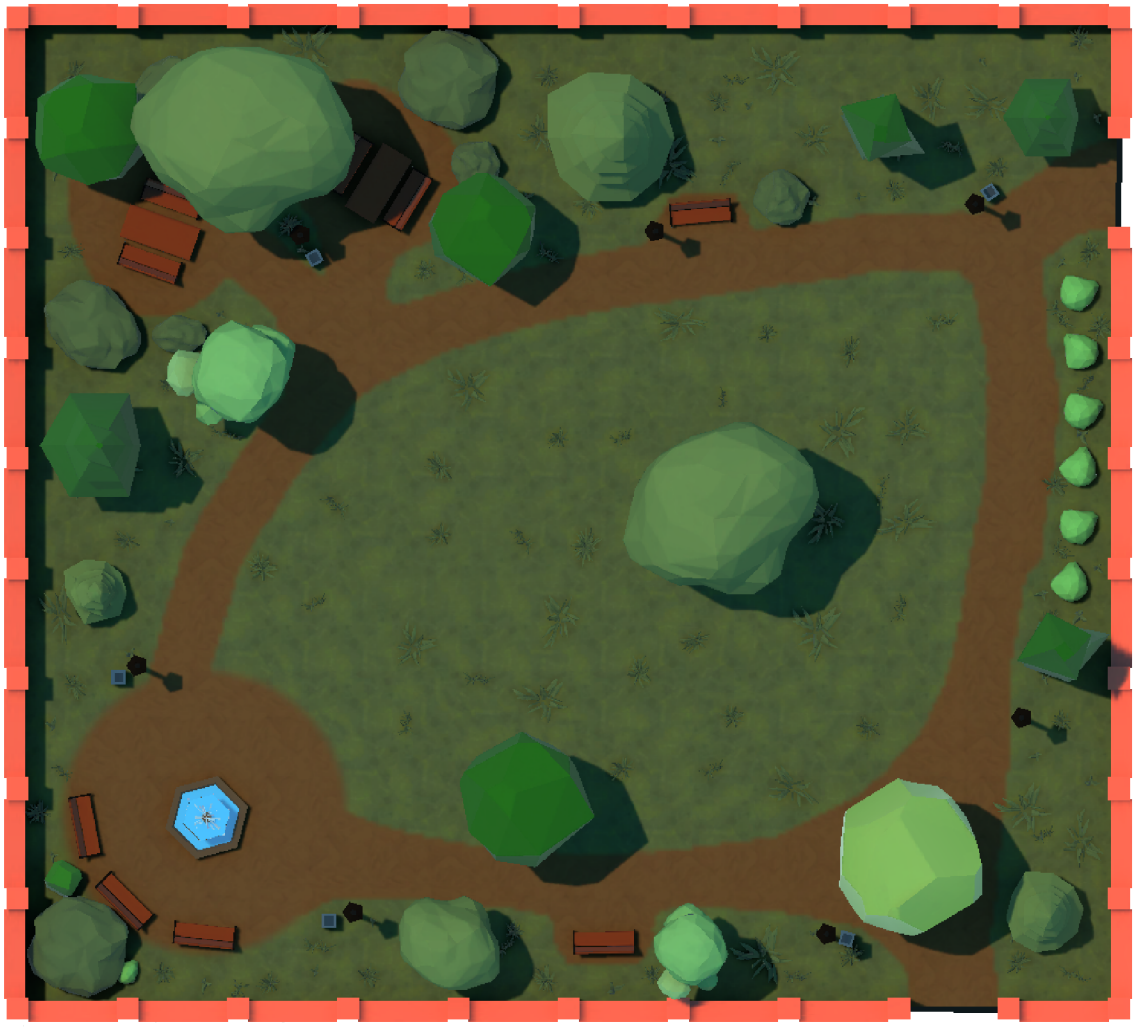

Figure 4.1: Top-down view of the scene layout.

- **Texture fidelity** – the sharpness and richness of surface appearances (texture resolution and layering)
- **Foliage density** – the amount and complexity of natural elements such as grass and tree canopies
- **Shader complexity** – how surfaces move and behave in the environment, such as foliage swaying in wind, and how realistically they respond to light
- **Lighting quality** – how light and shadow are computed and how accurately they reflect real-world behaviour (baked vs. real-time, shadow resolution)
- **Environmental effects** – the presence and richness of atmospheric and post-processing elements (particle systems, fog, bloom)
- **Ambient detail** – the accumulation of small incidental elements that suggest a lived-in world (scattered leaves, debris, wear marks on surfaces)

The LOD design in this study prioritises subjective user perception over strict technical parameter control. Certain variables that could vary across different LOD levels were intentionally held constant across conditions, as described in Section 4.3.

4.3 LOD Level Definitions and Philosophy

The user study employs three scenes to evaluate varying levels of environmental detail. Throughout this thesis, these environments are referred to by their primary characteristics: **Abstract**, **Low-poly**, and **Realistic**. When designing the different levels of detail, the hardware constraints of the target platform must be kept in mind, as described in Section 3.2. The term "realistic" is a relative nickname – the scene is the closest of the three to a naturalistic appearance, but is still far from photorealism. It should be understood as the highest-fidelity condition within the scope of this study.

The following subsections describe each LOD level in detail.

4.3.1 Abstract

The **Abstract** scene is the most minimal condition. Individual objects in the scene may not be recognisable in isolation. A bench, for example, is represented by a rectangular box, a tree by a rectangular trunk and a sphere canopy. The intent is to suggest the presence of park furniture and vegetation through spatial placement and approximate proportions, without providing enough visual information to conclusively identify any object. This condition represents the lower bound of the LOD spectrum – an environment that is spatially coherent but visually abstract.

4.3.2 Low-poly

The **Low-poly** scene uses low-detail objects. Objects are individually recognisable: a bench looks like a bench, a tree looks like a tree. Textures are small and stylised, consistent with the low-poly aesthetic. Sparse grass patches are present on the terrain.

This condition represents a middle ground that is common in stylised games and interactive applications: visually coherent and clearly readable, but with a deliberately simplified geometric and textures.

4.3.3 Realistic

The **Realistic** scene is the highest-fidelity condition. It uses more detailed objects with more detailed textures. Trees and bushes have visible leaves rather than having an imitation of tree canopy. Tree and bush leaves move slightly in the wind. Grass coverage is more dense and detailed.

4.4 Controlled Variables Across LOD Levels

To isolate the effect of environmental detail level on presence and cybersickness, a number of variables were held constant across all three scenes:

Layout and object placement. The position, orientation, and scale of all objects are identical across all three LOD conditions. The terrain shape and dimensions are identical.

Lighting direction. All three scenes use the same directional light direction, producing consistent shadow angles.

Shadows. Shadows were included in all three scenes and were not varied as part of the LOD manipulation. Varying shadow quality alongside geometry detail would introduce an additional confounding variable.

Audio. All three scenes featured identical audio: a single spatialised fountain water sound effect, growing fainter as participants moved away from the fountain and reacting to the intensity of the fountain jets. No ambient background audio was used.

4.5 Visual Comparison

The following subsections provide an object description and visual comparison of the three LOD levels for the most significant scene elements. More detailed scenes may employ multiple variants of the same object type, not all variants are shown. This section serves as a visual reference, not an exhaustive comparison.

4.5.1 Trees

- **Abstract scene** – rectangular trunk and a sphere canopy or conifer crown made from blocks.
- **Low-poly scene** – simplified trees with recognisable silhouettes and minimal geometry
- **Realistic scene** – detailed trees with visible foliage and wind animation

Figure 4.2: Comparison of deciduous trees across LOD levels (from left to right: Abstract, Low-poly, Realistic)

Figure 4.3: Comparison of coniferous trees across LOD levels (from left to right: Abstract, Low-poly, Realistic)

4.5.2 Bushes

- **Abstract scene** – half-sphere geometry
- **Low-poly scene** – more detailed bushes providing a recognisable silhouette with minimal geometry
- **Realistic scene** – more detailed bushes with visible leaves and wind animation

Figure 4.4: Comparison of bushes across LOD levels (from left to right: Abstract, Low-poly, Realistic)

4.5.3 Benches, Waste Bins and Lamps

- **Abstract scene** – block-shaped objects with no distinguishing features
- **Low-poly scene** – recognisable objects
- **Realistic scene** – most detailed objects

Figure 4.5: Comparison of benches, lamps and waste bins across LOD levels (from left to right: Abstract, Low-poly, Realistic)

4.5.4 Skybox

- **Abstract scene** – simple flat gradient sky, sun and clouds
- **Low-poly scene** – stylised skybox consistent with the low-poly aesthetic of the scene
- **Realistic scene** – realistic skybox providing a more detailed and naturalistic sky appearance

Figure 4.6: Comparison of skyboxes across LOD levels – facing sun (from left to right: Abstract, Low-poly, Realistic)

4.5.5 Full Scene Comparison

Fountain view

This section presents a comparison of the fountain-facing perspective, overlooking the rest of the scene.

Fountain LOD level variation:

- **Abstract scene** – square fountain with a simple jet
- **Low-poly scene** – more detailed fountain with a stylised fountain jet
- **Realistic scene** – round fountain with more detailed and realistic fountain jet

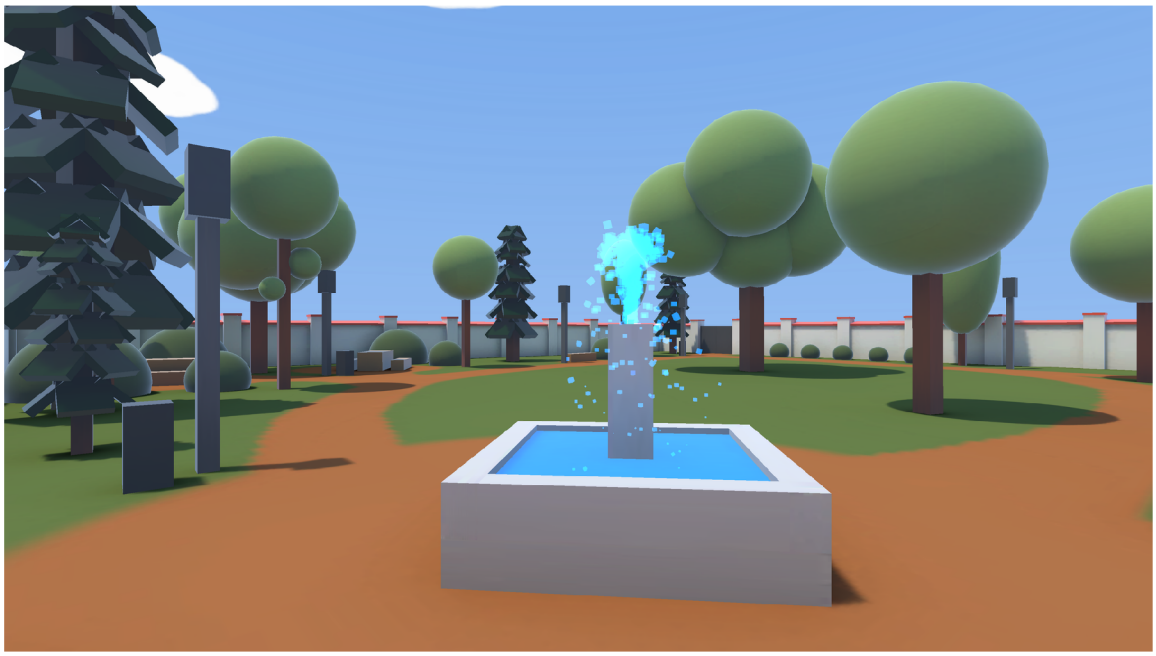

Figure 4.7: Abstract scene: Fountain view

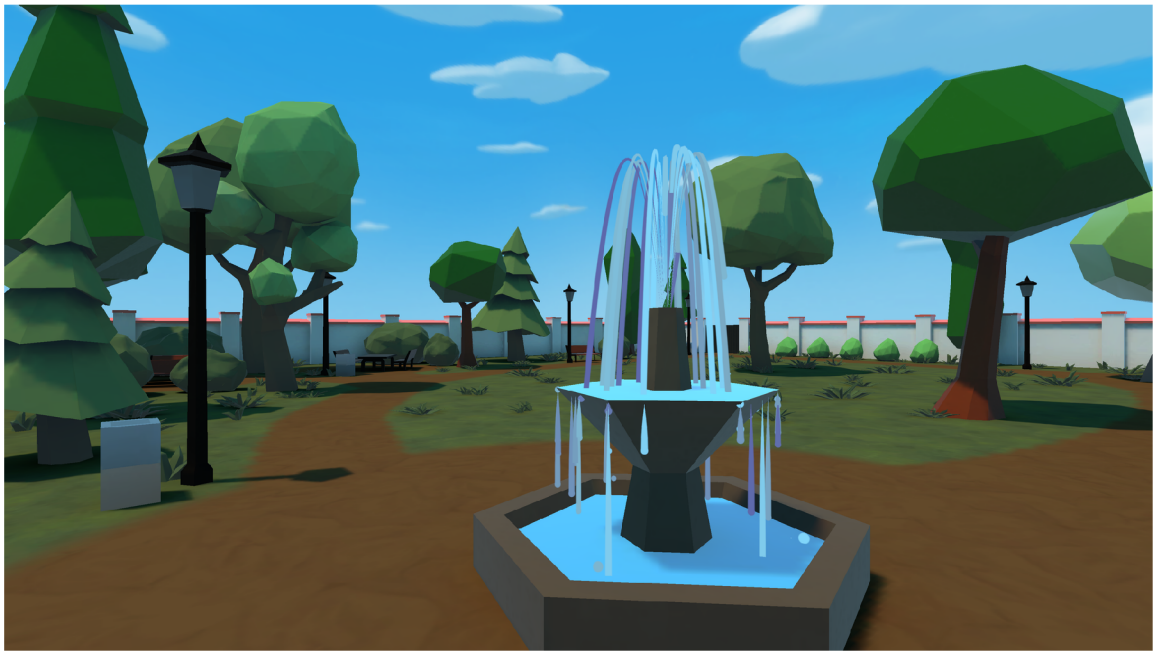

Figure 4.8: Low-poly scene: Fountain view

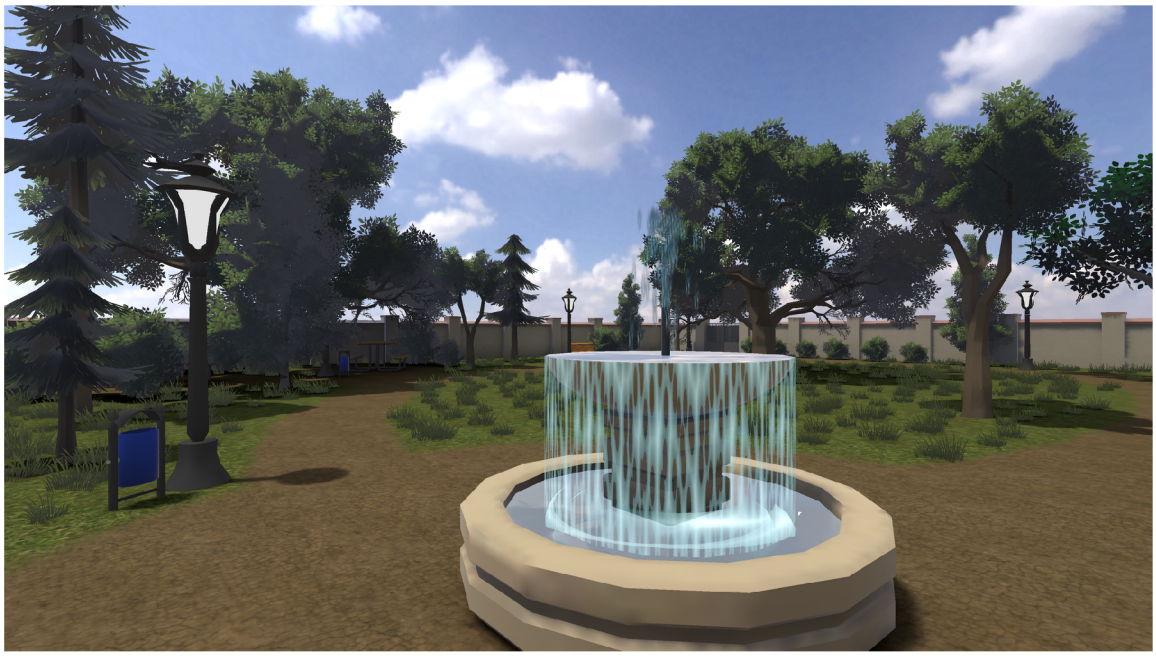

Figure 4.9: Realistic scene: Fountain view

Seating area

This section presents a comparison of the picnic area view.

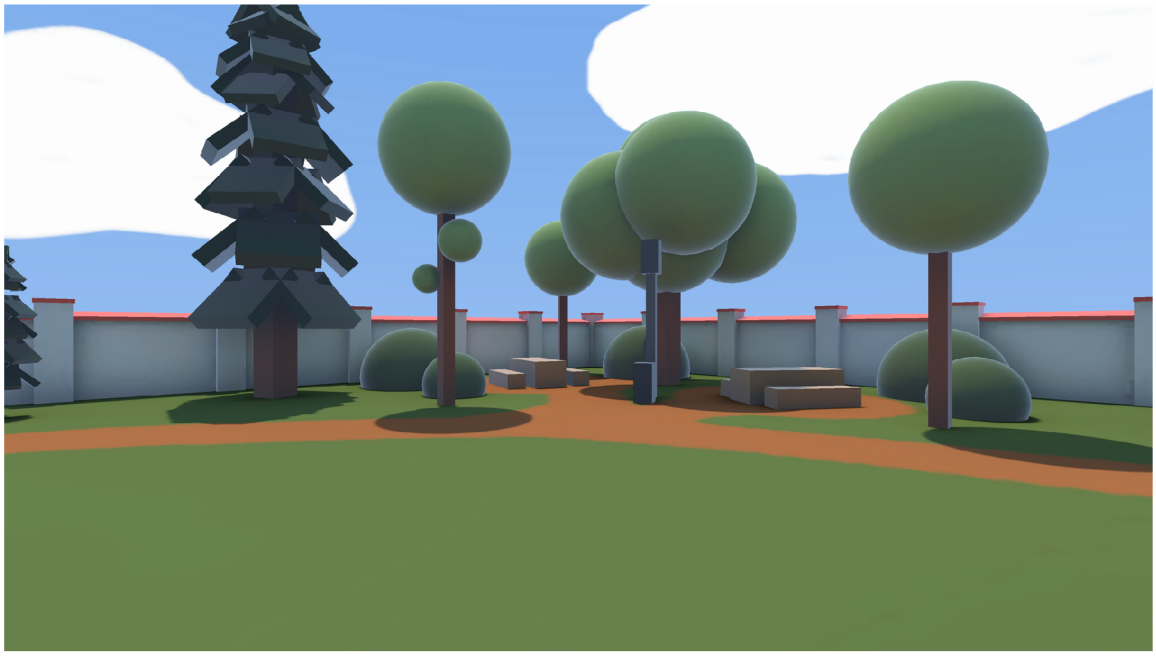

Figure 4.10: Abstract scene: Picnic area

Figure 4.11: Low-poly scene: Picnic area

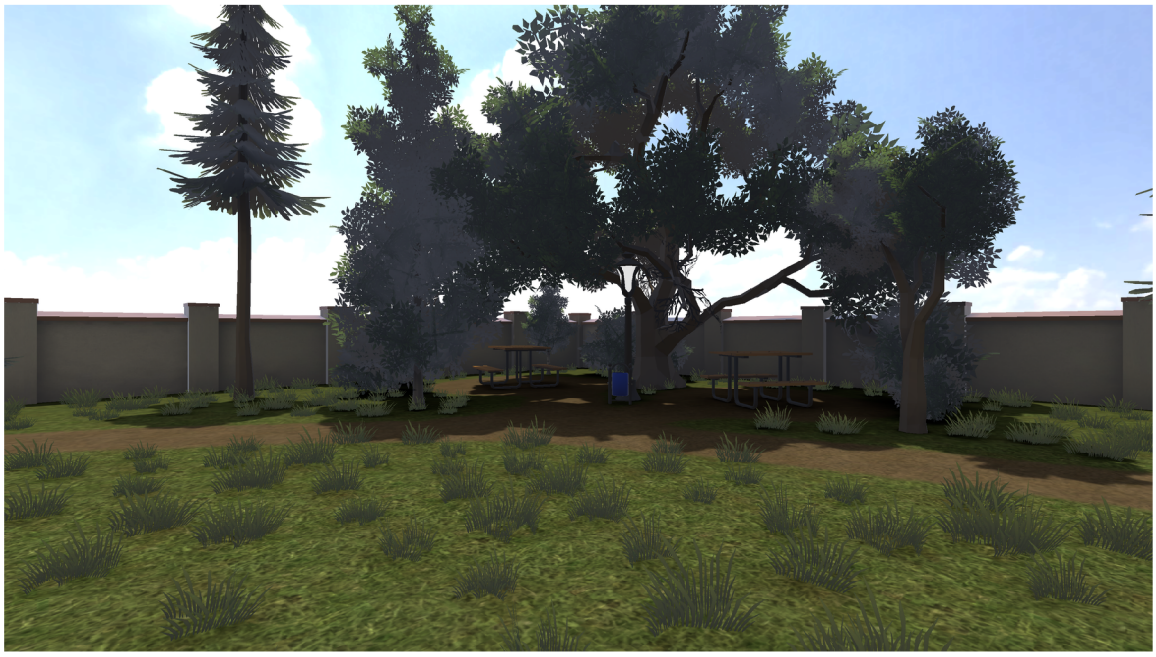

Figure 4.12: Realistic scene: Picnic area

Scene view

This section presents a comparison of scene perspective from one of the entrance gates.

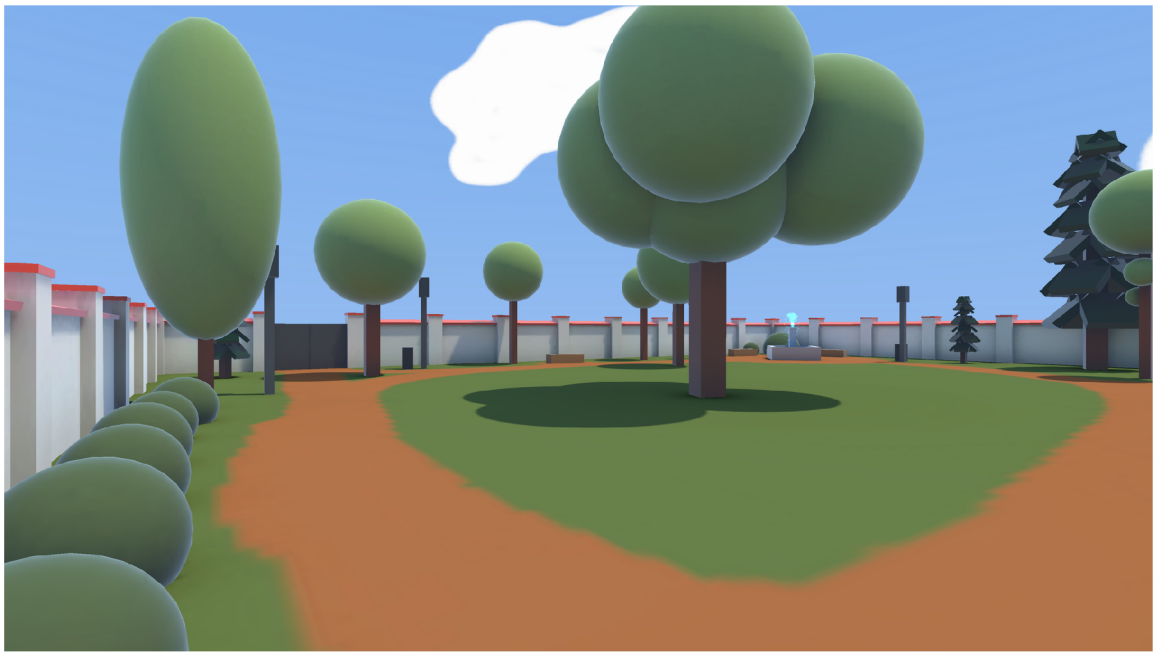

Figure 4.13: Abstract scene: Scene view

Figure 4.14: Low-poly scene: Scene view

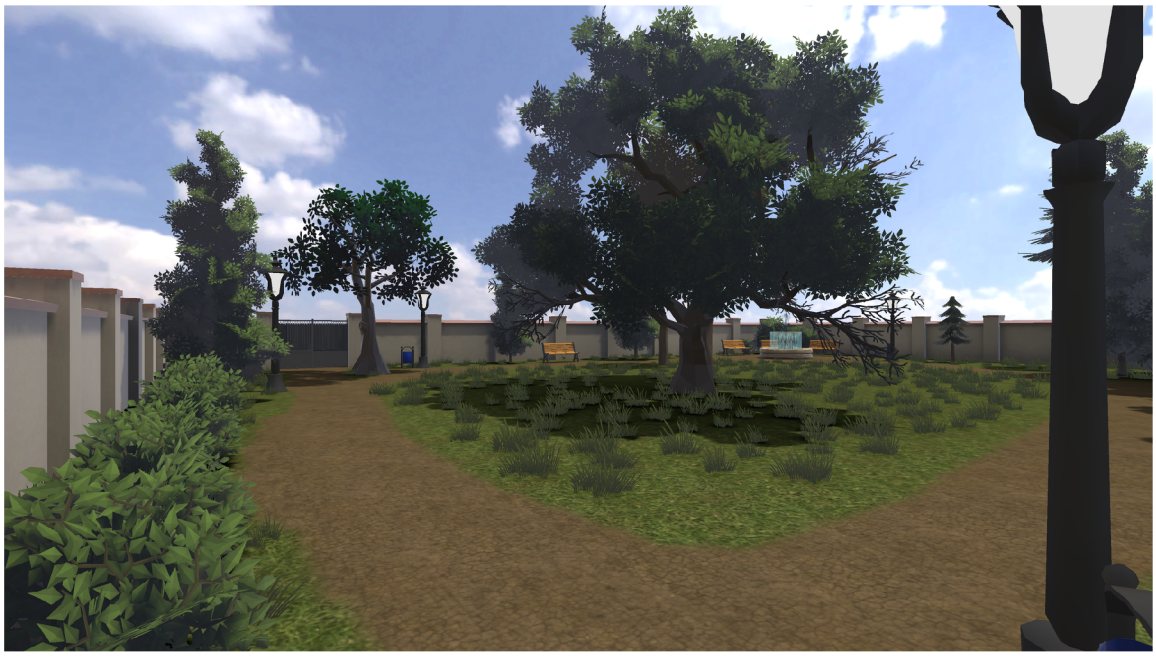

Figure 4.15: Realistic scene: Scene view

Chapter 5

Implementation

This chapter describes the technical implementation of the three virtual environments and their optimisation for target hardware.

5.1 Development Environment

The Ekhi framework is built on **Unity 6** using the **Universal Render Pipeline** (URP). The virtual environments developed for this thesis were implemented as separate scenes within the same Unity 6 project and integrated directly into the Ekhi framework.

Within the Ekhi framework, the URP is configured for standalone Android-based VR headsets. The application utilized the following settings:

- **Vulkan** as the graphics API
- **Single-pass stereo rendering (Multiview)**

Some of Ekhi's project settings were changed to meet target performance, these are described in Section 5.3.4.

The following Unity packages were used during development:

- **XR Interaction Toolkit** – provides teleportation locomotion and controller interaction abstraction using the OpenXR standard
- **OpenXR Plugin** – enables deployment to Meta Quest hardware through the OpenXR runtime
- **Visual Effect Graph (VFX Graph)** – GPU-accelerated particle simulation system used for the fountain spray effects

Texture assets were compressed using the **ASTC** compression format, which provides a favourable balance between image quality and memory usage on mobile GPUs. Application deployment and testing on the headset were performed using Android Debug Bridge (ADB) over USB.

5.2 Scene Creation

The three scenes were created using either self-made assets, assets provided by the Ekhi framework, or third-party assets sourced primarily from the Unity Asset Store. A complete list of all assets used in the project is provided in Appendix F.

The Abstract scene was created primarily using Unity built-in primitives and flat colored materials. The skybox for the Abstract scene was painted in Blender. The other scenes were created primarily from sourced assets.

5.2.1 Terrain

The ground in all scenes was implemented as a textured plane mesh rather than Unity Terrain. Initial experiments with the Unity Terrain system resulted in poor rendering performance on the target hardware. Instead, terrain textures were painted using the Unity Terrain tools and subsequently baked into a single texture applied to a static mesh. Each scene's terrain depicts the same spatial layout of grass and paths, differentiated only by the visual fidelity of the applied textures.

- The Abstract scene uses simple flat colors to distinguish path from grass.
- The Low-poly scene uses stylised but recognisable textures for both surfaces.
- The Realistic scene uses more realistic, higher resolution textures for grass and paving.

For vegetation, grass was placed using a prefab painting workflow, manually adjusted where needed. The geometric and material implementation varies across the scenes:

- The Abstract scene contains no grass geometry.
- The Low-poly scene uses simple flat-colored stylised grass meshes with low polygon counts.
- The Realistic scene uses denser grass geometry with alpha-clipped materials to show foliage detail.

5.2.2 Fountain effects

All fountain effects were implemented using Unity's built-in **Particle System** or **Visual Effect Graph** (VFX Graph), with runtime parameters exposed to the biofeedback integration layer.

The Abstract scene uses a simple single-jet particle effect implemented using the built-in Particle System. The Low-poly and Realistic scenes use more visually complex fountain spray effects implemented in VFX Graph. Although the built-in Particle System is more performant on the target hardware than VFX Graph, it did not provide sufficient expressiveness to achieve the desired visual complexity for these scenes. VFX Graph was therefore used despite the higher GPU cost. This trade-off became noticeable on the Meta Quest 2, whose mobile GPU has lower compute performance than that of the Quest 3 [9]. As a result, the fountain effects used in the Quest 2 builds were simplified to maintain performance.

5.2.3 Wind effects

Trees and bushes in the realistic scene use a shader that applies a subtle wind-swaying animation, which improves the appearance at close range but introduces shimmering artifacts when viewed from a distance. This is an acceptable compromise given the visual benefit of the animation. Furthermore, the artifacts were less pronounced on the Meta Quest 3, the headset the study was originally designed for (see Section 3.2).

5.3 Rendering Configuration

This section describes the rendering configuration used across all three scenes, covering both baseline requirements for comfortable VR and hardware-specific optimisation choices.

The target frame rate for all three scenes was a **minimum of 72 frames per second**, as required for interactive applications on the Meta Quest 2 [10]. Maintaining a sufficient frame rate is particularly important in VR applications, as low FPS is associated with increased likelihood of dizziness, nausea, and disorientation [23]. All scenes were therefore designed to sustain this target under normal interaction conditions.

5.3.1 Lighting

All three scenes use baked lightmaps generated using Unity's Progressive Lightmapper. Lighting setting were kept consistent across LOD levels.

5.3.2 Anti-aliasing

Anti-aliasing was disabled in all scenes to reduce rendering overhead, ensuring stable frame rates across all LOD conditions. While lower-detail scenes could perform well with anti-aliasing, a shared configuration was applied across all conditions to minimise its influence on the results. The resulting aliasing artifacts, including edge staircasing and shimmer on distant geometry, are acknowledged as a limitation of the implementation.

5.3.3 Static Batching

Static batching was enabled for all scene geometry to reduce draw call overhead.

5.3.4 Additional Optimisations

Following the Unity OpenXR Meta package recommendations for Meta Quest devices [21], several additional graphics settings were adjusted to improve rendering performance, primarily consisting of disabling HDR and post-processing.

5.3.5 Occlusion Culling

Occlusion culling was not applied, as the open scene layout offers minimal occluded geometry.

5.3.6 LOD Variants

Traditional geometric LOD switching techniques were not used. Runtime LOD transitions could introduce visible object popping and inconsistencies between scene variants, potentially confounding the experimental comparison between the three visual styles. Additionally, as the environment is intended for therapeutic use in a clinical psychiatric setting, minimising unexpected visual artifacts is of particular importance, since they may affect vulnerable patients more significantly than healthy participants. Instead, each scene was designed as a largely self-contained environment with a consistent level of detail throughout.

5.4 Objective Scene Comparison

While the three LOD conditions were designed to differ in perceived environmental quality, an objective characterisation of their technical and visual complexity is warranted to confirm that the conditions are meaningfully distinct. Two complementary approaches are used: engine-reported geometry and rendering metrics extracted from the Unity Editor, and an image-complexity proxy derived from screenshot compression ratios.

The viewpoints used are the same as those shown in Section 4.5.5.

5.4.1 Geometry and Rendering Metrics

Triangle counts and batch counts were recorded for each scene directly from the Unity Editor Statistics panel using a fixed camera position.

Table 5.1: Triangle counts and batch counts per LOD condition and viewpoint, recorded from the Unity Editor Statistics panel.

Condition	Viewpoint	Triangles	Batches
Abstract	Fountain View	35.1k	46
	Picnic View	15.5k	21
	Scene Overview	27.3k	52
Low-poly	Fountain View	36.5k	37
	Picnic View	15.2k	37
	Scene Overview	33.8k	41
Realistic	Fountain View	51.9k	63
	Picnic View	24.1k	47
	Scene Overview	49.3k	79

The higher batch count in the Abstract condition compared to Low-poly at certain viewpoints reflects its construction from multiple Unity primitives combined to form each object, resulting in a greater number of individual draw calls.

5.4.2 LOD comparison via Screenshot Compression

Triangle counts alone are an imperfect measure for perceived visual complexity: the Abstract scene, for instance, relies heavily on spherical geometry whose triangle counts are disproportionate to the amount of visible surface detail they produce. As a complementary measure, screenshots from each fixed viewpoint were compressed using the JPEG format at a fixed quality setting, and the resulting file sizes were compared. JPEG file size has been widely adopted as a computational measure of visual complexity [8]. The premise is straightforward: because intricate details resist compression algorithms more than simple visuals do, a larger file size directly reflects greater visual complexity in images of equal resolution. All screenshots were captured at identical resolution and post-processing settings.

Table 5.2: JPEG compressed screenshot file sizes (KB) per LOD condition and viewpoint, used as a proxy for visual complexity.

Condition	**Viewpoint**	**File Size (KB)**
Realistic	Fountain View	1244
	Picnic View	1205
	Scene Overview	1219
Low-poly	Fountain View	478
	Picnic View	424
	Scene Overview	432
Abstract	Fountain View	386
	Picnic View	325
	Scene Overview	314

Chapter 6

User Study

This chapter describes the methodology and design of the user study conducted to evaluate the impact of environmental level of detail in virtual reality on user experience, with a focus on presence and cybersickness. It covers the study design, participant demographics, session procedure, and the instruments used to collect subjective and physiological data.

6.1 Study Design

The study follows a within-subjects design, meaning every participant experienced all three virtual environments. This approach reduces the influence of individual differences on the results, as each participant serves as their own control.

To account for potential order effects – such as learning, fatigue, or carry-over between conditions – a Latin square counterbalancing scheme was applied. This ensured that all possible orderings of the three scenes were represented across participants, allowing any systematic order effect to be identified or ruled out.

6.2 Apparatus

Participants used a Meta Quest 2 head-mounted display to experience the virtual environments. Heart rate was recorded continuously throughout each session using the Garmin HRM-Dual chest strap sensor, which transmits data over Bluetooth Low Energy. Questionnaires were administered digitally via Google Forms on a tablet, chosen for convenience over a paper-and-pencil format to simplify data collection and eliminate manual transcription.

6.3 Study Location

Sessions took place at the university or participants' homes rather than in a fixed laboratory setting. The primary requirement for the location was a quiet, distraction-free environment to minimise external disturbances that could affect presence or physiological measurements. The researcher was present throughout each session to provide assistance and to observe the procedure.

6.4 Session Procedure

The overall session proceeded as follows:

1. Verbal introduction to the study
2. Signing of the consent form
3. Fitting of the Garmin HRM-Dual chest strap
4. Demographic questionnaire
5. Baseline VRSQ questionnaire
6. Training scene (teleportation familiarisation, up to 30 seconds)
7. Three VR scene exposures, each followed immediately by the IPQ and VRSQ questionnaires
8. Final post-study questionnaire

Before any VR exposure, participants received a verbal introduction to the study explaining its purpose and procedure. They then signed a consent form agreeing to participation (see Appendix A).

Following the consent form, participants completed a demographic questionnaire covering age, gender, level of education, field of study or work, gaming habits, prior VR experience, and susceptibility to motion sickness (see Appendix B). To establish a baseline measure of cybersickness symptoms prior to any VR exposure, participants also completed the VRSQ immediately after the demographic questionnaire.

Participants were then fitted with the Garmin HRM-Dual heart rate sensor. To familiarise themselves with the controller-based teleportation used in the study, participants spent up to 30 seconds in a dedicated training scene (a terminal environment from Unity's Universal 3D sample). After exiting the training scene, participants were returned to a neutral waiting screen. This waiting screen served as a consistent baseline starting point before each VR environment, ensuring every scene was entered under identical conditions regardless of the session order.

Participants then completed three consecutive VR scene exposures – one per LOD condition – in the order determined by their Latin square assignment. Each scene lasted exactly five minutes and followed a fixed schedule delivered via timed in-VR text popup notifications. The duration was chosen to allow sufficient time for presence to develop while avoiding participant fatigue and boredom across three consecutive exposures. Research on spatial presence formation in immersive VR indicates that presence forms rapidly – in some cases within the first few seconds of exposure [11]. Five minutes was therefore considered more than sufficient for presence to establish, while keeping the total session time manageable across three repeated exposures.

The in-scene schedule proceeded as follows:

1. **Free exploration (2 minutes):** Participants explored the scene freely without any specific task or instruction.
2. **Transition to fountain (15 seconds):** A popup instructed participants to move to the fountain and wait.
3. **Paced breathing exercise (2 minutes):** Participants performed a structured breathing cycle – 4 seconds inhale, 2 seconds hold, 4 seconds exhale, 2 seconds hold – repeated continuously until the next instruction. This phase was designed to elicit a

consistent and measurable heart rate response, and constitutes the interactive biofeedback element of the scene.

4. **Free exploration (45 seconds):** Participants could move freely again until a final popup instructed them to remove the headset.

After each scene, participants removed the headset and completed the presence (IPQ) and cybersickness (VRSQ) questionnaires on the tablet before proceeding to the next scene. Administering the questionnaires outside of VR was a deliberate choice. Prior work found that completing presence questionnaires inside VR does not affect mean scores compared to completing them outside VR [16]. Additionally, the time spent completing the questionnaires served as a natural reset period between scene exposures, helping participants mentally disengage from the previous environment before entering the next one.

Upon completing all three scenes and their respective questionnaires, participants filled in a final post-study questionnaire (see Appendix E). In addition to open free-text feedback, this questionnaire asked participants to:

- rank the three environments from most to least pleasant,
- rank the three environments from most to least realistic,
- identify in which environment they felt the strongest sense of presence, and
- identify in which environment they experienced the least discomfort.

6.5 Measuring Presence

Post-experience questionnaires remain the dominant method for assessing presence, largely due to their ease of deployment and their reliance on standard statistical analysis [20]. Among the many tools available, three have emerged as the most prominent in immersive VR research: Witmer and Singer's Presence Questionnaire (PQ), the Slater-Usoh-Steed (SUS) questionnaire, and Schubert et al.'s Igroup Presence Questionnaire (IPQ) [20]. Each of these instruments reflects a different theoretical understanding of presence and, consequently, targets different dimensions of the user experience. The choice of questionnaire is therefore not trivial: Degenhard et al. (2025) highlight that researchers frequently overlook how sensitive these tools are to specific presence dimensions. Consequently, failing to detect differences in user experience might stem from choosing an incompatible questionnaire rather than a true absence of experimental effects [3].

6.5.1 Overview of Major Presence Questionnaires

The following sections describe the three most widely used presence questionnaires in VR research. Each instrument is examined in terms of its structure, theoretical basis, and psychometric properties, providing the foundation for the selection rationale presented in Section 6.5.2.

Presence Questionnaire (PQ) – Witmer & Singer (1998)

The Presence Questionnaire, developed by Witmer and Singer, is among the most frequently cited presence instruments in the literature [20]. In the version examined by Schwind et

al. (2019), it comprises 32 items with subscales covering involvement and control, natural interaction, and interface quality [16]. A key characteristic of the PQ is that it emphasises properties of the simulated environment and of the interface rather than the user's subjective experience exclusively. Researchers have critiqued the PQ for relying heavily on subjective factors while dedicating relatively few questions to the direct measurement of presence itself [16]. Furthermore, the questionnaire's length imposes a significant burden in within-subjects designs where it must be completed multiple times.

From a psychometric standpoint, the PQ's subscales on interaction and interface quality are informative when hardware conditions differ across conditions. In the present study, however, all participants use identical hardware, meaning these subscales would remain constant across all three LOD conditions and thus contribute no discriminating information to the presence score.

Slater-Usoh-Steed Questionnaire (SUS)

The SUS questionnaire, developed across several studies by Slater, Usoh, and Steed from 1994 onwards, consists of only six items. The instrument focuses entirely on three core concepts: (1) the sense of being in the virtual environment, (2) the extent to which the virtual environment becomes the dominant reality, and (3) the extent to which the VE is remembered as a "place".

The brevity of the SUS is both its main advantage and a notable limitation. In a direct psychometric comparison of SUS, IPQ, and Witmer-Singer (WS), Schwind et al. (2019) found that the SUS had the lowest internal consistency of the three instruments tested. A further concern raised in the same paper is that Usoh et al. found that "WS and SUS are not able to discriminate between presence in a VE and physical reality" [16].

From the perspective of sensitivity to specific presence dimensions, Degenhard et al. (2025) observed that while the SUS excels at detecting shifts in the *place illusion* dimension of presence, it lacks responsiveness to other factors like embodiment, social presence, or general involvement [3].

Igroup Presence Questionnaire (IPQ) – Schubert et al. (2001)

The Igroup Presence Questionnaire (IPQ) was developed by Schubert, Friedmann, and Regenbrecht. It was initially developed in German through a process of reducing a broad item pool, validated against data from roughly 500 respondents across multiple survey iterations [15]. The current version consists of 14 items: one general item assessing the overall sense of "being there", and 13 items organised into three subscales that emerged from principal component analyses:

- **Spatial Presence (SP)** – the sense of being physically present in the virtual environment;
- **Involvement (INV)** – the degree of attention devoted to the VE and the involvement experienced;
- **Experienced Realism (REAL)** – the subjective experience of realism in the VE.

The general item ("In the computer generated world, I had a sense of 'being there'") is strongly correlated with all three subscales, though it is most heavily weighted toward Spatial Presence [15].

In contrast to the PQ's focus on hardware and interface metrics, the IPQ isolates the psychological experience and subjective perception of the user [3].

From the perspective of sensitivity to presence dimensions, Degenhard et al. (2025) determined that both the SUS and IPQ are highly responsive to variations in place illusion [3]. This is the dimension most directly related to visual fidelity of the environment – precisely the dimension varied in level-of-detail (LOD) studies.

Regarding longitudinal uptake, Tran et al. (2024) analysed over 20 years of IPQ usage, identifying 2208 publications and selecting 243 studies covering 9354 participants after strict exclusion criteria. The number of publications per year shows a consistent increase from 2003 through 2023, confirming the instrument's growing adoption. [20].

Comparison Summary

Table 6.1 summarises the key properties of the three major presence questionnaires discussed above.

Table 6.1: Comparison of major VR presence questionnaires. Reliability values (α) are from Schwind et al. (2019) [16]. Item counts are from Tran et al. (2024) [20].

Questionnaire	**Items**	**Subscales**	**Cronbach's α**	**Focus**
PQ (Witmer & Singer)	32	3	.82	System + environment properties
SUS (Slater et al.)	6	–	.75	Sense of being there
IPQ (Schubert et al.)	14	3 (+1 GP)	.87	User perception of VE

6.5.2 Rationale for Selecting the IPQ in This Study

The present study investigates the effect of three levels of detail on user experience in a VR environment delivered via the Meta Quest 2 headset. All participants interact with the same hardware and application, with only the visual fidelity of the virtual scene differing between conditions. Selecting an appropriate presence instrument therefore required an instrument that (1) is sensitive to environmental visual characteristics rather than hardware or interface quality, (2) offers sufficient psychometric reliability for repeated within-subjects measurement, and (3) imposes a reasonable completion burden within a session already comprising three VR exposures and two additional questionnaires. Given these constraints, the following criteria guided the selection of the IPQ as the primary presence measure.

Alignment with the research question. The primary manipulation in this study is the level of visual detail of the virtual environment. The IPQ measures the overall sense of presence as experienced by the user rather than technical properties of the VR system, making it well suited for detecting differences induced by changes to the visual character of the scene. The PQ subscales on interaction and interface quality would be constant across all three conditions, as none of those factors are varied.

Sensitivity to place illusion. As previously noted, both the SUS and IPQ are adept at capturing variations in place illusion, whereas the PQ is better suited for measuring plausibility [3]. Place illusion – the sense of physically inhabiting the depicted space – is the presence dimension most directly influenced by the visual quality of the environment, making the IPQ a well-matched instrument for LOD research.

Psychometric quality. The IPQ demonstrated the highest internal consistency ($\alpha = .87$) among the three main instruments compared by Schwind et al. (2019) [16]. This is particularly important in within-subjects designs, where repeated measurement across three conditions requires stable and reliable scores. The SUS, with $\alpha = .75$ and only six items, is more susceptible to individual item interpretation.

Brevity relative to the PQ. The IPQ's 14 items represent a favourable trade-off between measurement depth and participant burden. According to Tran et al. (2024), completion of the IPQ averages roughly two and a half minutes – less than half the typical duration required for the PQ [20]. The 32-item PQ would substantially lengthen a session that already includes three VR exposures and two additional questionnaires.

Established use as a comparative instrument. Tran et al. (2024) note that the IPQ has historically served as a standard tool for A/B testing in VR, where researchers seek to attribute shifts in presence directly to altered experimental conditions [20]. This matches the within-subjects design of the present study. Furthermore, the distribution of scores compiled by Tran et al. (2024) – based on 243 studies and 9354 participants – makes it possible to contextualise the scores obtained in the present study against prior literature [20].

For the reasons mentioned above, the IPQ was selected as the primary instrument for measuring presence in this study.

6.6 Measuring Cybersickness

The primary goal of this research is to evaluate the impact of environmental level of detail on user responses in VR. Therefore, monitoring cybersickness is imperative for two reasons. First, it acts as a critical confounder, because without tracking it, differences in subjective experience might mistakenly be attributed to perceptual properties rather than VR-induced discomfort. Second, it allows us to investigate whether specific levels of detail inherently trigger higher rates of cybersickness.

6.6.1 Available Instruments for Cybersickness Assessment

Several self-report questionnaires are available for quantifying cybersickness. The most relevant instruments are reviewed below.

Simulator Sickness Questionnaire (SSQ)

Despite its widespread adoption and strong reputation in virtual reality studies, the Simulator Sickness Questionnaire (SSQ) faces criticism regarding its psychometric validity and overall suitability for specifically assessing cybersickness. The SSQ was derived by re-analysing Motion Sickness Questionnaire data collected via simulator studies with participants employed in military, aviation, and marine services, from which 16 symptoms of motion sickness were confirmed as accurate predictors of simulator sickness. These symptoms indicate three constructs: Nausea, Oculomotor, and Disorientation, along with a higher-order Total Severity score [17].

The SSQ carries significant limitations when applied to consumer VR. Although considered a "gold standard" for visually induced motion sickness, its factor structure and professional-simulator origins do not translate well to modern HMD-based VR and general-audience users. Several items load onto multiple factors simultaneously, and some symptoms

– such as sweating – may reflect causes unrelated to VR sickness [17]. Confirmatory factor analysis further indicates that the SSQ lacks construct validity for consumer-grade headsets, whereas newer, shorter scales such as the VRSQ and CSQ have demonstrated validity in this context [17, 6].

Fast Motion Sickness Scale (FMS)

The Fast Motion Sickness Scale (FMS) is a verbally administered diagnostic tool that rapidly assesses motion sickness during exposure to a stimulus. It evaluates a participant's current level of discomfort on a rating scale ranging from 0 (representing no sickness) to 20 (frank sickness). [17].

Cybersickness Questionnaire (CSQ)

The Cybersickness Questionnaire (CSQ) is a refined assessment tool that extracts only the most definitive indicators of VR-induced illness from the older SSQ, purposefully excluding generalized symptoms that could stem from unrelated physiological triggers. The final, refined set of nine symptoms can be categorized into two distinct subscales: one measuring dizziness and another measuring visual focus issues. As reviewed by Sevinc and Berkman, the development of the CSQ relied on data gathered from 202 individuals who navigated three separate commercial VR applications. This dataset was subsequently evaluated using item-response models to refine the questionnaire. A direct psychometric comparison found that both CSQ and VRSQ were valid and reliable measures of cybersickness, sensitive to application aspects such as translational and rotational movements required for navigation, and that both revealed better indicators of validity compared to the SSQ and F-SSQ [17].

Cybersickness in VR Questionnaire (CSQ-VR)

The Cybersickness in VR Questionnaire (CSQ-VR), was developed in response to the limitations of existing cybersickness measures including the SSQ and the VRSQ. It assesses the full range of cybersickness symptoms – nausea, disorientation, and oculomotor – through six items (two per symptom type), presented on a seven-point Likert scale combining text and numeric labels ranging from absent feeling to extreme feeling. In addition to a paper-and-pencil form, a 3D-VR version is available that can be used inside any virtual environment and additionally benefits from eye tracking to measure gaze fixations and pupil size. Research indicates that the CSQ-VR outperforms both the SSQ and VRSQ in terms of overall reliability. Furthermore, it serves as a highly sensitive metric for identifying short-term performance decrements linked to cybersickness [7]. However, the CSQ-VR is a recently introduced instrument, and its 3D-VR administration mode requires eye-tracking hardware.

Virtual Reality Sickness Questionnaire (VRSQ)

The VRSQ was introduced by Kim et al. [6] as a cybersickness measure specialised for VR headsets. Starting from the 16-item SSQ, exploratory and confirmatory factor analysis on data from 24 participants using a Samsung Gear VR reduced the instrument to 9 items across two subscales: *Oculomotor* (general discomfort, fatigue, eyestrain, difficulty focusing) and *Disorientation* (headache, fullness of head, blurred vision, dizziness with eyes closed, vertigo). Items use the same 0–3 rating scale as the SSQ; subscale scores are normalised

to a 0–100 range, with the Total score computed as their mean. Internal consistency was Cronbach's $\alpha = 0.847$ (Oculomotor) and $\alpha = 0.886$ (Disorientation).

The nausea component was eliminated because SSQ nausea scores were the lowest contributor in VR contexts (proportional score 0.18 vs. 0.39 oculomotor and 0.42 disorientation), and because visually induced motion sickness in VR – seeing motion that is not felt – differs theoretically from simulator sickness [6].

Independent psychometric evaluation by Sevinc and Berkman [17] across seven consumer VR environments confirmed adequate model fit (SRMR = 0.037; CFI = 0.954) and discriminant validity of the two subscales. A German-language validation in a nursing simulation confirmed structural validity (SRMR = 0.040; CFI = 0.981), though the Oculomotor subscale showed low internal consistency ($\alpha = 0.670$) [1].

Two limitations apply: the original validation used only 24 participants on a single constrained task, limiting generalisation [6]; and the rationale for excluding nausea – the second most frequent cybersickness symptom – remains insufficiently substantiated [6, 7].

6.6.2 Rationale for Selecting the VRSQ in the Present Study

Given the characteristics of the present study, the VRSQ was selected as the instrument for measuring cybersickness for the following reasons.

VR-specificity The SSQ was developed on data from simulator studies and has been shown to lack construct validity for consumer HMD VR applications [17]. The VRSQ was specifically developed to measure motion sickness in VR environments and validated on a VR headset device, making it methodologically appropriate for the Meta Quest 2 platform used in this study [6].

Brevity and reduced participant burden The VRSQ's limited number of items makes it particularly practical to administer, as it requires less time and is easier for participants to complete [1]. This is important given that the session protocol in this study also includes the Igroup Presence Questionnaire and demographic questions.

Validated psychometric properties Questionnaires tailor-made for VR environments (CSQ and VRSQ) have been proven to be psychometrically superior for assessing HMD applications compared to traditional simulator sickness tools [17].

Established precedent The VRSQ was also selected due to its suitability for the specific demands of the present study: a controlled within-subjects experiment involving repeated exposure across multiple conditions, where minimising participant burden between conditions was an important practical consideration.

The VRSQ satisfied all methodological requirements for this study. The CSQ-VR was considered but excluded, as its more recent development offered no distinct advantage here. The SSQ was excluded due to its professional-simulator origins and confirmed lack of construct validity in consumer HMD environments [17].

6.7 Questionnaire Localisation

The study was conducted in the Czech Republic with Czech-speaking participants; all questionnaires were therefore administered in Czech. Neither the IPQ nor the VRSQ has

an officially published Czech translation. Czech versions were consequently created for this study. To verify translation quality, an independent back-translation procedure was employed: a translator unfamiliar with the original instrument translated the Czech version back into English, and the result was compared against the source to identify any semantic discrepancies. It should be noted that the translated versions were not subjected to full psychometric validation (e.g. factor structure verification or reliability testing on a Czech sample), as this falls outside the scope of the present work.

The Czech translation of the IPQ is provided in Appendix C. The Czech translation of the VRSQ is provided in Appendix D.

Chapter 7

Results and analysis

This chapter reports findings from 24 participants who completed the three-condition within-subjects study. Section 7.1 summarises sample characteristics. Sections 7.2–7.4 address the primary outcome measures. Section 7.5 reports subjective preference rankings.

7.1 Participants

A total of 24 participants took part in the study. The group consisted of 18 men and 6 women. As shown in Table 7.1, the majority of participants (13 out of 24) were in the 18–24 age bracket, while the remaining participants were spread across a broad age range, with the oldest participant being over 75 years old. No inclusion or exclusion criteria were applied when recruiting participants; neither prior VR experience nor any particular physical condition was required.

Table 7.1: Age distribution of participants.

Age group	**Count**
18–24	13
25–34	1
35–44	3
45–54	4
65–74	2
75 and older	1
Total	**24**

Prior VR exposure varied considerably: 7 participants had never used VR before, 10 had tried it 1–2 times, 3 had 3–10 prior sessions, and 4 reported more than 10 previous VR experiences.

7.2 Cybersickness (VRSQ)

Cybersickness was assessed using the Virtual Reality Sickness Questionnaire (VRSQ), scored on a 0–100 scale. A baseline measurement was collected prior to VR exposure to capture pre-existing symptom levels. Baseline scores were notably elevated ($M = 12.92$, $Mdn = 8.33$, $SD = 13.50$), exceeding post-exposure scores across all three conditions (see

Table 7.2). Computing baseline-corrected difference scores yielded predominantly negative values across all conditions, indicating that VR exposure did not increase cybersickness above pre-exposure levels. Given this pattern, baseline correction would have obscured rather than clarified the analysis. Raw post-exposure scores were therefore used as the primary outcome measure.

Table 7.2: Descriptive statistics for VRSQ total scores across conditions ($N = 24$, scale 0–100).

Condition	***M***	***Mdn***	***SD***
Baseline	12.92	8.33	13.50
Realistic	7.85	4.17	10.73
Low-poly	9.65	7.50	8.71
Abstract	8.61	7.08	9.83

A Friedman test revealed no significant effect of LOD condition on VRSQ scores, $\chi^2(2) = 3.97$, $p = .137$.

Overall, cybersickness levels were low across all VR conditions and did not differ significantly by LOD. The finding that post-exposure scores were consistently lower than baseline suggests that the VR environment was well-tolerated regardless of fidelity level, and that LOD manipulation did not introduce differential cybersickness as a confound.

7.3 Presence (IPQ)

Presence was assessed using the Igroup Presence Questionnaire (IPQ), resulting in four subscales: Spatial Presence (SP), Involvement (INV), Realism (REAL), and General Presence (GP), each scored on a 0–6 scale. Prior to testing, Shapiro–Wilk tests were conducted per subscale per condition to determine the appropriate statistical test. Where all three conditions satisfied normality, a repeated-measures ANOVA (RM-ANOVA) was used as the primary test with Bonferroni-corrected paired t-tests for post-hoc comparisons ($\alpha_{\text{adj}} = .017$). Where any condition violated normality, the Friedman test was used with Bonferroni-corrected Wilcoxon signed-rank post-hoc tests ($\alpha_{\text{adj}} = .017$).

Prior to the main analysis, a Kruskal–Wallis test was conducted to assess whether the presentation position of each scene (1st, 2nd, or 3rd) had any effect on IPQ scores. No significant effect was found for any subscale or condition (all $p > .16$), no evidence of order effects was observed.

Descriptive statistics for all subscales are summarised in Table 7.3, and statistical results in Table 7.4.

7.3.1 Spatial Presence

Spatial presence scores decreased monotonically across conditions (see Table 7.3). All three conditions satisfied normality, so RM-ANOVA was used as the primary test. A significant main effect of LOD condition was found, with the Greenhouse–Geisser correction applied for violated sphericity (Mauchly's $W = 0.541$, $p = .001$, $\varepsilon = 0.686$), $F(1.37, 31.56) = 14.15$, $p < .001$, $\eta_g^2 = .059$. Bonferroni-corrected paired t-tests revealed that Realistic scene differed significantly from both Low-poly ($t(23) = 5.09$, $p < .001$) and Abstract ($t(23) = 4.44$,

Table 7.3: Descriptive statistics for IPQ subscales across LOD conditions ($N = 24$, scale 0–6).

Subscale	**Condition**	***M***	***Mdn***	***SD***	**IQR**
SP	Realistic	4.12	4.20	1.17	1.35
	Low-poly	3.68	3.70	1.33	1.45
	Abstract	3.32	3.10	1.47	1.90
INV	Realistic	3.79	4.00	1.64	2.75
	Low-poly	3.37	3.38	1.57	2.31
	Abstract	3.46	3.50	1.72	3.06
REAL	Realistic	2.45	2.25	1.31	1.19
	Low-poly	1.67	1.25	1.48	1.06
	Abstract	1.50	1.38	1.27	1.06
GP	Realistic	3.71	4.00	1.68	2.25
	Low-poly	3.21	3.00	1.79	3.00
	Abstract	2.67	2.00	2.10	3.25

Table 7.4: Statistical results for IPQ subscales. SP: RM-ANOVA with paired t-test post-hoc; INV, REAL, GP: Friedman with Wilcoxon post-hoc. Only pairs surviving Bonferroni correction ($\alpha_{\text{adj}} = .017$) are listed.

Subscale	**Overall test**	**Effect size**	**Significant pairs**
SP	$F(1.37, 31.56) = 14.15$, $p < .001$	$\eta_g^2 = .059$	Realistic > Low-poly, Realistic > Abstract
INV	$\chi^2(2) = 6.66$, $p = .036$	$W = 0.139$	Realistic > Low-poly
REAL	$\chi^2(2) = 22.56$, $p < .001$	$W = 0.470$	Realistic > Low-poly, Realistic > Abstract
GP	$\chi^2(2) = 11.93$, $p = .003$	$W = 0.249$	Realistic > Abstract

$p < .001$), while Low-poly and Abstract did not differ significantly ($t(23) = 2.14$, $p = .043$, non-significant after Bonferroni correction).

7.3.2 Involvement

Normality was violated in the Abstract condition – the Friedman test was applied. A significant effect was found, $\chi^2(2) = 6.66$, $p = .036$, Kendall's $W = 0.139$, indicating a small effect. Post-hoc Wilcoxon tests revealed a significant difference only between Realistic and Low-poly ($W = 32.0$, $p = .011$), while Realistic vs. Abstract ($p = .049$) did not survive the Bonferroni correction, and Low-poly vs. Abstract was not significant ($p = .419$). The pattern was non-monotonic – Abstract scored marginally higher than Low-poly – and the effect size was the smallest of all subscales, suggesting that involvement is the least sensitive subscale to LOD differences in this study.

7.3.3 Realism

Normality was violated in the Low-poly and Abstract conditions – the Friedman test was applied. The result was highly significant, $\chi^2(2) = 22.56$, $p < .001$, Kendall's $W = 0.470$, representing a large effect and the strongest finding across all IPQ subscales. Post-hoc tests confirmed significant differences between Realistic and Low-poly ($W = 25.0$, $p = .003$) and between Realistic and Abstract ($W = 7.5$, $p < .001$), while Low-poly and Abstract did not differ ($W = 83.0$, $p = .628$).

7.3.4 General Presence

Normality was violated in the Abstract condition – the Friedman test was applied. A significant effect was found, $\chi^2(2) = 11.93$, $p = .003$, Kendall's $W = 0.249$, indicating a moderate effect. Post-hoc tests revealed a significant difference only between Realistic and Abstract ($W = 10.5$, $p = .003$), while Realistic vs. Low-poly was not significant ($p = .083$), and Low-poly vs. Abstract ($p = .022$) did not survive the Bonferroni correction. The result suggests that a meaningful drop in general presence occurs only at the extreme fidelity contrast, with the intermediate condition not distinguishable from either extreme after correction.

7.4 Heart Rate Analysis

Mean heart rate was computed for each participant across three phases of each scene: free exploration prior to the breathing exercise (Free 1), the paced breathing exercise (Breathing), and post-breathing free exploration (Free 2). As heart rate data were recorded as instantaneous bpm values derived from RR intervals by the application layer, with exact inter-beat timestamps unavailable, standard HRV metrics such as RMSSD could not be computed. Mean heart rate was therefore used as the primary physiological measure. Heart rate data were collected from 24 participants, two were excluded due to a connection failure resulting in incomplete data and failure to perform the breathing exercise, leaving 22 participants for the final analysis. As the exclusions were specific to the physiological data collection and did not affect the integrity of the questionnaire responses, all 24 participants were retained for the subjective measures (IPQ and VRSQ analyses).

A Friedman test was conducted separately for each phase to assess whether LOD condition had a statistically significant effect on mean heart rate. Results indicated no significant effect in any phase: Free 1 ($\chi^2(2) = 4.851$, $p = .089$, $W = .110$), Breathing ($\chi^2(2) = 3.364$, $p = .186$, $W = .076$), and Free 2 ($\chi^2(2) = 0.636$, $p = .728$, .014). These findings suggest that visual fidelity did not systematically influence autonomic arousal as measured by mean heart rate.

Although participants were not given a direct objective during the breathing exercise, correct execution caused the fountain's jet spray to lower to its minimum height. Participants reached the minimum in 58 of 66 recorded sessions; 18 out of 22 participants did so across all three conditions.

Descriptive statistics are presented in Table 7.5. Consistent with the statistical results, mean heart rate was nearly identical across all three conditions in every phase, with differences not exceeding 0.5 bpm between any two LOD conditions. Note that because all participants were exposed to each condition, individual differences in resting heart rate are pooled across conditions, limiting the interpretive value of raw per-condition means.

Table 7.5: Mean heart rate (bpm) per LOD condition and scene phase ($n = 22$).

Phase	Condition	Mean (bpm)	SD
Free 1	Realistic	84.17	11.56
	Low-poly	83.76	12.51
	Abstract	84.21	13.10
Breathing	Realistic	86.98	15.03
	Low-poly	86.37	14.64
	Abstract	86.51	15.92
Free 2	Realistic	87.39	14.07
	Low-poly	87.88	15.07
	Abstract	88.37	14.84

7.5 Post-Study Subjective Rankings

After completing all three conditions, participants ranked each scene on two dimensions: overall pleasantness and perceived realism. Rankings were converted to rank sums (1 = least preferred, 3 = most preferred, summed across all 24 participants; range 24–72), where a higher score indicates stronger preference.

Pleasantness

Rank sums for pleasantness were 63 for the Realistic scene, 41 for the Low-poly scene, and 40 for the Abstract scene. The Realistic scene was clearly the most pleasant condition, scoring notably higher than both stylised alternatives, which were rated nearly identically. This suggests that while participants could distinguish between the two lower-fidelity conditions on a realism dimension, they experienced them as equivalently less enjoyable relative to the realistic scene. The gap between the Realistic scene and the remaining two conditions (22–23 rank-sum points) indicates a meaningful step in subjective pleasantness between realistic and non-realistic rendering.

Perceived Realism

Rank sums for perceived realism were 68 for the Realistic scene, 48 for the Low-poly scene, and 28 for the Abstract scene, following a clean monotonic pattern aligned with the intended scene ordering. The Realistic scene was rated most realistic by a large margin, and the Abstract scene least realistic, confirming that participants perceived and ranked the visual fidelity manipulation as assumed. The 20-point gap between the Realistic and Low-poly scenes and the equal 20-point gap between the Low-poly and Abstract scenes suggest a roughly linear perceptual spacing across the three conditions.

Sense of Presence Across Conditions

Participants were asked in which environment they felt most strongly that they were actually there. The Realistic scene was selected by 17 of 24 participants, constituting a clear majority. The Abstract scene was chosen by 4 participants and the Low-poly scene by 3,

indicating a strong preference for the highest-fidelity condition across all three measures of subjective experience.

Perceived Comfort Across Conditions

Participants were asked which environment caused them the least discomfort. The Realistic scene was selected by 15 of 24 participants, the Abstract scene by 7, and the Low-poly scene by only 2.

These selections reflect subjective comfort judgements rather than cybersickness severity per se. Cybersickness – as operationalised by the VRSQ and capturing physiological symptoms such as nausea and disorientation – showed no statistically significant differences across conditions (Section 7.2), and overall VRSQ scores remained low across all three conditions. Perceived discomfort may therefore encompass factors beyond measurable sickness symptoms.

The most counter-intuitive finding is that 7 participants (29 %) preferred the Abstract scene over the Low-poly scene, despite the latter representing a more conventional middle ground between realism and abstraction. One possible interpretation is that a fully abstract, non-representational environment feels less cognitively demanding than a scene that retains recognisable geometry with visibly degraded fidelity. This distinction warrants further investigation: future work could examine what factors specifically drive perceived discomfort in VR environments of varying visual fidelity, independently of cybersickness induction.

Chapter 8

Discussion

This chapter interprets the findings reported in Chapter 7 in light of the research questions, situates them within the broader VR presence and cybersickness literature, and reflects on the limitations of the study and directions for future work.

8.1 Effect of LOD on Presence

The results suggest that visual fidelity influences presence in ways that are not straightforward. Across all four IPQ subscales, the Realistic condition consistently yielded the highest scores, while the two stylised conditions scored lower and were often statistically indistinguishable from each other.

8.1.1 Spatial Presence

Spatial presence showed the clearest and most statistically robust fidelity gradient (see Table 7.4), with significant differences between Realistic and both Low-poly and Abstract conditions, but no significant difference between Low-poly and Abstract after Bonferroni correction. The finding suggests that spatial presence is sensitive to whether the environment reads as realistic, but relatively insensitive to the degree of stylisation once a non-realistic rendering style is established. In other words, the transition from realism to any abstraction carries a meaningful perceptual cost, but further abstraction does not compound that cost proportionally.

This interpretation is corroborated by the post-study rankings: a clear majority of participants selected the Realistic scene as the environment in which they felt most strongly present.

8.1.2 Involvement

Involvement was the least sensitive subscale to LOD condition (see Table 7.4), and unlike the other subscales its pattern was non-monotonic: Abstract scored marginally higher than Low-poly. Involvement captures attentional engagement with the environment rather than the sense of physical presence within it [15], which may explain why it responded differently to the LOD manipulation than the remaining subscales. The Abstract scene's visual distinctiveness appears to have prompted active exploration and interpretation – participants examined and tried to identify objects rather than passively accepting the environment – which constitutes a form of engagement that the involvement items are sensitive to regard-

less of fidelity level. Participant feedback is consistent with this interpretation: several participants remarked that the Abstract scene prompted them to examine and interpret individual objects – for example, initially reading the Abstract rubbish bin as a sculptural artwork – which constitutes a form of attentional engagement even if it does not feel like naturalistic immersion.

8.1.3 Realism

Perceived realism showed the largest effect across all subscales (see Table 7.4), with a highly significant difference between Realistic and both lower-fidelity conditions, and no significant difference between Low-poly and Abstract. The post-study realism rankings supported this with a clean monotonic gradient, equally spaced across the three conditions, confirming that participants perceived and ordered the visual fidelity manipulation as designed.

8.1.4 General Presence

General presence showed a moderate effect (see Table 7.4), significant only for the Realistic versus Abstract contrast. The absence of a significant difference between Realistic and Low-poly suggests that participants' holistic sense of presence tolerated the Low-poly condition reasonably well, and that the perceptual threshold for a meaningful general presence decrement lies somewhere between the Low-poly and Abstract fidelity levels.

One participant described a presence dip specifically in the Realistic scene, finding its near-reality discrepancies more disruptive than the fully stylised environments – hinting at a U-shaped relationship where a near-realistic environment violates user expectations more than a consistently stylised one, consistent with the role of coherence in supporting Plausibility Illusion [18].

8.2 Effect of LOD on Cybersickness

No significant effect of LOD condition on cybersickness was found (see Section 7.2), and post-exposure scores were consistently lower than the elevated baseline across all three conditions. This is consistent with the sensory conflict hypothesis of cybersickness, which attributes symptoms primarily to vection (sensation of self-motion induced by visual stimuli [13]) and sensorimotor mismatch rather than visual fidelity alone [7], and aligns with the study design in which locomotion was limited to teleportation with no continuous self-motion.

While cybersickness did not differ across LOD conditions, participants did report rendering artifacts – notably aliasing and shimmering – as sources of visual discomfort. These artifacts arose as a consequence of anti-aliasing not being applied, and manifested differently depending on the LOD level: sharper edges in the Low-poly condition produced more perceptible aliasing, and shimmering was present in the Realistic condition due to animated foliage. Although these did not translate into measurable cybersickness differences, they represent a rendering quality confound that future studies should address by applying anti-aliasing consistently across all conditions.

8.3 Effect of LOD on Heart Rate

The Friedman test revealed no significant effect of LOD condition on mean heart rate in any scene phase (see Section 7.4), suggesting that visual fidelity did not produce differential autonomic arousal. As the test evaluates each participant relative to their own responses across conditions, individual differences in baseline heart rate do not confound the comparison, making this a robust null result.

Several factors may nonetheless account for this finding. Mean heart rate is a relatively insensitive physiological index, and higher-resolution HRV features, had they been measurable, may have revealed condition differences it obscures. Additionally, the 4-2-4-2 paced breathing protocol actively modulated heart rate during the Breathing phase, and this voluntary physiological regulation may have masked any subtle LOD-driven differences.

The observation that 18 out of 22 participants successfully reached the minimum fountain height during the breathing exercise across all three scenes confirms that the biofeedback mechanism functioned as intended and that participants engaged with the breathing task in all conditions, including the Abstract scene where the fountain's form was least naturalistic.

8.4 Rendering Quality as a Confounding Factor

A recurring theme in participant feedback was the role of rendering artifacts – shimmering and aliasing – in mediating the perceived quality of each scene. Multiple participants indicated that these artifacts were more disruptive to their experience than the LOD level itself, with one explicitly suggesting that shimmering and aliasing may have a larger influence than the graphic quality of the scene. This is an important methodological observation: in a within-subjects LOD comparison, any systematic difference in rendering artifacts prevalence across conditions constitutes a confound.

In the present study, aliasing was present across all conditions but most pronounced in the Low-poly condition due to its sharper geometric edges, while shimmering was observed in the Realistic condition due to animated foliage. Future work should apply anti-aliasing consistently across all conditions to avoid artifacts levels varying as a function of scene geometry.

8.5 Qualitative Patterns and Participant Observations

The open-ended feedback collected during and after sessions enriched the quantitative findings in several ways.

Sound as a presence anchor. Several participants commented positively on the fountain's water sound, describing it as calming and immersive across all conditions, suggesting it served as a consistent presence anchor independent of visual fidelity.

Curiosity and exploration in abstract environments. The Abstract scene prompted a distinct cognitive mode in several participants: rather than passively inhabiting the environment, they explored and interpreted it as a design intention. One participant initially perceived the Abstract scene as a garden of artworks, only recognising objects as park furniture after experiencing the higher-fidelity scenes. This suggests that radically abstract

environments may shift the user from an immersive mode to an aesthetic exploration mode, which has different implications for presence and task engagement.

Locomotion. One participant noted that teleportation-based locomotion felt limiting and suggested that continuous walking would have increased the sense of being in the environment. Teleportation is known to trade presence for comfort by eliminating the optic flow that causes cybersickness, though evidence on its precise effect on spatial presence is mixed [2]. This represents a design trade-off inherent to the study, and future work could explore whether locomotion modality interacts with LOD condition in its effect on presence.

8.6 Limitations

Several limitations of the present study warrant acknowledgment.

Sample characteristics. The sample was predominantly male and skewed toward the youngest age bracket, which limits generalisability. VR experience effects cannot be fully ruled out despite the familiarisation terminal scene, given that a substantial proportion of participants had minimal or no prior VR exposure.

Physiological measurement resolution. Heart rate was captured as instantaneous bpm values computed from RR intervals at the application layer, meaning raw inter-beat interval timestamps were not available for export. This precluded the computation of standard HRV metrics such as RMSSD, so mean heart rate served as the sole physiological measure. Access to direct RR interval streams would have permitted more nuanced HRV analysis and may have uncovered physiological differences between conditions that the mean measure was insufficiently sensitive to detect.

Rendering artifacts. As discussed in Section 8.4, differential aliasing and shimmering across conditions likely influenced perceived realism and comfort independently of the intended LOD manipulation.

Single-environment design. All conditions used variants of the same park scene. The generalisability of the findings to other scene types – indoor environments, abstract non-natural spaces, or dynamic scenes – is unknown.

Uncontrolled free exploration behaviour. During the free exploration phases, participants were not given a specific task or directed where to look, meaning different participants may have attended to different aspects of the scene. Future studies could benefit from a structured exploration protocol to ensure more comparable exposure across participants.

8.7 Implications and Future Work

The findings carry several implications for the design of VR applications where rendering budget is a constraint.

Spatial presence and perceived realism are meaningfully sensitive to the transition from realistic to stylised rendering, but relatively insensitive to the degree of stylisation thereafter. This suggests a non-linear relationship between visual fidelity and presence: if a

budget-constrained application cannot achieve full photorealism, further reductions beyond a clearly non-realistic threshold may not substantially worsen the user experience on most presence dimensions.

Cybersickness and mean heart rate were both robust to LOD variation in this study, suggesting that fidelity reduction does not introduce adverse physiological effects within the tested range.

The study also highlights that rendering artifacts quality – in this case the absence of anti-aliasing – may confound LOD comparisons by introducing perceptual differences unrelated to the intended fidelity manipulation. Future work should ensure artifacts levels are matched or measured across conditions.

Finally, one participant suggested decomposing the scene into constituent elements and testing them independently, which represents a promising direction for fine-grained LOD research and could inform targeted optimisation strategies for VR developers.

Chapter 9

Conclusion

This thesis evaluated the impact of environmental level of detail on user reactions in virtual reality, examining how fidelity affects subjective presence, cybersickness, and physiological response. Three virtual park environments were designed and implemented within the Project Ekhi framework – an **Abstract** scene composed of primitive geometric shapes, a **Low-poly** scene using stylised low-polygon assets, and a **Realistic** scene using detailed, naturalistic assets. A central design requirement shared by all three scenes was their role as biofeedback environments: all three depict the same park layout with identical object placement, differing solely in the visual fidelity of their assets, and each is built around a biofeedback fountain whose jet height is modulated in real time by the participant's heart rate variability. These design choices, alongside the limited hardware capabilities of the target platform, shaped key decisions across all three LOD levels, from the spatial layout and audio design to the consistency of the biofeedback element across conditions. The three scenes were evaluated in a within-subjects user study with 24 participants using the Meta Quest 2 headset. Each session consisted of three consecutive scene exposures, each lasting five minutes and following a fixed schedule: an initial free exploration phase, a structured paced breathing exercise at the biofeedback fountain and a final free exploration phase. User reactions were captured across three dimensions: subjective presence via the IPQ, cybersickness via the VRSQ, and physiological response via mean heart rate recorded with the Garmin HRM-Dual chest strap.

Across the subjective dimensions, LOD had a significant but non-linear effect on user reactions. The step from realistic to any stylised rendering produced a consistent and measurable shift: spatial presence and perceived realism dropped significantly when moving from the Realistic scene to either stylised alternative, and post-study realism rankings followed a clean monotonic gradient – Realistic, Low-poly, Abstract – confirming that participants perceived the three conditions as visually distinct and ordered them in accordance with their intended fidelity levels. User reactions to the Low-poly and Abstract scenes were largely indistinguishable – the two conditions did not differ significantly on spatial presence, realism, or general presence after correction – indicating that further reductions in detail beyond a non-realistic threshold do not proportionally worsen the subjective experience. General presence declined significantly only at the extreme contrast between the Realistic and Abstract conditions, with the Low-poly scene sustaining a level of overall presence not significantly different from either extreme. Involvement responded differently from the other subscales: its non-monotonic pattern, with Abstract scoring marginally above Low-poly, suggests that radically abstract environments can elicit a distinct curiosity-driven engagement that partially compensates for reduced fidelity on this dimension.

In terms of comfort and physiological reactions, LOD had no measurable impact. Cybersickness scores did not differ significantly across conditions, and post-exposure VRSQ scores were consistently lower than the elevated pre-exposure baseline, indicating that all three environments were well tolerated. Heart rate similarly showed no significant differences across LOD conditions in any scene phase.

The paced breathing biofeedback exercise produced consistent physiological engagement across all three environments, including the fully Abstract scene: 18 out of 22 participants successfully reached the target fountain response in every condition. This finding confirms that the biofeedback mechanism embedded in the Project Ekhi framework – a collaborative initiative between the Faculty of Information Technology, Brno University of Technology, and the University Hospital Brno, Department of Psychiatry – is robust to substantial variation in environmental visual style. Beyond their role as experimental stimuli, the three scenes developed in this thesis are intended to serve as reusable therapeutic environments within Project Ekhi, deployable in a clinical psychiatric setting as guided biofeedback experiences. Their differing visual character may accommodate varying patient needs or preferences, and the present findings suggest that even the most abstract variant is capable of supporting the biofeedback interaction for which the scenes were designed.

Several limitations constrain the interpretation of these findings. The sample was skewed toward young male participants, limiting generalisability across age groups and genders. Anti-aliasing was disabled across all conditions to favour rendering performance on the target hardware, which introduced differential artifacts and constitutes a confound that future studies should address. All conditions were variants of a single outdoor park scene, so the generalisability of the observed reaction patterns to other environment types remains an open question.

Future work could further isolate the LOD effect by ensuring rendering artifacts levels are consistent across conditions, and extend comparisons to other environment types such as indoor, abstract, or dynamically structured environments. A targeted approach suggested by participants – evaluating individual scene objects across LOD levels in isolation before assembling full environments – could yield finer-grained insight into which elements drive user reactions most strongly, and inform practical optimisation decisions for VR developers working under rendering constraints. The findings of this work suggest that environmental level of detail shapes user reactions in measurable but bounded ways: the transition from realistic to stylised rendering carries a real perceptual cost, while further reductions within the stylised range leave most dimensions of user reaction largely unchanged.

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Appendix A

Consent Form

Souhlas s účastí ve výzkumu

Potvrzuji, že jsem byl/a podrobně informován/a o výzkumné studii, která je součástí bakalářské práce studenta Ondřeje Jakuba Chromého na Fakultě informačních technologií Vysokého učení technického v Brně. Vše mi bylo sděleno a vysvětleno jasně a srozumitelně. Měl/a jsem dostatek času si vše zvážit, mohl/a jsem klást otázky a obdržel/a jsem na ně jasné a srozumitelné odpovědi.

Veškerá data získaná v průběhu studie jsou sbírána **anonymně** – žádný identifikátor ani jméno účastníka není v žádném okamžiku spojeno se zaznamenanými daty.

Na základě výše uvedených informací:

☐ Souhlasím s účastí ve výzkumu v rámci bakalářské práce na téma *"Hodnocení vlivu úrovně detailu prostředí ve virtuální realitě v kontextu reakcí uživatelů"* na FIT VUT v Brně.

☐ Souhlasím s možným budoucím využitím anonymních dat pro další výzkumné účely v oblasti počítačové grafiky, virtuální reality a interakce člověka s počítačem.

Účastník/účastnice studie:

Jméno a příjmení: _____ Podpis: _____

Místo: _____ Datum: _____

Za výzkumný tým (autor práce):

Jméno a příjmení: _____ Podpis: _____

Místo: _____ Datum: _____

Appendix B

Demographic Questionnaire

Tento dotazník slouží pro výzkumné účely v rámci bakalářské práce. Odpovědi jsou anonymní a budou použity pro analýzu uživatelských reakcí ve virtuální realitě. Anonymizovaná data mohou být v budoucnu využita také pro další výzkum v oblasti počítačové grafiky, virtuální reality a interakce člověka s počítačem.

Demografické údaje

1. **Věk**
   Méně než 18 18–24 25–34 35–44 45–54 55–64 65–74 75 a více

2. **Pohlaví**
   Muž Žena Jiné: _____

3. **Dosažené vzdělání**
   Žádné Základní Středoškolské bez maturity Středoškolské s maturitou
   Vyšší odborné Vysokoškolské (Bc.) Vysokoškolské (Mgr./Ing.) Vysokoškolské (Ph.D.)
   Jiné: _____

4. **Jaká je vaše hlavní činnost?**
   Student Pracující Student i pracující Nezaměstnaný/á Jiné: _____

5. **Jaký je váš studijní nebo pracovní obor?**
   Informatika / IT / Kybernetika Elektrotechnika / Elektronika Strojírenství / Mechatronika
   Architektura / Stavebnictví Přírodní vědy (matematika, fyzika, chemie, biologie...)
   Medicína / Zdravotnictví / Farmacie Psychologie / Sociální vědy
   Ekonomika / Finance / Management Právo Humanitní vědy (filozofie, historie, jazyky...)
   Umění / Design / Média Pedagogika / Školství Jiné: _____

Zkušenosti s technologiemi

6. **Hraní videoher**
   Vůbec nehraji Příležitostně (méně než 1× týdně) Pravidelně (1–3× týdně) Denně

7. **Kolikrát jste vyzkoušeli virtuální realitu?**
   Nikdy 1–2× 3–10× Více než 10×

Virtuální realita

8. **Jak často používáte VR?**
   Méně než 1× měsíčně 1× měsíčně Několikrát měsíčně 1× týdně
   Několikrát týdně Denně

9. **Jak dlouho jste strávili ve virtuální realitě?**
   Méně než 1 hodinu 1–5 hodin 5–20 hodin Více než 20 hodin

10. **Už jste někdy zažil/a nevolnost ve VR?**
    Ano Ne

Výskyt nevolnosti

11. **Trpíte nevolností při jízdě v autě?**
    Ano Ne

12. **Trpíte nevolností při čtení v pohybu?**
    Ano Ne

Appendix C

IPQ – Czech Translation

Scale: 1–7 (anchors vary per item as listed below)

1. V počítačem generovaném světě jsem měl/a pocit, že tam skutečně "jsem".
   1 = Vůbec ne – 7 = Velmi silně

2. Nějak jsem cítil/a, že mě virtuální svět obklopuje.
   1 = Zcela nesouhlasím – 7 = Zcela souhlasím

3. Měl/a jsem pocit, že vnímám jen obrázky.
   1 = Zcela nesouhlasím – 7 = Zcela souhlasím

4. Necítil/a jsem se přítomný/á ve virtuálním prostoru.
   1 = Vůbec jsem se necítil/a – 7 = Rozhodně jsem se cítil/a

5. Měl/a jsem pocit, že jednám ve virtuálním prostoru, spíše než že ovládám něco z vnějšku.
   1 = Zcela nesouhlasím – 7 = Zcela souhlasím

6. Cítil/a jsem se přítomný/á ve virtuálním prostoru.
   1 = Vůbec ne – 7 = Rozhodně ano

7. Jak moc jste si byli vědomi reálného okolního světa při navigaci ve virtuálním světě? (tj. zvuků, teploty v místnosti, ostatních lidí atd.)?
   1 = Zcela si vědom/a – 7 = Vůbec si nevědom/a

8. Nevnímal/a jsem své skutečné okolí.
   1 = Zcela nesouhlasím – 7 = Zcela souhlasím

9. Stále jsem věnoval/a pozornost skutečnému okolí.
   1 = Zcela nesouhlasím – 7 = Zcela souhlasím

10. Byl/a jsem zcela ponořen/a do virtuálního světa.
    1 = Zcela nesouhlasím – 7 = Zcela souhlasím

11. Jak reálný se vám virtuální svět zdál?
    1 = Zcela reálný – 7 = Nereálný

12. Do jaké míry byl váš zážitek ve virtuálním prostředí shodný s vaší zkušeností ze skutečného světa?
    1 = Vůbec ne – 7 = Zcela

13. Jak reálný se vám virtuální svět zdál?
    1 = Přibližně jako imaginární svět – 7 = Nerozeznatelný od skutečného světa

14. Virtuální svět vypadal reálněji než skutečný svět.
    1 = Zcela nesouhlasím – 7 = Zcela souhlasím

Appendix D

VRSQ – Czech Translation

Scale: 0 = žádné 1 2 3 = velmi silné/á

1. Celkové nepohodlí
2. Únava
3. Únava očí
4. Potíže s ostřením pohledu
5. Bolest hlavy
6. Pocit tlaku / plnosti v hlavě
7. Rozmazané vidění
8. Závrať (se zavřenýma očima)
9. Točení hlavy

Appendix E

Final Post-Study Questionnaire

Závěrečné otázky

1. Všiml/a jste si nějakých rozdílů mezi třemi virtuálními prostředími, která jste navštívil/a? Pokud ano, popište, co jste si všiml/a.

   _____

2. Seřaďte tři prostředí od nejpříjemnějšího po nejméně příjemné.
   Nejvíce příjemné: _____ Druhé nepříjemnější: _____ Nejméně příjemné: _____

3. Seřaďte tři prostředí od nejreálněji vypadajícího po nejméně reálné.
   Nejreálnější: _____ Druhé nejreálnější: _____ Nejméně reálné: _____

4. Ve kterém prostředí jste měl/a nejsilnější pocit, že tam skutečně jste?
   Prostředí 1 Prostředí 2 Prostředí 3

5. Ve kterém prostředí jste pociťoval/a nejmenší nevolnost či nepohodlí?
   Prostředí 1 Prostředí 2 Prostředí 3

6. Volná zpětná vazba

   _____

Appendix F

Third-Party Asset Credits

This appendix lists all third-party assets used in the study scenes, together with their sources and licenses. All URLs were accessed on 2025-04-15.

Sound

Table F.1: Sound assets

Asset	Author	License
Bubbling fountain https://freesound.org/people/cognito%20perceptu/sounds/36086/	cognito perceptu	CC0

Abstract Scene

No additional third-party assets were used.

Low-Poly Scene

Table F.2: Low-poly scene assets

Asset	Author / Publisher	License
Wooden texture background designed by Freepik https://www.freepik.com/free-vector/wooden-texture-background_851099.htm	dotstudio	Freepik Free
Fantasy Skybox Free https://assetstore.unity.com/packages/2d/textures-materials/sky/fantasy-skybox-free-18353	Render Knight	Unity AS EULA
Handpainted Grass & Ground Textures Free https://assetstore.unity.com/packages/2d/textures-materials/nature/handpainted-grass-ground-textures-top-down-rpg-terrain-tool-187634	Chromisu	Unity AS EULA
Low-Poly Park https://assetstore.unity.com/packages/3d/environments/urban/low-poly-park-61922	Thunderent	Unity AS EULA
Low-Poly Simple Nature Pack https://assetstore.unity.com/packages/3d/environments/landscapes/low-poly-simple-nature-pack-162153	JustCreate	Unity AS EULA
Low Poly Environment Park https://assetstore.unity.com/packages/3d/environments/low-poly-environment-park-242702	Palmov Island	Unity AS EULA

Realistic Scene

Table F.3: Realistic scene assets

Asset	Author / Publisher	License
Red Plaster Weathered (texture) https://polyhaven.com/a/red_plaster_weathered	Amal Kumar	CC0
Plastered Wall (texture) https://polyhaven.com/a/plastered_wall	Amal Kumar	CC0
Metal Gate (model) https://www.cgtrader.com/free-3d-models/exterior/house/gate-metal	Nicos60	CGTrader RF
Realistic Terrain Textures Free https://assetstore.unity.com/packages/2d/textures-materials/floors/realistic-terrain-textures-free-279940	ALP	Unity AS EULA
Low Poly Park Pack (FastMesh) https://assetstore.unity.com/packages/3d/environments/urban/low-poly-park-pack-created-with-fastmesh-asset-292938	Fast Mesh	Unity AS EULA
Low Poly Environment Nature Free https://assetstore.unity.com/packages/3d/environments/low-poly-environment-nature-free-lowpoly-medieval-fantasy-series-187052	Polytope Studio	Unity AS EULA