Investigating Rollenwahrnehmung, Perspective and Space through Virtual Reality related Game Interfaces

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Dedicated to my parents
Maria Elisabeth Wiedemann & Otto Allgaier

We do not stop playing because we grow old, we grow old because we stop playing!
– *Benjamin Franklin*

Unfortunately, no one can be told what the Matrix is. You have to see it for yourself.
– *Morpheus. The Matrix* (1999)

For me, the cool thing is doing things that could only be done in gaming.
– Warren Spector

Immersion: The pleasurable surrender of the mind to an imaginative world ...
– Janet H. Murray. Hamlet on the Holodeck: The Future of Narrative in Cyberspace (1997)

INVESTIGATING ROLLENWAHRNEHMUNG, PERSPECTIVE AND SPACE THROUGH VIRTUAL REALITY RELATED GAME INTERFACES – *DANIEL P. O. WIEDEMANN*

ABSTRACT

This thesis describes my explorations and investigative reflections on *Rollenwahrnehmung* (a newly coined phrase meaning role perception/fulfillment), *Perspective* and *Space* through *Virtual Reality (VR)* game interfaces.

Throughout this narrative, a number of important topics, relating to my thesis, will be addressed, like the creation of new experiences in the context of *VR*, the extension and new development of various interaction paradigms, various *User Experience* aspects and user guidance in a sophisticated new medium.

My research, placed in the field of design practice, focuses on the creation of digital gaming artifacts, while extrapolating insights and guidelines concerning *VR* interfaces. Both closely intertwined strands will be discussed in the narrative context of investigating the user's *Rollenwahrnehmung, Perspective* and *Space.*

The thesis describes practice-based research derived from a portfolio of specifically developed interactive artifacts, following the methodological approach of *Constructive Design Research (CDR)*. These include the games *Nicely Dicely*, *LizzE – And the Light of Dreams* and *Gooze*. They were used for user testing sessions during various *Lab* experiments and *Showroom* presentations (components of the *CDR* approach), while continually being refined throughout an iterative process.

Nicely Dicely is an abstract game based on physics. In *Local Multiplayer,* up to four players are able to compete or collaborate. It is not a *VR* game per se, but features both, *Monoscopic* and *3D Stereoscopic Vision* modes. As the latter is an important aspect of *VR,* this game was used to primarily investigate if *3D Stereoscopic Vision* increases *Player Immersion*, even in a possibly distracting *Local Multiplayer* game. Among further insights, the results confirmed that *Player Immersion* is increased when using a *3D Stereoscopic Presentation* compared to a *Non-3D Monoscopic* one.

LizzE – And the Light of Dreams is a *Singleplayer 3rd Person Hack and Slay* game based in a fantasy universe. The game basics were previously developed and further extended during this research. In an experiment, the game was used to primarily investigate in which ways *3rd Person VR* games can work for a broad audience. Five different *3rd Person* camera behavior modes were tested for their *Player Enjoyment* and *Support of Gameplay,* while closely looking at their influence on *Simulator Sickness.* The results led to using a default camera behavior based on the *Buffered Pulling* approach but providing users with the option to switch to a behavior based on the *Blink Circling* approach instead.

Gooze is a *1st Person VR* puzzle game, taking place in a realistic horror environment with supernatural aspects. It was designed with diverse *VR* interaction technologies in mind and offers users different options to play the game, depending on available hardware and preferences. In an experiment, the game was used to primarily investigate how three different interaction setups and their underlying *Locomotion* and *Virtual Object Interaction* mechanics affected several *User Experience (UX)* aspects like: *Player Enjoyment, Support of Gameplay,*

Simulator Sickness and *Presence*, with the latter being subdivided into the four sub-parameters: *General Presence*, *Spatial Presence*, *Involvement* and *Experienced Realism*. The results led to a detailed comparison of individual advantages and disadvantages of the assessed interaction modes and their mechanics.

The research is reported in three sections, one per artifact. Each section gives an overview of the artifact and documents its mechanics, style, content, feature set and discusses its design and development process. Furthermore, each section elaborates on the *Lab* and *Showroom* user studies that have been undertaken and their outcomes.

In summary, this thesis in combination with the portfolio of games, contribute to knowledge by providing three unique and documented artifacts, illustrating various game, interface and *VR* designs, extending the *CDR* approach to *VR* game development and informing the emerging field of the relationship between *UX*, interfaces and gameplay. Each single artifact and the whole collection can be used as a design and development precedent for practice and academia. Furthermore, guidelines for designing and developing specific aspects of *VR* games were identified, the experience related term of *Rollenwahrnehmung* was established in the area of *VR*, a *Hybrid Journaling Technique* was developed, using versioning commits for design reflection and an extension of *Constructive Design Research* to the field of digital games creation was undertaken. Additionally, this thesis offers a reflected rationale of different *VR* game interfaces affecting *Rollenwahrnehmung*, *Perspective* and *Space*. Eventually, it further provides an outlook on possible areas for future research, related to the overall study in a more general sense and more specific to individual artifacts and corresponding studies.

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My girlfriend **Katalin Klänhardt, I** thank with all my heart for her patience, motivation, participation and helping love.

CITATION STYLE

Throughout this thesis a form of the *Harvard* citation style is used. Inline quotes will either directly cite "the precise wording enveloped by quotation marks" or paraphrase its content and reference (Author/s date) in parentheses or directly in the text. The reference's details can be looked up in the section *References* from page 185ff.

Alterations or amendments to direct quotes are [enveloped by square brackets] and are only made to improve understanding of the text, filling in contextual gaps, making references to other elements of this thesis and enhancing the reading comfort, but do not alter the meaning of the quote in any way.

When citing a longer relevant passage or paragraph, the following design will present a precisely worded direct quote and its author and date:

> “ This might be a longer precisely worded passage or paragraph from a relevant reference, cited in a format convenient to the reader.
> (Author/s date)

INVESTIGATING ROLLENWAHRNEHMUNG, PERSPECTIVE AND SPACE THROUGH VIRTUAL REALITY RELATED GAME INTERFACES

DR. DANIEL P. O. WIEDEMANN

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1 INTRODUCTION

"Virtual Reality is like dreaming with your eyes open." (Spiegel 2016) and although the basic concept and realization were developed in the early 1960s, the assumption that its current implementation may offer endless possibilities and starts redefining how people live, work and play, has now become a significant cultural driving force (Luckey 2015).

In developer circles however, it seems a generally held view that we are still at the very beginning of understanding and handling the paradigms intrinsic to the medium, to enable us to create really enjoyable applications. So, "What the community now desperately needs is for content developers to understand human perception as it applies to *VR,* to design experiences that are comfortable (i.e., do not make you sick), and to create intuitive interactions within their immersive creations." (Jerald 2016).

Because of this unique and pivotal situation of laying the foundations of this significant medium, "We now have the opportunity to change the world [so] let's not blow it!" (Fuchs 2014).

The following thesis describes the context, the methodological process and the outcome of my *PhD* research investigating the three key areas of *Rollenwahrnehmung* (will be explained in detail later on, see page 4), *Perspective* and *Space* through *Virtual Reality (VR)* game interfaces. This research will focus on three designed artifacts in the form of digital games. As an overall methodology, *Constructive Design Research (CDR,* Koskinen et al. 2011) has been chosen for this study, because of its flexibility and focus on research through creation. Thus, three custom developed and unique digital gaming artifacts related to *VR* technologies form the core of this practice-based design research and its contributions to knowledge. This thesis further elaborates on how they were designed and developed and which diverse insights and extrapolated guidelines for *VR* games could be gathered by that.

Eventually, it discusses further contributions to knowledge, regarding establishing the term *Rollenwahrnehmung,* the applied *Hybrid Journaling Technique* using versioning repositories for reflection and the extension of *CDR* to the field of digital games.

1.1 PHD DESIGN RESEARCH PROCESS

This section will show how these contributions to knowledge evolved and in which ways the corresponding research process developed.

As is common in design research, the overall process for this *PhD* study was not a linear one (Markowski 2016, Phillips and Pugh 2005). It was clear from the beginning in 2014, that research involving the construction of digital games would form one major pillar of this *PhD* study. Investigating new approaches to enhance player experience in games would form the second one. This was undertaken through the creative as well as useful integration and sense making of novel interface technologies (e.g. gesture recognition, touch interfaces, interactive projections, *3D Stereoscopy, Augmented Reality - AR* and *Virtual Reality - VR).*

It was only over time and implementation of the first iteration of artifacts, that this research developed from exploring novel interface technologies in general to being more focused on *VR* related interfaces in particular. In certain flavors, *VR* already encompasses technologies that facilitate the use of novel interfaces like gesture recognition, skeletal tracking, *3D Stereoscopy* and many more (Jerald 2016). At the same time burgeoning public interest was stimulating a flourishing research and development scene. Faced with various design challenges, e.g. like managing *Simulator Sickness* and implementing mechanics and novel interaction paradigms fitting the versatile hardware capabilities, *VR* stood out as an ideal candidate for further explorations. After evaluating the first artifact iterations and while being guided by technological developments and an enthusiasm to investigate and develop diverse designs, it became clear, that this research would not lead to one generalized model. Instead, it led to a collection of transferrable specific insights related to digital games and *VR,* grounded in those same artifacts and their design and development.

Emphasizing the construction of artifacts and embracing non-linear design processes, *CDR* (Koskinen et al. 2011) was chosen as an overarching methodology. Providing proven and established flexible research toolsets, focusing strongly on the constructive process and supporting reflections, *CDR* offered sufficient explorative freedom and guidance whilst providing a framework for answering the emerging research questions. *CDR* will be discussed in detail in the sections *Literature* (see from page 17ff.) and *Methodology* (see from page 57ff.).

Beginning with a general interest in game design and novel interfaces, the central themes became clearer through later reflections. The three key areas *Rollenwahrnehmung, Perspective* and *Space* were introduced to interconnect what has been accomplished in this *PhD* research. For a better understanding of the process, the overall research has been structured into three partly overlapping time phases (see Figure 1).

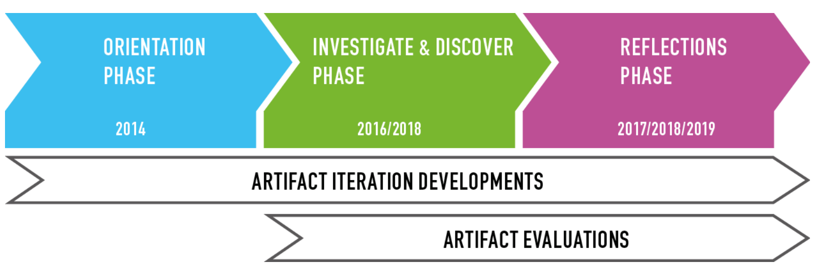


Figure 1: Timeline and phases of this PhD research

During the *Orientation* phase in 2014, at least first iterations of all three artifacts of the overall study were developed. Preliminary *Stereoscopic 3D* and *VR* versions of *LizzE* were developed (v2A/v2B), as the game including its full source code was already available and a *3rd Person VR* game seemed a rather unusual concept, compared to *1st Person VR.* As a developer, the technical skills to competently integrate the necessary technologies were established and the need to test various camera behavior modes to inform the initial game designs emerged. *Gooze* on the other hand, was developed from the ground up for *1st Person VR.* This provided a clean start in terms of *VR* game development and a platform to explore emerging design challenges, which eventually focused on *VR Locomotion (LOC)* and *Virtual Object Interaction (VOI).* The game *Nicely Dicely* started off as a game jam project that did not lead to a *VR* game per se, but later proved to be a perfect example for investigating a significant aspect of *VR*, namely *Stereoscopic 3D* and to include the *Multiplayer* element into the overall research. The three games were all radically different in concept from each other, to provide a greater field for exploration and investigation.

The first design challenges became apparent, while presenting the artifacts at *Showroom* events (see section *Methodology* from page 57ff.). Furthermore, in this phase, an understanding of the scope of this field of study emerged, though it was in later phases, that the actual scope of this *PhD* research became apparent. During most of 2015, my *PhD* studies were suspended, because of my work on a commercial project. Nevertheless, during this time I was able to improve certain development skills and to reflect on my previous research and an interconnecting preliminary structure was established.

Roughly at the beginning of 2016, the *Investigate & Discover* phase started. During this time, the two artifacts *Nicely Dicely* (see from page 71ff.) and *LizzE – And the Light of Dreams* (see from page 104ff.) traversed through further development iterations. Two related *Lab* studies (see section *Methodology* from page 57ff.) were conducted on the effect of *3D Stereoscopy* on *Immersion (Nicely Dicely)* and on the impact of *3rd Person VR* camera behavior modes *(LizzE)* on *User Experience (UX).* Through this process, further design challenges arose or became concrete and specifically developed solutions, as well as the artifacts themselves, could be evaluated. After the *Transfer* from *MPhil* to *PhD* and switching to part-time research, the third artifact *Gooze* was developed further and one final *Lab* study comparing different *VR Locomotion* and *Virtual Object Interaction* mechanics was conducted in 2018. This fitted well in the previously established research scheme exploring diverse *VR* interfaces with diverse game designs: One *Multiplayer* game investigating *Player Immersion,* one *Singleplayer* game investigating *3rd Person VR* camera behavior and a second *Singleplayer* game investigating *1st Person VR Locomotion* and *Virtual Object Interaction* mechanics. The outcomes of the three corresponding *Lab* studies complemented the overall study's contribution to knowledge and the collection of the three games represented a rich and diverse portfolio with very unique artifacts.

During the *Reflections* phase from 2017 to 2019, the artifacts, the previous corresponding research projects and their outcomes were structured in a central theme alongside the three key areas *Rollenwahrnehmung, Perspective* and *Space.* This was possible, by further reflectively evaluating the artifacts themselves.

For a chronological overview of artifact development phases and corresponding *Showroom* and *Lab* studies, see Figure 27 on page 70 in the section *Critical Reflection: Artifacts & Studies.*

1.2 KEY DEFINITIONS

The previously mentioned central theme of the thesis is arranged along the three key areas *Rollenwahrnehmung, Perspective* and *Space.* During the reflection on the accomplishments of this *PhD* research, these three areas in particular emerged and became clearer, as they best circumscribed the diverse underlying essence of the different research artifacts, while at the same time being able to interconnect them and provide a core structure for the thesis. Each artifact gives different answers to the questions of how players perceive and fulfill their role *(Rollenwahrnehmung),* a current perspective (visually and/or metaphorically) and the space around them (virtual and/or real). As will become apparent, the topics of *Virtual Reality (VR)* and *User Experience (UX)* play a fundamental role throughout this research, too.

These terms may be interpreted in various ways by numerous disciplines (e.g. *Human Computer Interaction (HCI),* philosophy and psychology). Thus, the following will give working definitions for them, which relate specifically to this thesis.

1.2.1 ROLLENWAHRNEHMUNG

Rollenwahrnehmung is a German term, which can be loosely translated into English as "role perception" but also "role fulfillment". This term was established for this thesis to describe the perception and fulfilling relationship of a user or player with his or her virtual representation – visible or invisible – within the artifact or game in the context of the current *User Experience (UX).* In other words, it describes in which ways the user recognizes the virtual role or character he or she is appointed to and how the user fulfills this part. E.g. a user could identify with a visible playable character or instead with the disembodied but interactive camera looking at that character. Additionally, the player may want to or even need to fulfill an appointed role to proceed within the game. For more details see section *Rollenwahrnehmung* from page 19ff.

1.2.2 PERSPECTIVE

Perspective either refers to the visual perspective, representing three-dimensional objects in a three-dimensional space from a certain point of view or the metaphorical equivalent of someone having a particular attitude towards a certain matter. This will be apparent from the context. E.g. a group of simultaneous players could share one visual *Perspective* on a game, or each player could be provided with an individual *Perspective* via a split screen design. In the metaphorical sense of the term, the *Perspective* of the player character on the storyline of a game could be clearly articulated, or it could be obscured, so the player can form his or her own thoughts instead. For more details see section *Perspective* from page 21ff.

1.2.3 SPACE

If not expressed differently, *Space* refers to the virtual space (e.g. the space of a *Virtual Environment (VE)* surrounding the player character), the actual physical space around the player or the mental space in which the player's mind might reside at some point. This will be apparent from the context. E.g. depending on the interaction mechanic design, a player may need large or little physical *Space* to properly perform within a game.

Furthermore, a technology like *VR* may fundamentally transform *Space* for the user, from simply looking through a window into a virtual world, to being completely encompassed by that world. For more details see section *Space* from page 22ff.

1.2.4 VIRTUAL REALITY (VR)

The *International Organization for Standardization (ISO)* defines *Virtual Reality (VR)* as a:

> set of artificial conditions created by computer and dedicated electronic devices that simulate visual images and possibly other sensory information of a user's surrounding with which the user is allowed to interact
> (ISO 2020)

This is further elaborated on with the following note:

> The artificial conditions do not reflect a user's real-time physical environment.
> (ISO 2020)

In other words, in relation to this thesis, *Virtual Reality (VR)* describes a solely virtual simulation, in which a possibly interacting user feels completely enclosed, with little or no reference to the physical reality (Sherman and Craig 2003 and Jerald 2016). In the most common case this involves the use of a *VR Head Mounted Display (HMD)* to track the user's position, movement and orientation in quasi real-time, which adjusts the virtual simulation accordingly. Thus, the user may think he or she is present in that *VE*.

Additionally, the *VR HMD* usually provides *3D Stereoscopic Vision* for the user (i.e. each eye is presented with a slightly different image). *3D Stereoscopy* is a very important aspect of *VR*, as it helps the user to perceive depth in the *VE*. Thus, this topic will be further elaborated on throughout this thesis (see e.g. sections *Stereoscopic 3D* from page 28ff. and *Nicely Dicely* from page 71ff.).

1.2.5 USER EXPERIENCE (UX)

User Experience (UX) is a complex concept, which is reflected in there being at least 27 definitions (All About UX n.d.). The *ISO* defines *UX* with the following words:

> user's perceptions and responses that result from the use and/or anticipated use of a system, product or service
> (ISO 2019)

This is further elaborated on with the following notes:

> “ Users’ perceptions and responses include the users’ emotions, beliefs, preferences, perceptions, comfort, behaviours, and accomplishments that occur before, during and after use.
> (ISO 2019)

> “ User experience is a consequence of brand image, presentation, functionality, system performance, interactive behaviour, and assistive capabilities of a system, product or service. It also results from the user’s internal and physical state resulting from prior experiences, attitudes, skills, abilities and personality; and from the context of use.
> (ISO 2019)

In other words, in relation to this thesis, *UX* describes the overall experience a user might have with an artifact (Bernhaupt 2010 and Koskinen et al. 2011). This includes all possible sensory aspects of a user, psychological effects provided through the artifact, the influential surrounding context and how all of this affects the user’s perception of certain aspects of the artifact or the artifact as a whole.

For an exhaustive glossary related to this thesis, including acronyms, see *Appendix A. Glossary & Acronyms* from page 197ff. and for a more in-depth contextualization of the three key areas see section *Clarifying Ambiguous Key Areas* from page 19ff.

1.3 RESEARCH QUESTIONS

In accordance with the previously mentioned *CDR* approach, which focuses on deriving knowledge through constructing designed artifacts, my initial overall research idea was concerned with designing and creating digital games and investigating different ways in which novel game interfaces may affect the player's experience. Corresponding, more specific research questions, with a focus on *VR* game interfaces, became focused only over time. Thus, over the period of this research, my main guiding research question developed to the following:

- **In which ways may *VR* game interfaces affect *Rollenwahrnehmung, Perspective* and *Space* for the player?**

This overall question naturally includes the three following contributory sub-questions, which will be answered through different aspects extrapolated from the creation and evaluation of the three artifacts of the overall study:

- **In which ways may *VR* game interfaces affect *Rollenwahrnehmung* for the player?**
- **In which ways may *VR* game interfaces affect *Perspective* for the player?**
- **In which ways may *VR* game interfaces affect *Space* for the player?**

Further individual research sub-questions have been addressed in dedicated experiments, presentational examinations and reflective discourses during this research. This either resulted in extending design guidelines for *VR* game interfaces, which is a general necessity for developing *VR* games, or in adding to answer the overarching research questions above or both.

These further sub-questions include:

- **In which ways can *3D Stereoscopy* affect *Immersion* for the player of a *Local Multiplayer* game?**
- **In which ways can *3D Stereoscopy* affect gameplay for the player of a *Local Multiplayer* game?**
- **In which ways can *3rd Person VR* games work for a broad audience?**
- **In which ways can *VR Locomotion* mechanics affect the *User Experience* of a player?**
- **In which ways can *VR Virtual Object Interaction* mechanics affect the *User Experience* of a player?**

One further research question is concerned with the applied reflection technique using versioning repositories for journaling:

- **In which ways can versioning repositories, used in software developments, contribute to journaling aimed for reflection?**

By applying different *Lab* and *Showroom* methods as well as reflection within the framework of *CDR,* the previous research questions will be answered in this thesis and lead to the following contributions to knowledge.

1.4 AIMS & CONTRIBUTIONS TO KNOWLEDGE

This doctoral research aimed to explore *VR* and gaming by creating three exemplary and individual artifacts. This resulted in different types of contributions to the overlapping areas of: *Human Computer Interaction (HCI),* design research, *Virtual Reality* research, games research, interaction design, game design and game development. In parts led by the previous research questions, the following contributions to knowledge will be established through the overall study.

1.4.1 THREE DIGITAL GAME ARTIFACTS

- The collection of unique digital games related to *VR,* documented in this thesis, serves in whole as a complex precedent. It contributes to academia by demonstrating work at a doctoral level, focusing on the construction of digital games and to practice by providing inspiration and guidance for a diverse range of digital games. Each artifact on its own individually contributes to knowledge as a dedicated precedent for research and practice:
  - *Nicely Dicely* and its *Immersion* related examinations will be of interest to the research communities of *HCI* and *Virtual Reality* research, as well as interaction and game design.
  - *LizzE – And the Light of Dreams* and its *3rd Person VR* focused investigations contributes to the research areas of *VR* and games, as well as game design and development.
  - *Gooze* and its insights in designing a *VR* game from the ground up, including *1st Person VR Locomotion* and *Virtual Object Interaction* mechanics will be particularly useful for *HCI* and *Virtual Reality* research, as well as the design and development of *VR* games.

1.4.2 GUIDELINES FOR SPECIFIC ASPECTS OF VIRTUAL REALITY GAMES

- Extrapolated from the three artifacts and in this thesis joined into a set, these guidelines will inform *Virtual Reality* research and design and development of *VR* games and *VR* experiences in general.

1.4.3 ROLLENWAHRNEHMUNG, PERSPECTIVE & SPACE

- Established to describe the relationship and perception of a user with his or her virtual representation within an artifact, the term *Rollenwahrnehmung* contributes to the areas of philosophy, psychology and game design.
- The reflected rationale of different *VR* game interfaces affecting the user's *Rollenwahrnehmung, Perspective* and *Space*, contributes to design, *VR* and games research, as well as inspires game design.

1.4.4 EXTENDING CONSTRUCTIVE DESIGN RESEARCH

- By using *CDR* as the overarching methodology for this study, it introduces *CDR* as an adaptive and reflective methodology for the development and design of digital games and *VR* artifacts. This contributes to the communities based in the areas of design, *Virtual Reality* and games research, as well as interaction and game design.

- The rationales behind the several conducted *Lab* and *Showroom* examinations of artifacts will be of interest to designers and researchers alike.

1.4.5 HYBRID JOURNALING TECHNIQUE USING VERSIONING REPOSITORIES

- The applied and reviewed *Hybrid Journaling Technique* accompanying my reflective approach, which combined using a more general journal and the messages regularly committed to a versioning system commonly used in software development, will be particularly useful to the communities of design research, software development and *HCI.*

1.5 BOUNDARIES OF THIS RESEARCH

As the previous contributions to knowledge are diverse in form and content, this research's limitations in scope needs to be explained, too.

Due to the nature of a practice-based *PhD*, it is essential to not interpret this thesis as a detached work of research, but instead as an accompanying exegesis to the three artifacts, which form the core of this design research. Vice versa, to understand this overall work's full contribution to knowledge, it is important to look at the portfolio of artifacts in combination with this thesis.

Nevertheless, even though the overall study does not result in some sort of generalized model, the specific insights related to digital games and *VR*, inherent in this research, can very well be transferred to other games and even non-gaming *VR* applications.

Although elements of this study are concerned with aspects of gaming and *VR* like *UX, Immersion* and *Presence* (see from page 22ff.), it should not be regarded as an attempt to establish in-depth knowledge in these highly complex topics or to give a somewhat complete listing of all related psychological aspects (e.g. *Player Engagement* will not be addressed). Though purely psychological research might try to provide this, this would clearly go beyond the scope of this design focused overall study.

Similarly, though the terms *Rollenwahrnehmung, Perspective* and *Space* are heavily used throughout this thesis, it is not the intention to provide deeper philosophical explorations of them beyond the context of this design focused work (see contextualizing sections *Rollenwahrnehmung, Perspective* and *Space* from page 19ff.).

Another remotely related area of this research is the business aspect of developing, marketing and selling digital games and *VR* experiences. Likewise, some of the insights and recommendations of the overall study eventually might result in business implications (e.g. feature development costs and hardware device market spread). Nevertheless, this thesis will disregard any of these in favor of creating the best possible design solutions for consumers.

The cultural aspects of gaming (Huizinga 1992 and Caillois 2001), *VR* and specifically related works of fiction like *Snow Crash* (Stephenson 1992), *Rainbows End* (Vinge 2006) and *Ready Player One* (Cline 2011) have influenced and inspired the design and development of the artifacts of this study to some degree. Again though, taking account of that and possible cultural discussions caused by the artifacts themselves, would again, clearly go beyond the scope of this study.

Eradicating *Simulator Sickness (SimSick)* seems to be an important issue in *VR*, in turn the overall study made several efforts in evaluating and especially reducing *SimSick* in its artifacts (see from page 69ff.). Although there are very detailed related nausea evaluation tools, like the *Simulator Sickness Questionnaire* by Kennedy et al. (1993), these would have made corresponding experiment designs and logistics considerably more complex and time-consuming – and ultimately too intrusive. Instead, more tractable experiment designs were chosen, with a simpler evaluation of possible nausea (i.e. a 0 to 10 rating was acquired of participants). Through this tradeoff, more comprehensive experiment designs were possible in terms of different interface designs and functionalities, while still attaining some insight relating to *SimSick.* In combination with qualitative participant data (e.g. verbal and free text comments), these 0 to 10 nausea ratings could be further interpreted to eventually also gain deeper insights.

Besides *SimSick,* there might be further issues with e.g. eyesight or emotional distress, which are beyond the focus of this research. Corresponding age restrictions by manufacturers for users have been more than complied with, though. Meeting the University's research ethics standards, experiment participants always were at least 16 years old, not pregnant, had no epilepsy, were informed about possible health and safety issues and gave their consent to take part accordingly.

Regarding software and hardware technologies, there is a variety of related areas unfathomed in this thesis, as again they would clearly go beyond the focus of this research. The following will briefly list some of these out of scope areas:

To mitigate the ubiquitous performance issues in *VR,* caused by the necessary high resolutions, high framerates and stereoscopic rendering, several low-level latency reduction software techniques were introduced throughout the time of this research. These techniques e.g. include *Asynchronous Timewarp, Asynchronous Spacewarp* and *Foveated Rendering* (Carmack 2017), which handle various sensor data very late in the rendering chain. By making tradeoffs in rendering precision, they reduce the possibility of visual judder in the rendered *VR* image by increasing the performance required to achieve a high framerate. Bypassing several hardware buffers for sensor data and rendering additionally supports this endeavor (Carmack 2017). These techniques are very important to deliver pleasant *VR* experiences with possibly high visual quality and partly have been "automatically" used in some of the artifacts of the overall study. They nevertheless will not be specifically covered in this research.

To develop the hardware needed for *VR,* a deeper understanding in the fields of data transmission and sensor technologies, as well as operating system compatibility is required. This research is not about developing actual *VR* hardware or "low-level" software, but only uses corresponding hardware and their low-level foundation as it is delivered by manufacturers. In minor cases, the latter may have been adjusted or extended during development, which will be clarified at the appropriate point.

Also, game engines and low-level rendering algorithms will not be subject of this research. Nevertheless, the game engine *Unity 3D* (Unity 2019) was used as an *Integrated Development Environment (IDE)* throughout the overall study to develop the three artifacts.

Finally, *VR* holistically draws on a variety of further techniques, research areas and formats like optics, haptics, 3D or binaural audio, 360-degree 3D videos and hybrid passive interactive *VR* experiences. Although some of these topics come up in the artifacts of this research, their in-depth investigation again would go beyond the scope of the overall study.

1.6 THESIS OVERVIEW

To give the reader an overview of this thesis, the following will elaborate on its different main sections and their inherent content.

Figure 2: Thesis flow

1.6.1 INTRODUCTION

The first chapter introduces the general topic of the overall study. It furthermore illustrates how its process evolved, provides definitions for certain key areas, explains the development of the research questions, introduces the overarching methodology and finally lists the contributions to knowledge and the boundaries of this research.

1.6.2 CONTEXT

To establish the uniqueness of this research, as well as to contextualize it and its different related aspects, the second chapter (see from page 15ff.) gives a state-of-the-art review divided into three sections: *Literature, Technology* and *Games & Experiences.*

The literature review informs about general practice-related research, approaches of design research with a constructive focus and key aspects of general *UX* with digital artifacts and *UX* specific to *VR.* Additionally, this section describes the three thesis-guiding areas *Rollenwahrnehmung, Perspective* and *Space,* as well as elaborates on related aspects of the *VR* ecosystem.

The next section of this chapter reviews the hardware technologies used in the overall study and furthermore explains the reasoning behind these choices. For a more extensive state-of-the-art technology review see *Appendix B. Technology Context (Extended)* from page 213ff.

The third section draws a non-exhaustive cross section of different *VR* related games and experiences and describes how they add to the research context regarding content and execution.

1.6.3 METHODOLOGY

To provide an in-depth understanding of the methodological approach behind the overall study, the third chapter (see from page 57ff.) gives an overview on various *Design Research* approaches, explains *CDR* and provides a critique on it. It further justifies why *CDR* has been chosen as the overarching methodology and in which configuration it was implemented for this research. In particular, the appropriateness of the approach will be established regarding its ability to provide a framework for addressing the research questions. Furthermore, the chapter will inform on the applied general process of iteratively designing and developing artifacts, the correspondingly used tools, the *Hybrid Journaling Technique* using versioning repositories for reflection and the procedures in user testing in *Lab* experiments and presentational *Showroom* events.

1.6.4 CRITICAL REFLECTION: ARTIFACTS & STUDIES

Augmenting the practical core work of the overall study and illustrating its different phases and various evaluations, the fourth chapter (see from page 69ff.) elaborates on the implemented three artifacts *Nicely Dicely, LizzE – And the Light of Dreams* and *Gooze*. Each artifact will be described sequentially. Nevertheless, their different design, development and user testing phases, which generated knowledge and understanding of the matter, may have overlapped or happened in a different chronological order.

Each artifact will be documented in terms of content and feature set in their different iterations, as well as their contributions to the overall research. Furthermore, conducted user testing sessions and their outcomes will be explained in detail and put into relation to the critical reflective discourse.

1.6.5 CONCLUSION

The fifth chapter (see from page 175ff.) rounds up the content of the previous chapters by giving answers to the research questions and clearly stating the contributions to knowledge, which were established by the overall study. The chapter additionally provides an outlook on areas for future research and generally concludes the thesis.

1.6.6 REFERENCES

The *References* section (see from page 185ff.) provides a complete alphabetical list of sources of any kind referenced in this thesis.

1.6.7 APPENDICES

The *Appendices* section (see from page 197ff.) supplements the main text with an exhaustive glossary (including acronyms), a state-of-the-art technology review, descriptions of specific software developments for the artifacts, descriptions of specific tools developed for this research, distinctions for included works, links to documentary videos, references to publications made during this research and a short curriculum vitae of the author.

2 CONTEXT

As previously mentioned, the nature of this research is practice-based. In turn, to fully capture the breadth and multidisciplinarity of the overall study, it needs to be contextualized not only in the area of *Literature,* but also in the areas of *Technology* and *Games & Experiences.* These topics will be considered in the three following sub sections. They will situate the overall study in its literary, technological and ludographical context, to provide an understanding on the general surrounding of this research and inherent challenges, to which the research questions relate to. This three-part review will furthermore highlight the uniqueness of the overall study.

2.1 LITERATURE

In this section, the *Literature* review for the overall study will be established, to provide a state-of-the-art literary overview for the reader and to justify the path this research has taken. Hence, the following will elaborate on relevant research and research areas and in which way the overall study is settled in this context.

2.1.1 PRACTICE-RELATED RESEARCH

In relation to the mode of this research, this section of the literature review is concerned with practice-related research in general and practice-based research specifically. Finally, it gives a brief overview of the chosen *CDR* methodology (Koskinen et al. 2011) as an advancement from Frayling's approach of "Research into, through and for art and design" (1993).

Research, in which the central focus lies in practice, may often be carried out by practitioners like designers, artists, writers, curators, teachers, musicians and others (Candy 2006). This has resulted in novel approaches in creating original knowledge, which may be applied within doctoral research programs (Candy 2006). It is essential though to clearly differentiate between pure practice and practice-related research. Scrivener argues, that the research artifact in combination with its correlating exegesis, should add to our generally shared store of knowledge, instead of just that of the practitioner and/or individual observers of the artifact alone (2002). He furthermore says, that visual art in itself typically only communicates superficial knowledge and "cannot account for the deep insights that art is usually thought to endow into emotions, human nature and relationships, and our place in the World, etc." (Scrivener 2002). Though the later statement may or may not be true for the, in some senses, more passive nature of consuming visual art, I disagree in regard to making the same claim about the cycle of user interactions with highly complex artifacts like digital games. The interactive nature of these artifacts, by itself, already typically creates a deep and more established dialogue between the user/s and the medium, resulting in a very potent transfer of information (PC Plus 2010, Muncatchy 2011 and Jones et al. 2014). The interaction provides an additional mode of engagement. Nevertheless, I agree with Scrivener and Candy that knowledge generated by practice-related research leading to a doctoral degree has to be original and communicated in a way, which is "defined and executed in a manner that is commonly agreed." (Candy 2006).

Regarding practice-related research, Mäkelä similarly highlights the constructive process and the created artifacts as integral parts of research. These developed products can be understood as answers to research questions as they are "a method for collecting and preserving information and understanding" (Mäkelä 2007). Still, Mäkelä also considers the artifacts alone as "mute objects" (2007), unable to communicate their inherent knowledge by themselves. Hence, only some form of documented interpretation within a research context provides them with a "voice" (Mäkelä 2007), which is able to spread their information.

For any kind of doctoral proposals, the *UK Arts and Humanities Research Council (AHRC)* defines research around three key features (2015): Research questions or problems must be defined and addressed during research to enhance knowledge, a research context must be specified for these questions or problems and finally the research methods to answer and address these questions or problems must be specified as well (AHRC).

This leads to the conclusion that practice can be undertaken and creative output can be produced as an essential part of research, but the corresponding processes and outcomes must be textually documented, explained and analyzed (e.g. in a thesis) in order to demonstrate critical reflection and to facilitate the corresponding position (Mäkelä 2007).

In the field of practice-related research there are two major types of research, which will be discussed in the following: practice-based and practice-led research. Though these two types of research can sometimes overlap in varying degrees and the lines between them may blur during the research process, their definitions point to two separate approaches, nevertheless.

> "Practice-based Research is an original investigation undertaken in order to gain new knowledge partly by means of practice and the outcomes of that practice. In a doctoral thesis, claims of originality and contribution to knowledge may be demonstrated through creative outcomes in the form of designs, music, digital media, performances and exhibitions. Whilst the significance and context of the claims are described in words, a full understanding can only be obtained with direct reference to the outcomes.
> (Candy 2006)

> "Practice-led Research is concerned with the nature of practice and leads to new knowledge that has operational significance for that practice. In a doctoral thesis, the results of practice-led research may be fully described in text form without the inclusion of a creative work. The primary focus of the research is to advance knowledge about practice, or to advance knowledge within practice. Such research includes practice as an integral part of its method and often falls within the general area of action research.
> (Candy 2006)

Though some elements of this thesis can certainly stand by themselves and aim to advance knowledge about practice in the spirit of practice-led research, nevertheless the main focus lies in practice-based research, meaning the created artifacts form an integral part of the overall study.

2.1.1.1 Research Into, Through & For Art & Design

In developing an overall approach to design related research, Frayling proposed three different categories: "Research into art and design", "Research through art and design" and "Research for art and design" (1993). In the case of this thesis, research through art and design seems to be the most relevant, as it roughly describes how the process of creating artifacts together with accompanying documentation can be used for performing research. However, this concept has been controversial for being unclear on the details of how this approach may be undertaken, as Frayling did not implement any practical guidelines.

2.1.1.2 Constructive Design Research

Others have sought to establish a more guided, but still flexible approach on design related research that develops Frayling's basic approach. *Constructive Design Research (CDR,* Koskinen et al. 2011), for example, will form the core methodology of this research (see section *Methodology* from page 57ff.). Its central focus lies on constructing designs in the form of prototypes and/or products. Though *MIT Media Lab's* (MIT n.d.) credo "demo or die" seems to take up a more important role than the common academic research motto "publish or perish", the overall study will elaborate on performed demos and published works alike. Jerald supports this "constructivist approach" by saying it creates "understanding, meaning, knowledge, and ideas through experience and reflection upon those experiences rather than trying to measure absolute … truths about the world." (2016). He further argues that it "emphasizes the integrated whole and the context that data is collected in." (Jerald 2016).

The *CDR* approach further accommodates very different projects, categorizing them into three loose groupings called *"Lab", "Field"* and *"Showroom"* (Koskinen et al. 2011).

- The *Lab* can be seen as the closest form of evaluating designs in a scientific laboratory-like manner.
- The *Field* on the other hand makes use of techniques, mostly used in social sciences like *Ethnography.*
- Finally, the *Showroom* leans on practices in design and art, where the articulation of an idea through a working design is more important than the production of a replicable process (Koskinen et al. 2011).

The *Methodology* section (see from page 57ff.) will elaborate further on the concept of *CDR*, why it was adopted over other methodologies, why it in particular is best suited to answer the previous research questions and in which form it was applied as the core methodology for the overall study.

2.1.1.3 Reflection in Software Development

As previously mentioned, *CDR* and design practice in general often use reflection to evaluate what was created. Although this method might as well seem obvious for software development, due to its constructive nature, it is not a very common practice in this field.

In recent years though, the collaborative "studio" environment was adapted from other design related disciplines like architecture (Hazzan 2002), to the field of software development and especially corresponding education (Prior et al. 2014). Although reflection plays an important role in the latter developments, they do not get into more detail, how their reflection method is exactly performed in practical terms.

Nakakoji et al. on the other hand developed the "*Design practice stream (DPS)* tools" to comfortably handle recordings of software design meetings (2012). *DPS* consists of a set of tools, which link various types of recorded meeting data together (e.g. videos, transcripts and whiteboard scribbles), based on timestamps. So a team member can watch a specific part of a recorded meeting, jump to a specific term in the transcript or look at a specific graph scribbled on the digital whiteboard, while having access to all other relevant data, as all data points are linked together by timestamps (Nakakoji et al. 2012). This enables users to retrace and evaluate decisions made during software design meetings of very large collaborative projects. Nevertheless, it is not applicable for the day to day decisions of developers of smaller projects with little to no additional team members.

Commenting in code may to some degree provide a way to document thoughts, ideas and processes, regarding a software project. However, there are clear downsides to this approach: The comments would likely be spread over several files, which could be renamed, moved or deleted. Hence, the information would not be accessible through a central interface and it would be prone for incompleteness and getting shifted around. Additionally, this approach may not conform to certain coding conventions and it may negatively influence technical processes like compilation, by unnecessarily bloating code files.

In other words, there generally seems to be a reflective deficiency in software development, which may be fine in practice alone, but may not be in specific research related projects. Furthermore, literature on workflows aiming at reflection and using standard programming tools seems to be scarce.

Although not involved in software development, other creative crafts like e.g. writing have utilized a combination of versioning repositories and tracking processes to automatically annotate their work progress (Doctorow 2009). The toolkit *"Flashbake"* uses *git* repositories and various *Python* scripts to automatically track changes made to text files and annotates those with meta data like e.g. timestamps, local weather data and the current individual *RSS* feed headlines of the author, to provide a creative context for later reflection (Doctorow 2009).

In turn, to comfortably document my thoughts and the design and development progress for later reflection, I developed a *Hybrid Journaling Technique* during this research. It combines a rather general manual journal with my detailed and timestamped commit messages in a versioning repository. Using the latter for productivity reasons is common practice in software development. In addition to this usage, I added streams of thought concerning research, design and development to it, which are accessible through a central interface and do not interfere with the actual code files. The section *Reflection based on Hybrid Journaling Technique* from page 67ff. will elaborate on this further.

2.1.2 CLARIFYING AMBIGUOUS KEY AREAS

The three key areas *Rollenwahrnehmung*, *Perspective* and *Space* best circumscribe the diverse underlying essence of the different research artifacts, while at the same time being able to interconnect them and provide a core structure for the thesis

Expanding on the previous brief definitions of these central theme guiding terms *Rollenwahrnehmung*, *Perspective* and *Space*, the following will illustrate their context relating to other research fields and in which way they are intended to be interpreted throughout the rest of the overall study.

2.1.2.1 Rollenwahrnehmung

As previously mentioned, *Rollenwahrnehmung* is a German term consisting of the two German words *Rolle* (in Engl.: "role") and *Wahrnehmung* (in Engl.: "perception" or "fulfillment").

When consulting *Oxford Dictionaries*, the following relevant definition for "role" is concerned with the most abstract and encompassing meaning of the term:

> " The function assumed or part played by a person or thing in a particular situation.
> (Lexico 2019a)

More specifically regarding games, the user's role in a *3rd Person* game may be to identify with the visible playable character, but the identification could also be with a separate invisible entity, naturally controlling the camera looking at the same character (see "*Entity Split*" from page 127ff.). Furthermore, a role and thus the connection between a player and the playable character, can be kept loose or tight, depending on the concept of the game. Similarly, the user's role within the narrative of a game may be clear from the beginning, it may only be uncovered over time, or it will not be disclosed by the game at all but needs to emerge completely from the player's imagination.

The two relevant definitions for "perception" are highlighting the sensing and understanding of "something":

> " The ability to see, hear, or become aware of something through the senses.
> (Lexico 2019b)

> " The way in which something is regarded, understood, or interpreted.
> (Lexico 2019b)

The relevant definition for "fulfillment" is concerned with the actual performance of a role with its apparent properties:

> " The performance of a task, duty, or role as required, pledged, or expected.
> (Lexico 2019c)

Besides the common usage of the term *Rollenwahrnehmung* in the German language, it is used in other research areas as e.g. marketing management (Hahn 2013), German family law (Schumann et al. 2011), theology (Anselm 2008) and psychotherapy (Teske et al. 2013). Although these areas are clearly outside the scope of this research, their usage of the term *Rollenwahrnehmung,* in a more abstract way is very similar to the one in this overall study.

Due to the history of academic psychology in Germany, influential German speaking psychologists and philosophers like Immanuel Kant, Wilhelm Wundt and Sigmund Freud (Wikipedia 2019b) and my personal German background, the term *Rollenwahrnehmung* was deliberately chosen to discuss the matter of *how a user perceives and/or fulfills a certain role in an immersive experience.* Additionally, the term *Rollenwahrnehmung* is more confined and less overloaded with different meanings than related terms like "the self" (Ewing 1990, LeDoux 2002 and Quinn 2006), which was discussed and excluded as an alternative key term during this research.

The role of a character or entity in a game can be quite complex and may involve diverse facets, which can be designed to be more or less pronounced. These include e.g. an envisaged motivational strategy for the player, the integration of a character within a story or fiction, the intended strength of the connection between player and character and the general identification of the player with the character etc.

Although it is possible to design games and playable characters to fit certain motivational strategies of players, i.e. the *"Achievers",* the *"Socializers",* the *"Explorers"* and the *"Killers"* (Bartle 2003), this was not the case in the creational process of the artifacts of the overall study. Hence, while a motivational strategy may be part of the role of a character and in turn also of *Rollenwahrnehmung,* it was not the focus of this research and therefore not specifically treated.

The role of a character may be further partly defined through its *"Fictional Positioning"* (Chinn 2008). This means, apart from the actual available gameplay mechanics, the fiction or lore in which a game takes place also possibly delimits the actions a character, and thus its player, can take (Chinn 2008). E.g. in a medieval scenario it is unlikely that a character is supposed to fire a laser shot from a high-tech space blaster. On the other hand, if time travel might be involved in the fiction, it could very well be an option. Similarly, due to *Fictional Positioning* a game could prohibit a player from shooting a friend, even though the mechanic is otherwise available (Chinn 2008). Or instead it could be designed in exactly that way, that this action is possible and that it affects the further development of the narrative.

This position of the player on the gradient between limitation and freedom to take part in designing the fiction of the game, closely related but not exclusive to *Role-Playing Game Stance Theory* (Costisick 2010), may also be part of the role a player has to fulfill.

So, in the case of this thesis, *Rollenwahrnehmung* was established as a term to describe the perception and fulfilling relationship of a user or player with his or her virtual representation – visible or invisible – within the artifact or game in the context of the current *UX*. In other words, in the context of this research, the term describes in which ways the user recognizes the virtual role or character he or she is appointed to and how the user fulfills this part.

2.1.2.2 Perspective

For the second key term *Perspective*, there is rich literature on for example calculations for computerized rendering of different perspectives, digitally recreating traditional setups of physical cameras, the influence of optics on perspective including optical illusions and more, though these areas would exceed the domain of the overall study. In this case, *Perspective* refers to the common use in speech of the term, which either relates to the visual point of view, or the metaphorical equivalent.

There are three relevant definitions for "perspective" when consulting *Oxford Dictionaries.* The first two are concerned with the visual background of the term:

> The art of representing three-dimensional objects on a two-dimensional surface so as to give the right impression of their height, width, depth, and position in relation to each other.
> (Oxford Dictionaries 2017b)

> The appearance of viewed objects with regard to their relative position, distance from the viewer, etc.
> (Oxford Dictionaries 2017b)

> A particular attitude towards or way of regarding something; a point of view.
> (Oxford Dictionaries 2017b)

The second definition relates to the more general use of the term in a natural environment, whereas the first aims at the artificial visualization of perspective, as it will be used in rendering 3D imagery for the artifacts of this study. The third definition is concerned with the metaphorical equivalent of a point of view.

When investigating *Perspective* in the context of digital games, often genre defining variants of *1st Person* or *Ego Perspective* and *3rd Person Perspective* or bird's eye view come to mind.

> In "The Benefits of Third-Person Perspective in Virtual and Augmented Reality?" the advantages and disadvantages of *3rd Person* and *1st Person Views* are compared in the context of *Augmented* and *Virtual Reality* (Salamin et al. 2006). They argue that, *3rd Person Perspective* is usually preferred by users "for displacement actions and interaction with moving objects while the *1st Person View* is required when we need to look down or just in front of us for hand manipulations with immobile objects" (Salamin et al. 2006). Furthermore, *3rd Person View* seems to improve evaluation of distances and the anticipation and extrapolation of the trajectory of mobile objects. This seems to be due to the "larger field of view provided

> by the position of the camera for this perspective. The user can thus better appreciate the situation and the distance." (Salamin et al. 2006).
> (Wiedemann et al. 2016)

As mentioned before, throughout the rest of the overall study and apparent from the clearly stated context, *Perspective* will either refer to the visual perspective from a certain point of view or its metaphorical equivalent, an attitude towards a matter.

2.1.2.3 Space

The term *Space* can be used in various regards, for example the outer space between the celestial bodies, a blank area between typed characters or a mathematical structure defined by a set of points (Oxford Dictionaries 2017c). In the case of the overall study though, the relevant definitions are the following:

> “ A continuous area or expanse which is free, available, or unoccupied.
> (Oxford Dictionaries 2017c)

> “ The dimensions of height, depth, and width within which all things exist and move.
> (Oxford Dictionaries 2017c)

Both definitions are concerned with an area, in which "things" may exist, because of its relative dimensions. This notion of *Space* will be regarded in physical and virtual matters throughout the overall study, correspondingly to the current context. E.g. *Space* may refer to the physical gaming area in which a group of players are present, or it may refer to the virtual world within which a game takes place.

2.1.3 SUBJECTIVE ASPECTS OF IMMERSIVE EXPERIENCES

Using the *CDR* approach, the construction of artifacts stands in the focus of this research. This has led to a portfolio of three individual gaming experiences, of which their central nature can be described as being "immersive" (Stuart 2010). Therefore, certain key aspects of immersive experiences, related to this research, will be elaborated on in the following to inform on defining and evaluating corresponding aspects.

2.1.3.1 Immersion

One of these subjective key aspects is *Immersion* itself. "The term *Immersion* is rather often used in relation to various media. Nevertheless, it is still an area for great discussion on properly defining the term and measuring this experiential aspect." (Wiedemann et al. 2017c). Relating to all the immersive artifacts of the overall study in general, but also specifically to the *Lab* study on *Local Multiplayer Immersion Affected by 3D Stereoscopy* (see from page 91ff.), the following will investigate some of these definitions and evaluation methods accordingly.

One of the definitions for "to immerse" in the *Oxford Dictionaries* is:

> Involve oneself deeply in a particular activity: 'she immersed herself in her work'.
> (Oxford Dictionaries 2017a)

The term originates from the Latin equivalent for "to dip into" (Oxford Dictionaries 2017a). In general, this seems to suggest that *Immersion* is not restricted to *VR/AR* when looking at the context of *HCI*, whereas the related *UX* aspect *Presence* seems to be (see section *Presence* from page 24ff.).

> Summarizing the work of Slater et al. on a *"Framework for Immersive Virtual Environments (FIVE)"* [1997], Jerald states that "*Immersion* is the objective degree to which a *VR* system and application projects stimuli onto the sensory receptors of users in a way that is extensive, matching, surrounding, vivid, interactive and plot informing." [2016]. Jerald further elaborates on these six aspects of *Immersion:* Extensiveness correlates to the amount of different sensory inputs for the user (e.g. visual, auditory and haptic), matching means the congruence of these inputs to the user's interactions (e.g. visual representation reflects head movement appropriately), surrounding addresses the degree of panoramic-ness (e.g. spatialized 3D audio, *FOV [Field of View]* and 360 degree tracking), vividness correlates to the output quality and resolution (e.g. screen refresh rate, resolution and audio quality), interactability concerns the degree in which a user can influence the *Virtual Environment (VE)* including its characters and objects and finally informing on the plot, addresses the consistency of how the story of the experience is presented [Jerald 2016]. In combination and possibly varying configurations, these aspects are supposed to make up the sense of *Immersion* in *VR* [Slater and Wilbur 1997].
> (Wiedemann et al. 2017c)

> So, contrary to the feeling of *Presence* [see section *Presence* from page 24ff.], which seems to be intrinsic to *VR* only [Jerald 2016], [I] argue that the *FIVE* concept is also true for *non-VR* applications (e.g. *Monoscopic* digital games). Only the *degree* of *Immersion* is [affected] by the technology [in use]. Furthermore, [one] experiment of this [overall study] will look more closely into the aspect of extensiveness. Specifically, it will show that *3D Stereoscopy*, compared to a *Non-3D Monoscopic Presentation*, can increase *Player Immersion*, even in a highly distracting *Local Multiplayer* situation [see section *Lab Experiment: Local Multiplayer Immersion Affected by 3D Stereoscopy* from page 91ff.].
> (Wiedemann et al. 2017c)

Furthermore, in contrast to Jerald's statement, that *Immersion* is an objective trait of *VR*, I would argue, that only its technological background is objective in the way explained by the *FIVE* framework (Slater and Wilbur 1997), but the experiential part of *Immersion* still seems to be a subjective matter. This appears to be supported by the diverse *Immersion* ratings of study participants e.g. in the before-mentioned *Local Multiplayer* experiment. Finally, even Jerald seems to think that way, when he states that immersive technologies can only "lead the mind", but not control it (2016).

But how should one "measure" *Immersion?*

> Trying to develop "more quantifiable and therefore objective measures of *Immersion*" [2006], Cairns et al. conducted an experiment, in which subjects were switched from playing an immersive game to performing a different task. They argue, that *Immersion* could be measured, by observing the subject's performance in real-world tasks, after he or she transferred from performing immersive game tasks [Cairns et al. 2006]. From the difference in real-world task performance, one could supposedly more reliably infer the degree of *Immersion* in the previous game tasks [Cairns et al. 2006]. The study seemed to infer this relation, though Cairns et al. also noted two shortcomings. It could not be clearly distinguished, if just certain aspects of *Immersion* were causing this effect or "*Immersion* per se" [Cairns et al. 2006]. Furthermore, the experiment design was highlighted as complex and interruptive. Finally, Cairns et al. suggested to instead test a combination of eye tracking and body motion analysis, validated via subject-reported *Immersion* ratings [2006].
> (Wiedemann et al. 2017c)

Another method of evaluating *Immersion* – using a subset of the *igroup Presence Questionnaire* – will be presented in the following section. Because as previously mentioned, Jerald claims that the immersive technologies can only "lead the mind", but not control it and that it needs human perception to interpret these stimuli (2016). Finally, this subjective and instinctive experience of *Immersion* is what he calls *Presence* (Jerald 2016).

2.1.3.2 Presence

As the linking technology of all three artifacts of the overall study is *VR* and its most compelling feature is *Presence*, this needs to be explored in more detail. Hence, the following will illustrate the difference between *Presence* and *Immersion*, what subparts *Presence* may consist of and how *Presence* may be evaluated.

Though I agree that *Immersion* seems to be the vehicle for users to reach a sense of *Presence*, I do not believe *Immersion* necessarily needs to lead to *Presence*, as users can also be immersed in *non-VR* activities.

> Slater and Wilbur express that "[*Presence*] may be concomitant with *Immersion*" [1997] but does not have to be and Jerald supports this notion by explaining "*Immersion* does not always induce *Presence*" [2016].
> (Wiedemann et al. 2017c)

However, it is important to note that the more immersive a *VR* system and its application are, and the more natural interactions are performed, and sensory stimuli are perceived, the more likely it is that users feel present in the *VE* (Jerald 2016).

It is difficult to describe *Presence*, as it is "an internal psychological state and a form of visceral communication", but in short it is the feeling of being in a place, while physically being in a different one (Slater and Wilbur 1997 and Lombard and Ditton 1997). Enforced through technology, arguably only some form of *VR/AR* can establish this effect (Schubert et al. 2001).

A more detailed definition has been given by the *International Society for Presence Research:*

> *Presence* (a shortened version of the term "telepresence") is a psychological state or subjective perception in which even though part or all of an individual's current experience is generated by and/or filtered through human-made technology, part or all of the individual's perception fails to accurately acknowledge the role of the technology in the experience.
> (International Society for Presence Research 2000)

When the illusion of being present in the *VE* collapses for some reason, this is called a *"Break-in-Presence"* (Slater and Steed 2000). Being able to destroy a *VR* experience, *Breaks-in-Presence* (e.g. restrictive wires, auditory influences from the outside that are not part of the experience, loss of tracking etc.) should be avoided as well as possible (Jerald 2016).

Research has identified four different core components of *Presence,* where each one reflects a different aspect of *Presence* in *VR.*

The illusion of a "stable spatial place" is the most important component of *Presence* and is part of Slater's "place illusion" (2009). The general congruence of the *VR* system's stimuli to the user's sensory expectations and particularly depth cues are needed for establishing this stable place (Jerald 2016). Furthermore, especially temporal discrepancies between user movements and visuals should be avoided to preserve the in this regard sensitive "sense of agency" (Kilteni et al. 2012). Low frame rates, too long screen persistence, miscalibration of tracking and other *VR* system components as well as too long latency can further lead to discomfort and a *Break-in-Presence* (Jerald 2016). As a rule of thumb, Carmack suggests a "motion-to-photons" latency of up to 20 milliseconds to get to a point of general imperceptibility (2013).

The illusion of *"Self-Embodiment",* establishes when a user recognizes a virtual representation of his or her body as his or her own in *VR* (Jerald 2016). *Presence* can be obtained without a virtual body. Seeing one that matches the user's movements appropriately on the other hand increases the level of *Presence* drastically (Jerald 2016). Body shape, color and even gender are not as important in respect to *Presence* but have been used to create awareness in certain racial or gender bias experiences (Peck et al. 2013). In fact, the user's perception of him or herself in general may tolerate a certain amount of distortion (Maltz 1960). Hence, virtual bodies quite diverging from the actual ones, may be supported in a compelling way.

Also, further increasing *Self-Embodiment,* the illusion of "physical interaction" and sensory feedback (e.g. audio, visual, haptic and olfaction) can greatly enhance *Presence* in *VR* experiences in general. Being able to interact with objects or characters in the *VE* can give users "a sense that [he or] she has in some way touched the world." (Jerald 2016). Especially haptic feedback can elevate such a *VR* experience further. Though, because of the complexity to obtain haptics in a completely realistic manner, substitutes like vibrations are often used with success. The so called "rubber hand illusion" (Botvinick and Cohen 1998) can be produced when touch or other haptic stimuli are matched with corresponding visuals. It is for example triggered when a user physically holds a vibrating hand controller, while virtually holding a light saber in *VR*.

Finally, the illusion of *"Social Presence"* can establish, when a user believes he or she is really communicating with other entities in the *VE*, whether they might actually be other users or *Artificial Intelligence (AI)* controlled *Non-Player Characters (NPCs)* for example (Jerald 2016). It needs to be noted though that, even though realism of communicative aspects as facial expressions, gestures and other body language increases *Social Presence* (Guadagno et al. 2007), even simple and low-fidelity representations of these have been observed to have an immediate effect (Slater et al. 2006a and 2006b).

> " In terms of self-evaluating overall *Presence* in a *VE*, the *igroup Presence Questionnaire (IPQ)* seems rather promising … [Schubert et al. 2001 and igroup 2016]. Originally based on a combination of works of Slater and Usoh [1994], Witmer and Singer [1994], Hendrix [1994], Carlin et al. [1997] and Schubert et al. [1999], the questionnaire was condensed to 14 questionnaire items. These items lead to the four sub scales *"General Presence"*, *"Spatial Presence"*, *"Involvement"* and *"Experienced Realism"* [igroup 2016] …
>
> Due to its critically discussed empirical foundation, its evaluation and adjustment through several iterations with over 500 participants, corresponding factor analyses and finally its practicality by consisting of only 14 questions, the *IPQ* seems both settled and fit enough for assessing *Presence* (and its subpart *Immersion)* in a practical but thorough manner.
>
> This led to the decision of using a subset of the questionnaire (with minimal wording adjustments) for evaluating *Player Immersion* in [the *Lab Experiment: Local Multiplayer Immersion Affected by 3D Stereoscopy]*, which will be explained in more detail later on [see from page 91ff.].
>
> (Wiedemann et al. 2017c)

The *IPQ* in its complete form was additionally used to evaluate *Presence* of the participants of the *Lab Experiment: UX Evaluation of VR Locomotion & Virtual Object Interaction Mechanics.* For more details see from page 150ff.

Other similar self-evaluation tools like the *Presence Involvement Flow Framework (PIFF,* Takatalo 2011) and the *Game Experience Questionnaire* (IJsselsteijn et al. 2013) were considered for this research. However, they were excluded because of their specific focuses, their complexity and ultimately unpracticality in already complex study designs. Furthermore, using the *IPQ* in two *Lab* experiments had the advantage of creating comparable results within the overall study.

2.1.3.3 Flow

When developing immersive experiences and specifically digital games, another essential aspect is to find the right balance between posing challenges and the player's skill level, because "In an ideal situation where skills and challenges are high and in balance, an optimal state of *Flow* occurs." (Csikszentmihalyi 1991). If, on the other hand, challenges are too low compared to the user's skill level boredom may be the result, whereas if challenges are too high anxiety or frustration may establish in players (see Figure 3, Csikszentmihalyi 1991).

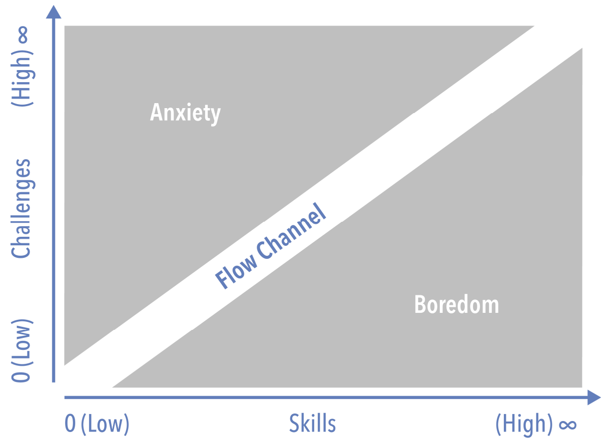


Figure 3: Reproduced Flow Channel visualization (Csikszentmihalyi 1991)

In theory, to achieve what Csikszentmihalyi called an "optimal experience" or *"Flow"* (1991), players are supposed to be guided by the game's design to stay in the *Flow* channel and neither be bored nor anxious (see Figure 3). Though tenacious balancing of game elements against themselves and against certain player skill levels is a crucial process in game development, in practice though it is almost impossible to reach the right balance for each and every player alike.

Although no study of this research specifically evaluated degrees of *Flow* of players with the developed artifacts, the concept needed to be mentioned, as trying to balance challenges to user skills was always an essential requirement when designing and developing the games for the overall study. Furthermore, corresponding experiment results often varied a lot between subjects, because of their diverse skill levels.

2.1.3.4 Simulator Sickness

Although *Stereoscopic 3D* in rare cases may cause a certain amount of *SimSick* by itself, it is much more of an issue in *VR*. Hence, reducing it as much as possible, is one of *VR's* biggest challenges.

The following will illustrate aspects that nourish *SimSick* and corresponding evaluation methods:

> " Reducing nausea and *Simulator Sickness* while maintaining an attractive gameplay does not only pose challenges for *Virtual Reality*, but for other sorts of developments too. The experiment on "Altering Gameplay Behavior using *Stereoscopic 3D Vision*-based video game design" (Schild et al. 2014), explored among other topics, the effect of *Stereoscopic 3D* on *Simulator Sickness* of subjects, while playing a *3rd Person* flying game, either in "side-scrolling view" or "behind-view" perspective. Schild et al. did not register a significant impact on *Simulator Sickness*, when using a constant perspective with an *UI [User Interface]* optimized to reduce parallax changes in vision, while using the side-scrolling view without a constant

> change in depth animation. The behind-view with a lot of depth animation on the other hand, did show an impact on *Simulator Sickness* (Schild et al. 2014).
> (Wiedemann et al. 2016)

> “ Other studies support the notion, that the reduction of perceived self-motion illusions (“vection”) (Riecke and Feuereissen 2012) seems very important when trying to reduce nausea [in *VR]* (Yao 2014). Switching from passive observation to actively controlling *Locomotion* significantly impaired vection, as vection onset latencies were raised and vection occurrence was reduced (Riecke and Feuereissen 2012). However, Riecke and Feuereissen's experiment also showed that the relevant parameter to reduce vection was not interactivity in general, but instead the specifics of the active motion control used (a *Gyroxus* motion chair for some sort of flying simulation). This seems to imply the benefit of using more natural inputs instead of metaphorical devices like joysticks or gamepads.
> (Wiedemann et al. 2016)

> “ In terms of very detailed evaluation of *Simulator* or *Motion Sickness* in the aeronautic industry, the *Simulator Sickness Questionnaire* is widely used (Kennedy et al. 1993). It features 16 different questionnaire items on a scale of 0 to 3, which result in the two latent variables “Nausea” and “Oculo-motor” (Kennedy et al. 1993).
> (Wiedemann et al. 2016)

Regarding the evaluation of *SimSick* in this research, as previously mentioned, a more simplified approach was used throughout the different studies. I.e. participants were asked for a simple 0 to 10 rating of their nausea. This drastically reduced the complexity of sometimes already complex studies and maintained the comparability of results between these studies. In addition, qualitative comments were able to retain some of the details concerned with this area.

2.1.4 INTERFACE RELATED ASPECTS

After illustrating the experiential aspects of immersive experiences, it is also necessary to present the research areas concerned with more technical and mechanical specifics of *VR* and its interfaces with the users. Hence, the following will elaborate on these interface related aspects.

2.1.4.1 Stereoscopic 3D

To create depth perception in *VR, Stereoscopic 3D Vision* is an important technique. Nevertheless, it also serves as an independent technology in e.g. *3D TVs* and *3D Cinema* (see *Appendix B.9 Stereoscopic 3D Projectors & TVs* from page 240ff.). With this relation in mind, this section will illustrate certain effects of *Stereoscopic 3D* relating to gaming, game development in general and to the *Lab* experiment on *Local Multiplayer Immersion Affected by 3D Stereoscopy* in specific (see from page 91ff.).

> “ In their … study on design practices and challenges in *Stereoscopic 3D* video games, Mahoney et al. stated that “*Stereoscopic 3D* in games can enhance *Immersion* under certain conditions.” [2011]. Nevertheless, they also stated how crucial it is to understand *3D Stereoscopy* not as some easily applicable post effect. Instead, the game should be designed for it from the ground up [Mahoney et al. 2011]. Overlaying meta information like *Head-up-Displays (HUDs)* need to be redesigned to properly work in *3D*, or different paradigms should be used instead [Mahoney et al. 2011]. Furthermore, “*Stereoscopic 3D* can offer new possibilities for new game types.”, though the current generation of compatible games only uses *3D* for visual, but not gameplay improvements [Mahoney et al. 2011].
> (Wiedemann et al. 2017c)

The section on *Critical Reflection: Artifacts & Studies* will further elaborate on the issue of properly implementing *Head-up-Displays (HUDs)* and possible gameplay improvements through *Stereoscopic 3D* (see from page 57ff.).

> “ In terms of *3D Stereoscopy* affecting players' in-game performance, [Litwiller and LaViola] performed a corresponding study [2011]. They investigated quantitative and qualitative measures of player performance and learning rates, throughout five different digital games, coming from “racing, first and third person shooter, and sports game genres” [Litwiller and LaViola 2011]. Though subjects preferred the *3D Stereoscopic* over the *Non-3D Monoscopic Presentation*, the study could “not provide any significant advantage in overall user performance.” [Litwiller and LaViola 2011]. The results of [my] experiment [on *Local Multiplayer Immersion Affected by 3D Stereoscopy]* will show a similar outcome, in terms of [player] in-game performance.
>
> More closely related to [that] experiment, Schild et al. performed an investigation of the specific effects of *3D Stereoscopy* on *User Experience* in digital games [2012]. In their study with 60 participants, Schild et al. analyzed player experience in three different games, presented in *3D Stereoscopic* and *Non-3D Monoscopic Vision*. None of the games were primarily developed for *3D Stereoscopy*, though [Schild et al. 2012]. Self-reporting via questionnaires and a headset measuring electroencephalogram *(EEG)* data were used to evaluate *User Experience* [Schild et al. 2012]. Their results led to three conclusions: *Stereoscopic 3D* is preferred over *Monoscopic Non-3D*, as it “increases experiences of *Presence* and *Immersion”*, these effects seem to be game and gender dependent though and *EEG* data indicate that *3D Stereoscopy* provides “a more natural player experience” via “a more direct and unconscious interaction” with the game [Schild et al. 2012]. Despite using slightly different *User Experience* evaluation tools and a different experiment design, the results of [my] experiment [on *Local Multiplayer Immersion Affected by 3D Stereoscopy]* will point in a similar direction and confirm an increase in *Immersion* through *3D Stereoscopy.*
> (Wiedemann et al. 2017c)

2.1.4.2 Camera Behavior

Whether using *Non-3D Monoscopy* or *3D Stereoscopy,* there needs to be at least one camera, which captures the scene, to e.g. send it to the renderer and display it to the user. As was explained in the previous section on *Perspective* (see from page 21ff.), this process commonly leads to either a *1st Person* or *3rd Person* (bird's eye) *Perspective* in the experience.

The following will elaborate on further possibilities of different camera behaviors and how the overall study is confined in this area. E.g., another aspect of this topic is concerned with handling cut scenes and interactive dialogues:

> “ as [they] are often occurring [in digital games], further research is needed on how to implement these, specific for *VR.* In a *Non-VR* context, Galvane et al. (2014) looked into narrative-driven camera control to create cinematic replays of digital games, with little to no manual adjustments. Instead of using an idiom-based technique, as in a stereotypical way of shooting a specific action, their approach is independent of the type of action happening (Galvane et al. 2014). Their technique is reliant on a certain game engine, specialized on dialogue and the computation and interpretation of importances of dialogue parts. Though this approach seems highly reasonable for dialogue heavy games, it comes with the requirement of manually extending the meta data to the dialogues and the related game engine. “Using a physically based model to control cameras offers a practical way to avoid unrealistic camera movements and ensures continuity.” (Galvane et al. 2014) seems like an interesting technique for camera movement, which also might be viable for *VR,* though would need further research.
> (Wiedemann et al. 2016)

Although, handling cut scenes and interactive dialogues in *VR* seems an interesting area for further research, it exceeds the domain of the overall study.

> “ Additionally, to the pure functionality and usability of camera behaviors for users [of digital games], they certainly also drastically affect the visual style of a medium. In filmmaking, camera movement is used to control pace, point of view and rhythm in a scene (Joshi et al. 2014). By manipulating camera movement, viewers or users can be pulled into [the] scene or get disconnected from it and its characters (Joshi et al. 2014). Furthermore, “Camera motion, as a stylistic choice, is often so powerful that it can be the primary memory of a film or video” (Joshi et al. 2014), or other medium.
> (Wiedemann et al. 2016)

Even though, certain stylistic characteristics of camera capturing are always present, in the case of the *Lab* experiment on *VR 3rd Person Camera Behavior Modes* (see from page 111ff.), they were not specifically examined. Instead, the experimental focus was aimed at establishing *3rd Person VR* camera behavior, which is generally enjoyed by players, supports the gameplay and reduces *SimSick* to a minimum.

2.1.4.3 Locomotion

Also very much concerned with the reduction of *SimSick* is the field of *Locomotion* in *VR,* which encompasses many diverse mechanics:

> “ Reddit lists 24 different *VR Locomotion* mechanics, categorized into teleportation, motion, room scale and artificially based ones (2016). These different approaches lead to the assumption, that providing an attractive gameplay, while solving *Simulator Sickness* caused by *Locomotion* is not only a technical issue, but rather a challenge in design.
> (Wiedemann et al. 2017b)

The *Lab* experiment on *UX Evaluation of VR Locomotion & Virtual Object Interaction Mechanics* (see from page 150ff.) investigates the most prominent mechanics by comparing individual integrations alongside several *UX* aspects. Eventually, the study provides recommendations for designers and developers regarding those mechanics (Wiedemann et al. 2017b).

> “ On the basis of “travel time, collisions (a measure of accuracy), and the speed profile” through a *Virtual Environment (VE)* consisting of orthogonally arranged corridors, Ruddle et al. (2013) evaluated different *Locomotion* mechanics like using a joystick, actual walking in *VR* and using industrial linear and *Omnidirectional Treadmills.* Their study “illustrates the ease with which participants could maneuver in a confined space when using an interface that was ‘natural’” like using an *Omnidirectional Treadmill* or walking completely freely (Ruddle et al. 2013). Furthermore, user issues with translational movements seem to be inherent in abstract interfaces “(e.g., a joystick, keyboard or mouse) … irrespective of whether or not an immersive display is used” (Ruddle et al. 2013).
> (Wiedemann et al. 2017b)

> “ [Similarly,] the study by Nabiyouni et al. investigates the navigational speed and accuracy of different *VR Locomotion* techniques (2015). They compared “fully natural” (real walking), “semi-natural” and “non-natural” (via gamepad) *Locomotion* methods, by their usage speed and accuracy (Nabiyouni et al. 2015). The semi-natural technique is based on walking in some kind of large-scale spherical hamster wheel, the *“Virtusphere”* (Nabiyouni et al. 2015). The study has shown that natural “high-fidelity” and well-designed non-natural “low-fidelity” techniques can outperform semi-natural “medium-fidelity” *Locomotion* mechanics (Nabiyouni et al. 2015). They argue that their results were “an effect of interaction fidelity”, but they also requested more research with differently designed semi-natural techniques, because of the *Virtusphere’s* downsides related to its mass and friction (Nabiyouni et al. 2015). This seems reasonable, as one might expect the spherical shape of the *Virtusphere* to influence navigation accuracy and its mass and friction to affect acceleration.
> (Wiedemann et al. 2020)

> “ Relating to testing consumer ready *Omnidirectional Treadmills*, [Cakmak and Hager] have introduced the *"Cyberith Virtualizer"* (2014). This device consists of a low friction base plate and a pillar structure holding a vertically movable harness for the user. Strapped into the harness a user then walks over the low friction surface on the spot. Sensors provide data on the user's orientation, current height and movement speed, to be interpreted into *Locomotion* commands [Cakmak and Hager 2014]. [See *Appendix B.8.2 Cyberith Virtualizer* from page 239ff.]
> (Wiedemann et al. 2017b)

Following up on the research of Nabiyouni et al. (2015), the *Locomotion* part of the *Lab* experiment on *UX Evaluation of VR Locomotion & Virtual Object Interaction Mechanics* (see from page 150ff.) investigates the *UX* of another semi-natural *Locomotion* device, the *ROVR Omnidirectional Treadmill* (Wizdish 2017). Although the *Virtualizer* seems to be a technically more sophisticated *Omnidirectional Treadmill*, the nevertheless similar treadmill *ROVR* (Wizdish 2017) was used in the experiment, because of availability issues (Wiedemann et al. 2017b). In contrast to the *Virtusphere*, the *ROVR* uses a fundamentally different design, which excludes any of the former's inherent problems with getting a sphere in motion in a controlled way. Nevertheless, the *ROVR* also showed issues with accuracy, due to its tracking being based on movement noise (see section *Omnidirectional Treadmill* from page 41ff).

> “ Concerned with "the effect on cognition" or the "knowledge, understanding and application, and higher mental processes" regarding a *VE*, the study by Zanbaka et al. compares four different virtual "travel techniques" (2005). Additionally, Zanbaka et al. evaluate their effect on *Presence* (2005), using the *"Steed-Usoh-Slater Presence Questionnaire"* (Usoh et al. 2000). Three of the four *Locomotion* methods were tested using a *VR HMD* and included: *"Real Walking (RW)*" in a space, which has the same size as the virtual one (4.5 x 4.6 m^2). *"Virtual Walking using Six-Degrees-of-Freedom Tracking (VW6)*" in a restricted physical space (1.2 x 1.2 m^2), so the user can still naturally move within the confined space but needs to use joystick buttons to move forward or backward beyond the restrictions alongside the user's looking direction. *"Virtual Walking using Three-Degrees-of-Freedom Tracking (VW3)*" which also uses joystick buttons to move and the same restrictions as *VW6*, but without the possibility to physically move within the bounds. Finally, the fourth method *"Joystick with a Monitor (M)"* was *Non-VR* and required the participant to sit in front of a computer screen and use a joystick to control movement and view direction in an arguably more conventional manner (Zanbaka et al. 2005). Their results regarding cognition unsurprisingly suggested that real walking in a "large tracked space" shows advantages over "common virtual travel techniques", if "evaluation of information is important or ... opportunity to train is minimal" (Zanbaka et al. 2005).
>
> In contrast, the results on *Presence* surprisingly could not show any significant differences between any of the three *VR* methods. Zanbaka et al. could only report a significant difference between the *Real Walking* and the *Joystick/Monitor* condition.
>
> [The *Lab* experiment on *UX Evaluation of VR Locomotion & Virtual Object Interaction Mechanics]* did not

specifically evaluate any effects of *Locomotion* mechanics on cognition, but the qualitative results highlight those mechanics, that required more concentration of untrained participants. Regarding *Presence* ratings, [the *Lab* experiment on *UX Evaluation of VR Locomotion & Virtual Object Interaction Mechanics]* clearly showed significant and detailed differences between the three tested *VR Locomotion* mechanics (see from page 150ff.).
(Wiedemann et al. 2020)

One of these investigated mechanics is based on the concept of virtual teleportation, another category of *VR Locomotion,* as previously mentioned. Also related to teleportation are the studies by Bozgeyikli et al. (2016) and Cherep et al. (2019).

> More concerned with *UX* of *Locomotion* mechanics, Bozgeyikli et al. conducted an experiment comparing point and teleport, walk-in-place and joystick *Locomotion* mechanics (2016). Their findings indicated, that their implementation of a point and teleport mechanic is "an intuitive, easy to use and fun *Locomotion* technique", while reducing *Simulator Sickness* to [a] minimum (Bozgeyikli et al. 2016).
> (Wiedemann et al. 2017b)

> [In contrast,] the study by Cherep et al. investigated "implications of teleporting" on "spatial cognition" (2019). They compared real walking ("concordant") with two teleport mechanics: One mechanic without ("partially concordant") and one with ("discordant") the ability to control the view direction or rotation before the teleport takes place (Cherep et al. 2019). Their results showed an increase in spatial cognition error from the concordant to the partially concordant and from the latter to the discordant mechanic. In other words, spatial cognition declined from real walking over teleport without rotation control to teleport with rotation control (Cherep et al. 2019).
>
> The teleport mechanic (with rotation control) in combination with room scale tracking of real walking, examined in [the *Lab Experiment: UX Evaluation of VR Locomotion & Virtual Object Interaction Mechanics],* confirmed these results, as in minor cases, it showed signs of disorientation in untrained users. Especially, when they misused the rotation control. Nevertheless, it was overall regarded as enjoyable and intuitive [see from page 150ff.]. What differentiates [my] experiment is including an *Omnidirectional Treadmill* as a *Locomotion* mechanic and using the real-world game *Gooze* as a platform, which evaluates *Locomotion* in combination with *Virtual Object Interaction,* instead of a pure experimental application, which lacks real-world challenges.
>
> [In a similar fashion, but different in other ways,] Shanmugam et al. developed a framework to "both navigate and interact with objects in virtual worlds", while only using a low-cost *Google Card-board VR* system, without any external sensors or hand controllers (2017). They investigated the *UX* of three *Locomotion* mechanics in combination with a simplified *Virtual Object Interaction* mechanic. For

Locomotion Shanmugam et al. implemented their own *"Walk in Place"* mechanic and tested it against previously established *"Look down to Move"* and *"Click to Move"* mechanics (2017). Whereas to interact with virtual objects, a timer driven reticle was implemented. Once the reticle would hover long enough over an object for the timer to run out, a single pre-defined action with the object would be triggered. Their *Walk in Place Locomotion* mechanic scored best amongst the other two *Locomotion* mechanics (Shanmugam et al. 2017).

In contrast to their study, [my *Lab Experiment: UX Evaluation of VR Locomotion & Virtual Object Interaction Mechanics]* did not only compare the *UX* of several *Locomotion,* but also of different *Virtual Object Interaction* mechanics, which additionally offered more versatile and sophisticated interactions. Furthermore, [my] study was aimed at high-end consumer hardware, while still maintaining a broad range of rather common setups, covering different investment costs [see from page 150ff.].
(Wiedemann et al. 2020)

2.1.4.4 Virtual Object Interaction

As was already noted, besides moving through a *VE* by *Locomotion,* it is equally important for users to be able to interact with virtual objects in that *VE.* Similar to *Locomotion,* there are very diverse input devices and interface methods concerned with *VOI,* but most of the related studies seem to be investigating inherent sub tasks of *VOI,* instead of more holistic approaches.

“ E.g., the literature survey by Argelaguet and Andujar is concerned with a plethora of virtual object selection mechanics using mostly industry and research-based hardware (2013). They come to the conclusion that, "Although 3D interaction techniques for target selection have been used for many years, they still exhibit major limitations regarding effective, accurate selection of targets in real-world applications" (Argelaguet and Andujar 2013). They argue, that current limitations arise through a combination of "visual feedback issues" (e.g. occlusion and depth perception in *Stereoscopic 3D)* and "inherent features of the human motor system" (e.g. neuromotor noise, Argelaguet and Andujar 2013). Argelaguet and Andujar propose that designing 3D interaction mechanics with improved efficiency, would involve developing novel "strategies for controlling the selection tool" and enhancing provided visual feedback (2013). [I] further agree with Argelaguet and Andujar, that "in the real world selection tasks are mixed with other primary tasks such as manipulation and navigation" and should in turn be evaluated not only in isolation, but in a more holistic manner. This will be the case with [the *Lab* experiment on *UX Evaluation of VR Locomotion & Virtual Object Interaction Mechanics* (see from page 150ff.)].

Kim and Park investigated *Virtual Object Interaction* (grabbing and transporting) with a hand and finger tracking device in the context of causing "awkwardness and manipulation difficulties" in users, which they named "*VR* interaction-induced fatigue symptom" (2014). Their study inferred e.g. duration time, maximum grip aperture and the number of trials and errors to induce "fatigue and difficulties in manipulation" (Kim

and Park 2014). Their design guidelines include enhancing object "contact cues" through sensory user feedback and adjusting the "input action strategy" and the viewpoint (Kim and Park 2014). The latter aspect will likely not be feasible to control in a completely dynamic *VR* application and although the input action strategy might be optimized to some degree, the game's gameplay for the *[Lab* experiment on *UX Evaluation of VR Locomotion & Virtual Object Interaction Mechanics* (see from page 150ff.)] will still require certain durations of grabbing and interacting with objects.
(Wiedemann et al. 2017b)

" The two studies by Tian et al. (2018) and Holl et al. (2018) are both concerned with more natural appearing methods of grabbing and holding virtual objects in real-time using the *Leap Motion* controller as an interface. The approach by Tian et al. uses machine learning and particle swarm optimization in an offline process to pre-compute "stable grasp configurations" based on the possibly complex 3D models of the hands and objects (2018). During runtime, these stable grasp configurations are then used in combination with "dynamics/non-penetration constraints" and "motion planning techniques to compute plausible looking grasps" (Tian et al. 2018).

Aiming at a similar goal, Holl et al. used a very different approach, not requiring a pre-computational step. Their solution uses a physics method, based on the *Coulomb* friction model running in a performance efficient way (Holl et al. 2018). This enables simulating many types of dexterous interactions between hands and objects (e.g. spinning objects between fingers), while using a common *VR* engine (Holl et al. 2018). Both approaches are pushing *VOI* further towards the high fidelity of interacting with objects in reality
(Wiedemann et al. 2020)

Nevertheless, they mark an area in which the *Lab Experiment: UX Evaluation of VR Locomotion & Virtual Object Interaction Mechanics* was limited, due to the range of assessed input devices (see from page 150ff.). This means, a simpler approach for posing virtual hands and objects was used: Based on a single grab and/or pinch parameter the object would snap into the hand and both would transition to corresponding pre-defined grabbing poses (Wiedemann et al. 2020). Yet, the methods to achieve high fidelity *VOI* will likely be developed and explored further in future research, especially when trying to simulate more dexterous interactions with virtual objects.

2.1.5 LITERATURE SUMMARY

The previous sub sections have provided a literary context, which illustrates how different aspects of the overall study are related to other research and research areas and in which ways the scope of the overall study is confined.

The section on *Practice-Related Research* introduced the concept of research with a focus on practice in art and design and how the overall study fits into this as practice-based research. Subsequently, it presented *Constructive Design Research*, which was chosen as a suitable methodology for this research. As reflection is an integral part of *CDR* and software development is an essential aspect in creating the artifacts, the relation of these two topics was discussed. Additionally, the *Hybrid Journaling Technique* using commit messages in versioning repositories was introduced for the overall study. Both, *CDR* and the developed *Hybrid Journaling Technique* will be discussed in more detail in the section *Methodology* from page 57ff.

The following section on *Clarifying Ambiguous Key Areas* was concerned with the central theme guiding areas: *Rollenwahrnehmung*, *Perspective* and *Space.* Their definitions were delimited for the overall study and their relation to it was established.

The section on *Subjective Aspects of Immersive Experiences* discussed the experiential topics of *Immersion*, *Presence*, *Flow* and *Simulator Sickness* and connected them to the corresponding studies in this research.

Finally, the section on *Interface related Aspects* covered more technical and mechanical specifics of *VR* related interfaces with the user/s. These included the areas of *Stereoscopic 3D, Camera Behavior*, *Locomotion* and *Virtual Object Interaction.*

2.2 TECHNOLOGY

Following the *Literature* review, a context regarding *Technology* of the overall study needs to be established, to provide a technological overview for the reader and to justify the selection of used technologies in this research. Hence, the following will briefly elaborate on used technologies and devices and why they were chosen for this research.

See *Appendix B. Technology Context (Extended)* from page 213ff. for a more comprehensive state-of-the-art review of related, as well as for the overall study utilized technologies and devices. Furthermore, the *Appendix* describes what kind of technological principles were used to achieve *VR* relevant features like for example a wide *Field of View (FOV),* high display refresh rates, *Stereoscopy* and rotational and positional tracking.

2.2.1 PC VIRTUAL REALITY

For this *PhD* research, I chose *PC VR* (see *Appendix B.2 Tethered VR Head Mounted* Displays from page 217ff.) over *Mobile VR* equipment (see *Appendix B.3 Mobile VR Head Mounted* Displays from page 226ff.) for several reasons: to make use of a greater part of *VR's* full potential, to be less restricted by mobile platform restrictions and finally to reduce development effort. The later would be caused, among other reasons, by further needed performance optimizations, longer development times through mobile build pipelines, as well as energy consumption and heat development issues. In addition, *Mobile VR* only later – in the middle of this *PhD* research – became a real option. Thus, as this research first started with developments with *PC VR* equipment, while providing the best connectivity with other devices and the most possible high-end experiences, *Mobile VR* was disregarded technology wise for the overall study. Nevertheless, most design related insights of the overall study are transferable to *Mobile VR* as well, although some corresponding mechanics might require some hardware features, which at the moment of this writing, are only available for *PC VR.*

Figure 4: Oculus Rift Development Kit 1 (Oculus 2016a)

Figure 5: Oculus Rift Development Kit 2 with separate Infrared camera (Oculus 2016a)

Being the first available new generation *VR Head Mounted Display (HMD),* the *Oculus Rift Development Kit 1 (DK1,* see Figure 4) was the starting point for the development of *VR* artifacts for the overall study in 2014.

During the development and user testing of some of the artifacts of the overall study the *DK1's* successor, the *Development Kit 2 (DK2,* see Figure 5) was used most of the time. This was the case, as it was the most common *HMD* at the time and because I already had experience with the corresponding *Oculus Software Development Kits (SDKs).* At the time, it furthermore had the best implementation in popular game engines like *Unity 3D.* Compared to the *DK1*, the *DK2* offered higher resolution, higher display refresh rates and positional tracking via a separate *Infrared (IR)* camera (see Figure 5).

Figure 6: Oculus Rift Consumer Version 1 (Oculus 2016b)

Figure 7: Oculus remote and IR camera (Oculus 2016b)

At its time, the successor of the *DK2,* the *Oculus Rift Consumer Version 1 (CV1,* see Figure 6) was one of the most advanced *VR HMDs,* offering high-end specs in display resolution, display refresh rate, tracking robustness, optics and user-friendliness. In turn, after the *CV1's* release, it was chosen for further developments in the overall study, as it fits right into previous artifacts' developments and offers great development support, in terms of *SDK* and development community. Although the *Oculus Rift S* (Oculus 2019a) was released as an evolutionary successor to the *CV1*, at the moment of this writing, due to its robust external tracking system the latter is still regarded as a high-end *VR HMD.*

2.2.2 CONTROL PERIPHERALS

For users to interact with a *VE* control peripherals are necessary devices. Over the years, the most common hardware interfaces for gaming included gamepad, joystick, keyboard and mouse. In the case of *VR,* new innovative controllers were released, which complemented the more conventional ones with new features more fitting for the medium.

2.2.2.1 Gamepad

Figure 8: Wireless Xbox One Controller (Microsoft 2019a)

Far from being the optimal input device for *VR*, common game controllers are still a viable solution for certain applications though. Because of their quasi industry standard design (Ulanoff 2013), easy integration and availability, several *Xbox* controllers *(360* and *One*, see Figure 8) have been used in different configurations for several artifacts of the overall study. E.g. see sections *Nicely Dicely* from page 71ff. and *LizzE – And the Light of Dreams (LizzE)* from page 104ff. For more information on the device see *Appendix B.4.1 Xbox Controller* on page 231.

2.2.2.2 Controllerless Hand Tracking

Figure 9: Leap Motion controller mounted to an HMD tracking hands and fingers (Leap Motion 2016a)

Providing *Controllerless Hand Tracking*, the *Leap Motion* controller (see Figure 9) mounted to an *HMD* can translate a full skeletal representation of the user's hands and fingers into *VR*. Still, its tracking, based on an internal *IR* camera system and image recognition algorithms, is lacking robustness in certain situations (e.g. occlusion and suboptimal lighting). Even though not being perfect, the controllerless *Virtual Object Interaction* via this device, nevertheless immensely increases *Presence* in *VR* (see section *Lab Experiment: UX Evaluation of VR Locomotion & Virtual Object Interaction Mechanics* from page 150ff.).

Originally developed for desktop-based gesture recognition, the relatively small device quickly became a very interesting companion for *HMDs*, once the *VR* movement was revived. Offering an extensive *SDK* with proper documentation, lots of example projects and various template assets helped with acquiring a wider developer base.

Because of its formerly unique capabilities, the *Leap Motion* controller has been used in different forms in several artifacts of the overall study (e.g. see section *Gooze* from page 130ff.). For more information on the device see *Appendix B.6.1 Leap Motion Controller* on page 235.

It needs to be mentioned that, during the end of this research, further hand and finger tracking technologies became available like integrated *Controllerless Hand Tracking* in the *Oculus Quest HMD* (see *Appendix B.3.6 Oculus Quest* from page 230ff.) and finger tracking via the *Valve Index (Knuckles)* controllers (see *Appendix B.5.6 Valve Index Controllers (Knuckles)* from page 234ff.). These, in the main *VR* hardware integrated solutions have clear advantages over third-party technologies like the *Leap Motion* controller (e.g. no tinkering needed, no extra cable required and system wide software integration etc.). Nevertheless, the majority of the results of this research concerning *Controllerless Hand Tracking* can be transferred to these technologies, too.

2.2.2.3 Spatially Tracked Hand Controllers

Figure 10: Oculus Touch controller set (Oculus 2016c)

Figure 11: Oculus Touch controller in a hand (Oculus 2016c)

Relatively robust tracking provided, two separate and fully tracked hand controllers seem to massively contribute to *VR* experiences and the feeling of *Presence* (Lang 2016b).

Because of their superior asymmetric ergonomic design, feature set (gesture recognition and vibration haptics) and compatibility to the *CV1* tracking system and *SDK* ecosystem, the *Oculus Touch* controllers (see Figure 10 and Figure 11) were used in one artifact of the overall study (see section *Gooze* from page 130ff.). For more information on the devices see *Appendix B.5.1 Oculus Touch Controller* from page 232ff.

2.2.2.4 Omnidirectional Treadmill

Figure 12: Wizdish ROVR and ROVR shoes (Wizdish 2017)

Though there are various ways of simulating *Locomotion* through different metaphorical mechanics, *Presence* in *VR* benefits the most of some form of natural walking or running movement. The issue of simulating a possibly endless *VE* in a confined physical space remains though.

Like other *Omnidirectional Treadmills,* the *Wizdish ROVR* (see Figure 12) tries to fill this interface gap, by providing some sort of walking cage. Wearing special shoes, users relatively naturally walk and run in this confined space on a curved and super low friction surface. Using a forward/backward sliding motion of the feet in opposite directions is recommended. Via a very simple tracking technique, these user movements get translated into forward only motion in *VR,* towards the direction the user is looking at. This supposedly helps to reduce *Simulator Sickness* issues caused by other completely unnatural metaphoric *Locomotion* mechanics (e.g. like using an analogue stick on a common game controller). Nevertheless, there are various downsides to this specific *Omnidirectional Treadmill.* Due to its simple tracking method, based on a quasi-microphone detecting the noise volume of user movements and translating it into forward motion, a user can only move forward and not backward or sideways. Additional issues were concerned with unintended *Locomotion* while turning, movement accuracy and generally different user movement styles (see section *Lab Experiment: UX Evaluation of VR Locomotion & Virtual Object Interaction Mechanics* from page 150ff. and *Appendix C.3.6 Wizdish ROVR Implementation* from page 255ff.).

Though the *ROVR* might not be the most advanced *Omnidirectional Treadmill* in production, it was the only one available for this research. This, its impact on more natural user behavior in *VR* and its relatively supposedly easy software integration were the reasons to add it as a *Locomotion* interface for one artifact of the overall study (see section *Gooze* from page 130ff.). For more information on the device see *Appendix B.8.3 Wizdish ROVR* on page 240.

2.2.3 STEREOSCOPIC 3D

Figure 13: Panasonic PT-AT6000E 3D projector (Panasonic 2017a)

Figure 14: Panasonic TY-EW3D3ME 3D IR active Shutter Glasses (Panasonic 2017b)

Though *Stereoscopic 3D* in itself does not provide a *VR* experience, it is nevertheless a crucial technique to create depth perception in *HMDs* and thus an essential aspect of *VR*. For this reason and because one artifact of the overall study implemented this technology (see from page 71ff.), the category of *3D* capable *Projectors* and *TVs* is mentioned here.

Exemplary for *3D Projectors* and *TVs*, the *Panasonic PT-AT6000E 3D Projector* (see Figure 13) was used with four *Panasonic TY-EW3D3ME* active *Shutter Glasses* (see Figure 14) in the *Local Multiplayer* artifact *Nicely Dicely* (see from page 71ff.). For more information on the device setup see *Appendix B.9 Stereoscopic 3D Projectors & TVs* on page 240.

2.2.4 TECHNOLOGY SUMMARY

The previous sub sections have given a brief technological context of the overall study (see *Appendix B. Technology Context (Extended)* from page 213ff. for a more exhaustive review) and justifications for the selection of used technologies in this research.

PC VR in general was selected, as it provided the most powerful and versatile platform for *VR* development. Nevertheless, most design related insights of the overall study are transferable to *Mobile VR* as well. The *Oculus Rift HMDs* specifically *(DK1, DK2* and *CV1)* were chosen for development, because of a combination of different factors (e.g. early availability, superior feature set, development support and extensive *SDK).*

In terms of control peripherals, a mixture of diverse input devices was selected to test various setups. Although not being an optimal input device for *VR,* the quasi industry standard *Xbox* controller was included, as the lowest common denominator for user setups and because of its versatility. The *Leap Motion* controller, on the other hand, was selected because of its unique and controllerless, if still not completely robust, hand tracking capabilities. On the contrary, the additionally chosen *Oculus Touch* hand controllers offered robust tracking, compatible to the *CV1* tracking system, and a rich and superior feature set, compared to other hand controllers. Finally, the *Wizdish ROVR Omnidirectional Treadmill* was added, because of its availability and *Locomotion* tracking capabilities, providing a relatively natural walking experience.

Forming an essential aspect of *VR,* a *Stereoscopic 3D Projection* setup was selected to test this particular *VR* component in isolation and broaden the artifact portfolio by a *Multiplayer* experience.

2.3 GAMES & EXPERIENCES

Following the brief review of utilized technologies in the overall study, this section will create a context of related *Games & Experiences* regarding content and/or execution and how they relate to artifacts of the overall study.

2.3.1 ALTSPACEVR & OCULUS SOCIAL

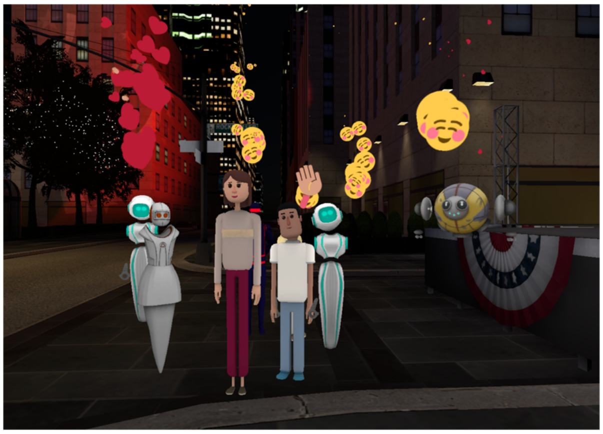


Figure 15: AltspaceVR (AltspaceVR 2016)

Figure 16: Oculus Rooms (Oculus 2016d)

Relating to the social aspects of the *Local Multiplayer* artifact *Nicely Dicely* (see from page 71ff.), the following will illustrate some of the social capabilities in *VR* and present two corresponding platforms.

Due to the encapsulating nature of an *HMD,* one might think social activities in *VR* are a contradiction, but the opposite is easily possible through *Multiplayer VR* and social *VR* platforms, which connect multiple users via the internet or local networking. Nevertheless, social *VR* does not yet provide the same high level of sensual fidelity and complexity like Neil Stephenson described his all-encompassing *Metaverse* (1992), Ernest Cline his more game-based *OASIS* (2011) or Vernor Vinge his *AR/MR* equivalent (2006). Still, there are already some early phase platforms, which strive for similar experiences, like *AltspaceVR* (see Figure 15) and the *Oculus/Facebook* social features like *Parties* and *Rooms* (see Figure 16) and their successor *Facebook Horizon* (Oculus 2020).

On both platforms, users can design their own avatars in varying degrees, meet, play and communicate with each other in *VR* (AltspaceVR 2015 and Oculus 2016d).

In *AltspaceVR* it is possible to consume media either alone or together on a shared virtual cinema screen (AltspaceVR 2015). This is possible in a similar way through *Oculus Rooms,* though the content gets delivered through *Facebook* (Oculus 2016d).

Similar to *Second Life* (2017) and *VRChat* (2020), *AltspaceVR* is an open platform that can be extended by users via standard 3D web technologies like *WebGL* and other frameworks (AltspaceVR 2015).

Oculus' social features like *Parties* and *Rooms* on the other hand, are more designed to streamline getting together, sharing content and communicating in *VR* in a comfortable and stylish place (see Figure 16), as well as starting up group or *Multiplayer* sessions of other *VR* apps, like for example *AltspaceVR* (Oculus 2016d).

The history of communication in the web and the success of social networks like *Facebook* have shown, that these aspects are likely to become a strong force in this medium and it is very much possible, that the next big social network will be one based in *VR.*

For the *Lab* experiment on *Immersion Affected by 3D Stereoscopy* (see from page 91ff.), the artifact *Nicely Dicely* was used as a platform. The foundation of this game is based on *Local Multiplayer* with up to four players, which facilitates chatting and friendly banter between players, due to either its cooperative or competitive gameplay. Despite this fact, the results of the experiment still showed an increase in *Player Immersion,* when using *3D Stereoscopy.* Except for this relation the overall study did not investigate social aspects of *VR* any further.

2.3.2 DERREN BROWN'S GHOST TRAIN

Figure 17: Derren Brown's Ghost Train (Summers 2016)

Figure 18: Visitors of Derren Brown's Ghost Train (Nafarrete 2016)

Relating to the shared experience of multiple players in the artifact *Nicely Dicely* (see from page 71ff.), the following will present another *VR* experience in which several users participate at the same time and the concept of location-based *VR* in general.

The entertainer and mentalist Derren Brown and *Thorp Park* (theme park) created a modern ghost train experience (see Figure 17, Summers 2016). In this horror entertainment spectacle, groups of several park visitors (see Figure 18) are able to live through a short-term hybrid *VR* and theatrical experience. Though the storyline on drilling to the earth's core for some new energy source and a resulting zombie apocalypse seems a bit "unoriginal [and] … stitched together" (Summers 2016), the setup and execution are considered very sophisticated. Up to 58 visitors per session (Nafarrete 2016) will be led into a big warehouse to get on a train. When inside the internally rather *London Tube*-like looking train, visitors are told by "railway personnel" to put on their "protective masks" (slightly modified *HTC Vives,* see Figure 18) to avoid infection (Summers 2016). The experience involves passive and scary 3D animated movie-like sequences in *VR.* These are enhanced by accentuating physical touches of actual personal. Furthermore, the train "stops" in between for a theatrical zombie performance of real actors, which takes place on a train station scenery. After living through some group panic, the visitors are led back into the train and provided with masks again, so they finally can experience the animated apocalyptical finale (Summers 2016). “Indeed, the attraction shows how *VR* and its immersive nature can be mixed in with more traditional and theatrical forms of escapism.” (Summers 2016).

Although *Derren Brown’s Ghost Train* is a well-executed example of a well-integrated, location-based and shared *VR* experience, it lacks interaction possibilities with the *VE* and other participants. During the *VR* phases other real passengers of the train were ignored in your personal experience and a set of pre-rendered performances of actors would be played instead. Although this concept is understandable for a theme park attraction for practical reasons, it nevertheless excludes any real interactions between participants. Furthermore, it does not take advantage of the full range of possibilities in *VR.* In contrast to this, although not strictly a *VR* game, players of the *Local Multiplayer* game *Nicely Dicely* very much interact with each other, inside the game as well as outside of it.

Although the concept of location-based *VR* experiences needed to be mentioned in this thesis, it is nonetheless an area outside the scope of this research.

2.3.3 SUPER SMASH BROS. ULTIMATE

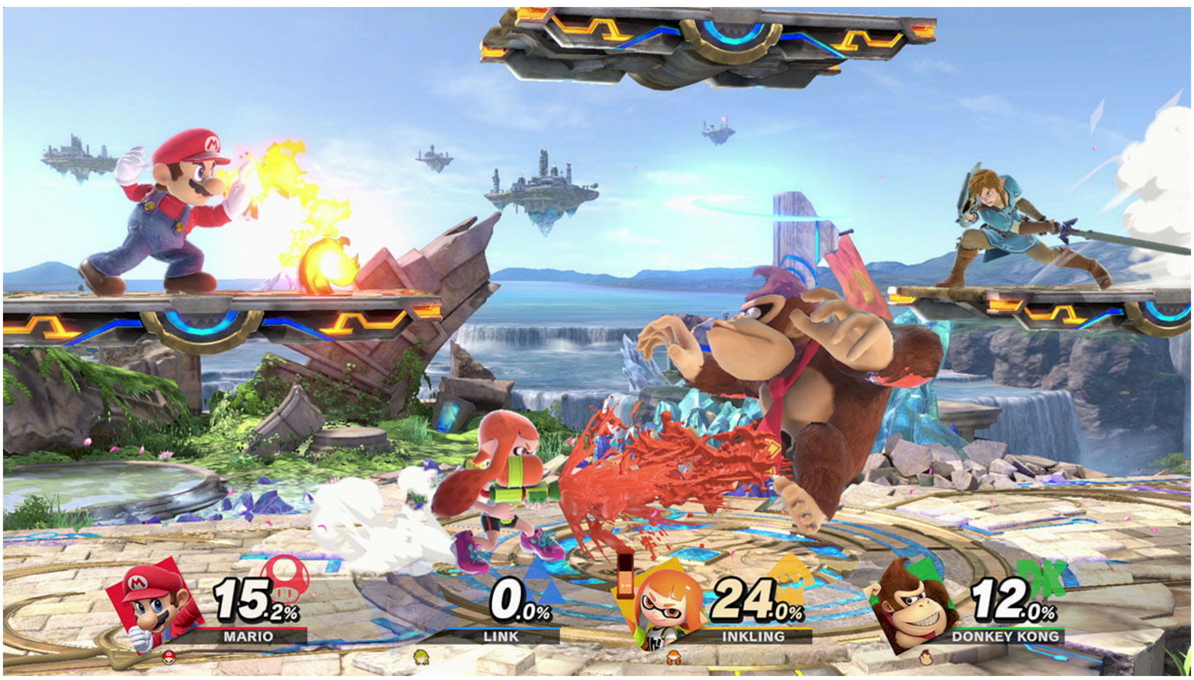


Figure 19: Super Smash Bros. Ultimate (Nintendo 2018)

Relating to the competitive *Multiplayer* party game concept of *Nicely Dicely* (see from page 71ff.), the following will present *Super Smash Bros. Ultimate* (see Figure 19) and its rather limited *VR* mode.

Super Smash Bros. Ultimate is the fifth part of a very popular fighting game series (Marks 2018). Being designed as a party game for the *Nintendo Switch,* besides providing a *Singleplayer* mode its *Multiplayer* mode for up to eight parallel players (Marks 2018) marks the foundation for its gameplay. The clue of the game are the 74 fighters from a pool of very diverse popular game franchises and its massive amount of 108 stages (Marks 2018).

> Having *Mario* and *Zelda* duke it out against *Street Fighter's Ryu* and *Final Fantasy 7's Cloud* on a battlefield from *Metal Gear Solid* is a weird, wonderful thing that only the *Smash Bros.* series can deliver – and *Ultimate* is undoubtedly *Smash Bros.* done big and done right.
> (Marks 2018)

The fighters all have special abilities and attacks and the players' skills in mastering these is the key to winning, which is a common trait of fighting games. Additionally, although the stages are practically 2D platform levels, their animated presentation provides players with an always dynamic scenery.

In terms of *VR*, the support for the *Nintendo Labo VR* cardboard system offers only limited additional benefits, as it is only compatible in the *Singleplayer* mode and additionally "limited to either fighting against *AI* opponents or simply taking in the view while computer-controlled characters duke it out" (Webster 2019).

In contrast to the game's *Labo VR* mode, *Nicely Dicely* offers *Stereoscopic 3D* for up to four players. In terms of actual *Multiplayer* party game gameplay though, it is seemingly impossible for *Nicely Dicely* to keep up with a *Nintendo* game of this scale.

2.3.4 LUCKY'S TALE

Figure 20: Lucky's Tale (Oculus 2016e)

Relating to the *Lab* experiment on *VR 3rd Person Camera Behavior Modes* with the artifact *LizzE* (see from page 114ff.), *Lucky's Tale* and its approach on this topic will be illustrated in the following.

> The game studio *Playful* (2016) recently released the popular *3rd Person VR* game *Lucky's Tale* [see Figure 20], a game very much in the spirit of *Super Mario 64* and *Banjo-Kazooie* (Hurd and Reiland 2016). While developing the game, they were trying different approaches of creating an attractive gameplay and level design but also reducing the possibility for nausea to a complete minimum. Their solution was a combination of reducing user *Locomotion* in general, mostly aiming *Locomotion* away from the user and a clever more linear level design that does not require a lot of turning around (Hurd and Bettner 2014 and Hurd and Reiland 2016).
> (Wiedemann et al. 2016)

In contrast to the approach for *Lucky's Tale* to design levels in a more linear way to reduce camera turning in general and thus minimize *Simulator Sickness*, the *Lab Experiment: Virtual Reality 3rd Person Camera Behavior Modes* (see from page 114ff.) provides some camera behavior solutions for game designs, which are based on exploring levels freely in full 360 degrees, like *LizzE.*

2.3.5 EVE VALKYRIE

Figure 21: Eve Valkyrie (CCP 2017)

Relating to the *1st Person Perspective* in *Gooze* (see from page 130ff.) and because it uses some form of smooth *Locomotion* mechanic, which in a different implementation is also available in *Gooze*, the following describes the space shooter *Eve Valkyrie.*

Alongside *Lucky's Tale*, *Eve Valkyrie* (see Figure 21) by *CCP* belongs to the launch titles of the *Oculus Rift CV1* and is a great example for a well-crafted *VR User Experience* in the *First Person Shooter (FPS)* genre (Stapleton

2016b). The user is seated in a cockpit of one of the three playable ship classes, which are fighter, heavy fighter and support-class (Stapleton 2016b). As the game was developed for *VR* from the start, it is optimized really well for the medium. The user can freely turn his or her head inside the cockpit, not only to look around, but also to aim for example missiles at an opponent, while flying a different route. This creates a "whole new level of dogfighting" (Stapleton 2016b). Though the game also offers *Singleplayer* content, its main focus seems to lie in *Multiplayer* battles. Among other playable modes, the users can group together for *Team-Deathmatches,* two *Point-Capture* modes and *Carrier Assault.* In the later, one team has to defend a bigger carrier ship, whereas the other team first has to destroy the carrier's shield and then shoot it down directly (Stapleton 2016b). When using a suitable *PC,* the visual fidelity is high-end (Stapleton 2016b). Still, by controlling the *Locomotion* of the game via a common game controller, a considerable amount of vection and thus *Simulator Sickness* can arise. Even though this effect is lessened by successfully using the cockpit as a reference frame (Prothero and Parker 2003, Duh et al. 2001 and Jerald 2016), *Oculus* promotes the game with a comfort level of "intense" in their digital store.

As previously mentioned, a different version of smooth *Locomotion* via gamepad was also implemented in *Gooze* and its *UX* was evaluated in the *Lab Experiment: UX Evaluation of VR Locomotion & Virtual Object Interaction Mechanics* (see from page 150ff.).

Although using a reference frame (i.e. the cockpit in *Eve Valkyrie)* to reduce *Simulator Sickness* was also an option in *Resident Evil 7: Biohazard* (see from page 52ff.), this technique was not specifically investigated in this research.

2.3.6 DOOM VFR

Figure 22: DOOM VFR (Bethesda 2019)

Relating to investigating *VR Locomotion* mechanics with the artifact *Gooze* (see from page 130ff.), the following will illustrate *DOOM VFR* and its corresponding teleport-dash mechanic.

> In its fourth *Non-VR* iteration, released in early 2016, *DOOM* [see Figure 22] had a great impact on *First Person Shooters (FPS)* by reviving some of the raw old school trademarks of the genre (Shoemaker 2016). The game is played really fast and the user is practically forced to quickly move into the middle of close combat to succeed (Shoemaker 2016). These are aspects not easily transferable to *VR.* Moving quickly through virtual space without creating *Simulator Sickness* has been a huge challenge so far. There are a plethora of methods handling *Locomotion* based on teleportation, physical motion, room scale tracking (TechTarget 2016) and artificial input devices like common controllers (Reddit 2016). The *FPS* genre though, lacked an appropriate method, which could deliver a fast pace without creating vection and *Simulator Sickness.* [DOOM VFR] seems to have solved this, by implementing a subtly fine-tuned teleportation mechanic (Butterworth 2016). Using one *HTC Vive* controller to fire at enemies and the other to teleport-dash through space seems to even enhance the experience (Butterworth 2016). Though compared to other teleportation mechanics, *DOOM* slows down the game to bullet time, when holding the teleport trigger and when released dashes the user in super speed to where she or he was aiming (Butterworth 2016).
> (Wiedemann et al. 2017a)

A similar version of the teleport-dash mechanic was implemented in *Gooze.* It included slow motion time when selecting a teleport destination and rotation and a very quick translation animation for the dash, to provide the user with subtle motion cues, minimizing disorientation. For more details see section *Lab Experiment: UX Evaluation of VR Locomotion & Virtual Object Interaction Mechanics* from page 150ff.

2.3.7 JOB SIMULATOR

Figure 23: Job Simulator (Owlchemy Labs 2017)

Relating to the reduction of *Simulator Sickness* through game design and investigating *Virtual Object Interaction* mechanics with the artifact *Gooze* (see from page 130ff.), the following will elaborate on the design of the *Job Simulator* experience.

> From the ground up designed for *VR*, the *Job Simulator* [see Figure 23] (Owlchemy Labs 2017) delivers a really successful *User Experience* … (Stapleton 2016a). The user's purpose is to use hand controllers, e.g. *HTC Vive*, *Oculus Touch* or *PlayStation Move* controllers (HTC 2016a, Oculus 2016c and PlayStation 2016a), to fulfill rather mundane and menial jobs. These include working at an office desk, preparing dishes in a diner, serving at a convenience store and repairing cars in a garage (Stapleton 2016a). Though by reducing the visuals and interactive objects to a cartoonish style, lots of humorous and absurd situations evolve. This in combination with some funny robotic dialogues establishes the game's charm. The comic style has another effect, which is the reduction of required performance and thus a higher possible frame rate and less possibility for *Simulator Sickness* (Pausch et al. 1992 and Jerald 2016). Furthermore because of the game's rather stationary design no *Locomotion* method is needed, as the user keeps standing on the same spot. This in turn again reduces the possibility for *Simulator Sickness* as no vection effect (Riecke and Feuereissen 2012 and Yao 2014) is involved and more complicated teleportation techniques are unnecessary.
> (Wiedemann et al. 2017a)

In contrast to *Job Simulator*, *Gooze* requires the user to also move around the *VE* and in turn does provide several options for *Locomotion.* Regarding *Virtual Object Interaction, Job Simulator* does a really good job in offering trivial interactions with objects with a good and believable implementation. The possible base interactions with objects in *Gooze* are relatively on par with those in *Job Simulator.* The users are able to push objects with their hands, grab them, carry them and touch other objects with them with more or less force. One obvious exception is throwing objects, which is not a trivial feature and sadly could not be implemented in *Gooze*, due to time constraints. Another one is, that interactions in *Gooze* with partly stationary objects, e.g. like a door, are semi-automatic, which means a predefined animation gets triggered on touch, instead that the user actually grabs the door and turns it around its hinges. Again, this is not a trivial issue and its implementation was skipped, due to time constraints. Nevertheless, when using the capacitive sensing *Oculus Touch* controllers or *Controllerless Hand Tracking* with the *Leap Motion* controller, quite complex hand and finger poses are possible. For more details see section *Lab Experiment: UX Evaluation of VR Locomotion & Virtual Object Interaction Mechanics* from page 150ff.

2.3.8 RESIDENT EVIL 7: BIOHAZARD

Figure 24: Resident Evil 7: Biohazard for PSVR (Capcom 2016)

Relating to general good *VR* game design and investigating *Locomotion* and *Virtual Object Interaction* mechanics with the artifact *Gooze* (see from page 130ff.), the following will illustrate the design of *Resident Evil 7: Biohazard* for the *PlayStation VR (PSVR).*

The game is played in *1st Person Perspective* and built from the ground up with *VR* in mind (i.e. *PSVR).* It is generally paced rather slowly for an optimized *VR* experience. As a fair number of zombie-like creatures can be expected in this game, players have to run and hide or fight for survival with enemies and each single one might cause in-game death.

In terms of *VR* interface design, *Capcom* iteratively optimized the game's handling and provides players with options "to adjust rotation speed, *FOV* dimming" (Jagneaux 2017) and toggle a subtle grid-like reference frame to reduce the possibility of *Simulator Sickness.* Additionally, turning with the analogue stick of the *DualShock 4* controller is restricted to 30-degree steps to avoid creating nausea through gradual turning. This feature was also implemented in the gamepad *Locomotion* mechanic of *Gooze* for the *Lab Experiment: UX Evaluation of VR Locomotion & Virtual Object Interaction Mechanics* (see from page 150ff.).

Finally, "*Resident Evil 7* embraces *Virtual Reality* as a medium and proves that you don't have to cut corners or make sacrifices to create a compelling *VR* experience." (Jagneaux 2017).

2.3.9 LONE ECHO

Figure 25: Lone Echo (Kotaku 2018)

Again, relating to generally well-executed *VR* game design and *Locomotion* and *Virtual Object Interaction* mechanics, the following will illustrate the game *Lone Echo* (see Figure 25).

The *Oculus* exclusive title *Lone Echo* is a *Singleplayer* game developed specifically for the *Oculus PC VR* devices. In *1st Person Perspective* the player takes on the role of a robot *AI* character *Jack.* His mission is to help the human captain *Liv* (see Figure 25) with work on a mining station in space close to *Saturn* (Fahey 2018). And all of that, in zero gravity. The narrative quickly develops to a catastrophic and mysterious situation and the already close relationship between *Jack* (the player character) and *Liv* will not only be elaborated on but gets even stronger over the course of the events. Even though the player knows he or she is playing an *AI,* feelings of affection and support towards *Captain Liv* easily establish (Fahey 2018).

The clue of the gameplay consists of several aspects. First of all, it cleverly integrated any needed meta information as visual aspects of the 3D geometry. E.g. the "health" of the current robot chassis – when the player "dies", he or she restarts in a new chassis – is visible in how corroded the robot body looks and additionally a corresponding bar on the wrist shows the level of the "radiation filter". Furthermore, more complex information on open tasks and dialogue options can be interacted with via temporary movable *Graphical User Interfaces (GUIs).* These interactions are based on intuitive gestures like pulling, scrolling and touch-selecting, similar to the use of touchscreen on a virtual smart phone in 3D. But there is no typical constant *HUD* overlaid on top of the main camera view. Along the wrists, the user also finds access to several tools and features, like the laser or the scanner, which when activated can be used with other objects to perform various tasks. In general, the game's *Virtual Object Interaction* feels well-implemented and designed to make the most of the features of the *Oculus Touch* controllers.

The most important clue of the game, is most certainly its zero gravity *Locomotion* system:

> The *Locomotion* system is brilliant, having the player maneuver by grabbing the environment and pushing off in the direction they wish to travel. It's the perfect movement method for a device that gives players virtual hands but no virtual feet.
> (Fahey 2018)

It consists of the before-mentioned grab and push mechanic and two "impulse" style propulsion mechanics. The player can either use the fine-grained jets around his or her wrists to accelerate, which take the orientation of the hands into account. Or the player uses the stronger jets attached to a special suit, which one receives later in the storyline.

Lone Echo is a very good example for a well-designed *VR* game in many respects. In the case of this research though, its *Virtual Object Interaction* mechanic can almost be seen as a blueprint for what can be achieved with the *Oculus Touch* controllers. Hence, it guided the design of some aspects of the *VOI* mechanics implemented in *Gooze* (see from page 130ff.), which were evaluated in the *Lab* experiment on *UX Evaluation of VR Locomotion & Virtual Object Interaction Mechanics* (see from page 150ff.).

2.3.10 GAMES & EXPERIENCES SUMMARY

The previous sub sections have given a brief context of related games and experiences, regarding content and/or execution and how they relate to artifacts of the overall study.

AltspaceVR, Oculus Social and *VRChat* illustrated the great potential of social interactions within *VR.*

Derren Brown's Ghost Train showed how *VR* can integrate groups of people seemingly within the same location-based *VR* experience.

Although only the *Singleplayer* mode of *Super Smash Bros. Ultimate* is actually *VR* compatible, it is still a good example of a competitive *Multiplayer* game with *VR* capabilities.

Hence, the former three sections were related to the *3D Stereoscopic Local Multiplayer* experience *Nicely Dicely* (see from page 71ff.).

Lucky's Tale was a particularly good example on how certain challenges of a *3rd Person VR* game can be handled, by designing the game around them. In contrast, the *Lab* experiment with *LizzE – And the Light of Dreams* (see from page 104ff.) specifically looked into ways of handling camera behavior in a game, which is designed for 360-degree exploration.

The space shooter *Eve Valkyrie* was described because of its smooth *Locomotion* and reference frame techniques and how they are related to *Gooze* (see from page 130ff.).

DOOM VFR on the other hand, presented a promising teleport-dash mechanic, which would allow fast paced and attractive *1st Person* gameplay, while reducing *Simulator Sickness* to a minimum. This mechanic was of particular interest for the *Lab* experiment with *Gooze* (see from page 130ff.), as a similar approach was adopted.

Job Simulator was described as well, because of two reasons. Its design approach, of excluding any form of artificial *Locomotion* – only natural walking in the confined area of the tracking system is possible – showed that *Locomotion* free gameplay may still be attractive. It furthermore illustrated several trivial *Virtual Object Interactions* with corresponding hand controllers. The design of these interactions is of particular interest for the *Lab* experiment with *Gooze* (see from page 130ff.), as certain aspects were adopted.

Resident Evil 7 is a great example for a released *AAA VR* game title, which was developed for *VR* from the ground up. Various innovative options for controls and visuals and the general pace of the game provide an inspirational starting point for *1st Person VR* experiences like *Gooze* (see from page 130ff.).

Finally, the *1st Person VR* game *Lone Echo* was described because of its exemplary zero-gravity *Locomotion* mechanic and its well-integrated and convincing *Virtual Object Interaction* mechanic.

2.4 CONTEXT SUMMARY

To fully capture the multidisciplinary nature of this practice-based research and to establish an understanding of its surrounding, the previous sections provided a three-part context for the overall study.

The *Literature* review discussed *Practice-Related Research* and how the overall study fits into it via the *CDR* approach. In the sub section on *Clarifying Ambiguous Key Areas* the review furthermore establishes the meanings of the three terms *Rollenwahrnehmung*, *Perspective* and *Space* for the context of this research. The two following sub sections discussed research on the relevant experiential aspects *Immersion*, *Presence*, *Flow* and *Simulator Sickness* as well as the relevant interface related topics *Stereoscopic 3D*, *Camera Behavior*, *Locomotion* and *Virtual Object Interaction.*

The brief *Technology* review listed the hardware technologies used for this research and discussed why they were selected. *PC Virtual Reality*, specifically the *Oculus* desktop *HMDs* were used because of their high-end feature set, rich developer community, strong software base and availability. The implemented *Control Peripherals* ranged from the common *Gamepad (Xbox* controller), over *Controllerless Hand Tracking (Leap Motion* controller) and *Spatially Tracked Hand Controllers (Oculus Touch* controllers) to an *Omnidirectional Treadmill (Wizdish ROVR)*. Eventually, also *Stereoscopic 3D* was mentioned as a crucial aspect of *VR* and because of its implementation in one of the artifacts (using a *Panasonic 3D Projector* and *Shutter Glasses).*

The *Games & Experiences* review covered a non-exhaustive list of various *VR* games and experiences, which touched the topics of game design, gameplay, social *VR*, location-based *VR*, *Multiplayer* party gaming, *1st Person* and *3rd Person Perspectives*, camera behavior, *Simulator Sickness* reduction techniques and various *Locomotion* and *Virtual Object Interaction* mechanics. Furthermore, the section provided relations of the games and experiences to the three artifacts of the overall study.

Finally, the *Context* section settled the overall study within its literary, technological and ludographical context and provided information on relevant topics and challenges surrounding it.

3 METHODOLOGY

The following chapter of this thesis will elaborate on how the overall study was achieved. An overview of *Design Research* will be given, the overarching methodology *Constructive Design Research (CDR)* will be illustrated in more detail and its individual configuration for this research will be specified. Finally, also the applied *Hybrid Journaling Technique* for reflection will be explained.

3.1 DESIGN RESEARCH

There are certainly other research approaches that, to some degree, also try to explore design and its corresponding aspects like problem solving, iterative design and the role of the end-user. These methodologies, partly share *CDR's* broad approach, including for example *Design Research Methodology* (Blessing and Chakrabarti 2009), *Critical Design* (Dunne 1999 and Dunne and Raby 2001), *User-Centered Design* (e.g. *Participatory Design, Ethnography* and *Usability Testing,* Bannon 1991 and Tilley and Dreyfuss 2002), *Action Research* (Denscombe 2010), *Systems Theory* (von Bertalanffy 1968, Simon 1996, Forlizzi and Battarbee 2005 and Forlizzi 2011) and *Operations Research* (British Army 1947, Gedenryd 1998 and Informs 2017).

These latter approaches, *Systems Theory* and *Operations Research,* were originally conceived and developed during World War II and the corresponding post-war era. *Systems Theory* tried to provide a generalized approach to problem solving in all kinds of areas. It attempted to represent real-world situations as abstract systems with sensors, supplying data on the situation, and actuators to perform corresponding changes to the system (Simon 1996). *Operations Research,* on the other hand, was initially concerned with assisting the British military with combat operations and tactics, by statistically analyzing empirical data (Fortun and Schweber 1993). Regarding design research, both *Systems Theory* and *Operations Research* have been used to try and rationalize the design process (e.g. by Herbert Simon, Christopher Alexander and J.C. Jones). Mathematics and strict logic should describe the natural human processes inherent in design practice and research. A resulting rational and abstracted approach should supposedly lead to an orderly and rigorous procedure, which methodically gathers data, determines goals and calculates corresponding design solutions. However, as noted by several researchers, these approaches “barely tackled the human and artistic faces of design” (Koskinen et al. 2011). Hence, they have neither been universally appropriate nor very successful in adoption, as design practitioners do not perform in this manner and designing along the proposed processes just does not seem to work (Gedenryd 1998), which is why it was dismissed for this research.

Action Research has a long history in the social sciences, i.e. pursuing transformation via performing research and taking corresponding action in parallel. It is described as comparing "conditions and effects of various forms of social action and research leading to social action", by making use of "a spiral of steps, each of which is composed of a circle of planning, action and fact-finding about the result of the action" (Lewin 1946). In other words, regarding design research, it tries to gather knowledge about a community or group, with that community or group, to then co-create solutions for systemic issues (Koskinen et al. 2011). These issues may often be rooted in service systems and business concepts of local communities. Hence, the *Action Research* approach is rather concerned with changing and improving those real-world systems, than with developing new products (Pacenti and Sangiorgi 2010). As the overall study aimed at creating product-like artifacts with no specific relation to a certain group of people and as *Action Research* seems to lack the artistic imagination needed for this specific research, it was dismissed as a methodology.

Furthermore, *Critical Design* (Dunne and Raby 2001) specifically aims to establish a firm theoretical basis for examining the process of creating artifacts. It does so while challenging common assumptions regarding the products' relations to design, arts and culture. This approach concentrates on building a critical position on common consumer culture (Dunne and Raby 2001), which is not the focus of this research and as such will not be of relevance.

Also, the well-established *User-Centered Design* with its related branches of *Participatory Design* (Ehn 1988), *Ethnography* (Wasson 2000) and *Usability Testing* (Nielsen 1993), as well as methods like *Cultural Probes* (Gaver et al. 1999 and Mattelmäki 2006), *Scenarios* and *Personas* (Koskinen et al. 2011) are valid choices for certain design-centered projects and have been considered in informing the approach the overall study has taken.

Nevertheless, they were dismissed for several reasons: The focus of *Participatory Design* lies on heavily involving stakeholders (e.g. users, partners and designers) in the design process, by performing corresponding workshops and co-design meetings (Ehn 1988). It is applied in a diverse range of design areas (e.g. sustainability, architecture and software) related to people's lives in e.g. cultural, emotional and practical ways (Ehn 1988). This shifts the responsibility for the designs to a group of people and away from the professional.

Ethnography has a long history outside of the design domain. "Ethnographic field research involves the study of groups and people as they go about their everyday lives." (Emerson et al. 1995). This means the researcher needs to immerse him or herself into a community and participate in it, while systematically taking notes of observations of lives and generally of what is going on (Emerson et al. 1995). Regarding design research, *Ethnography* focuses on evaluating mostly early-stage prototypes within a community to circumnavigate cultural issues (Salvador et al. 1999). In a design context it may later involve co-design meetings with community members to create mock-ups or to capture ideas in mood boards and collages. Both *Participatory Design* and *Ethnography* further lead to a design procedure very different from the one intended for this research: The overall study keeps the responsibility for the designs and their inception with the professional, but lets them be evaluated by users and influenced through gathered corresponding information over iterations.

Usability Testing, on the other hand, is very much concerned with analyzing end-products (e.g. websites, computer applications, consumer products and documents) based on intuitiveness, ergonomics and task execution performance (Dumas 2007). However, it lacks to integrate the context of a design, or the environment in which it is used, into the analysis (Koskinen et al. 2011) as well as misses to consider the user as an experiential being instead of just an information processing unit (Crowther-Heyck 2005). Although *Usability* definitely plays an important role for the designs of this research, it alone does not cover the breadth of certain *User Experience* evaluations.

Regarding *Cultural Probes* (Gaver et al. 1999 and Mattelmäki 2006), *Scenarios* and *Personas* (Koskinen et al. 2011), these methods were dismissed as it was neither possible nor the focus of the overall study to send out self-explanatory artifact probes. Also, the very specific *Scenarios* and *Personas* did not conform to the inherent properties of the pursued design, development and evaluation process and its resulting individual *User Experiences.*

Finally, *Design Research Methodology* (Blessing and Chakrabarti 2009) to some degree overlaps with *CDR,* in that it guides the researcher with a procedural framework, rather than being restricted to very specific methods. However, it focuses only on a strictly scientific approach of formulating and validating theories and models (Blessing and Chakrabarti 2009). Although this may lead to easily comparable works, it seems to be applicable only to certain design research projects, while the knowledgeable artistic aspect of the constructive design process and of its artifacts will be rather disregarded.

3.2 THE CONSTRUCTIVE DESIGN RESEARCH APPROACH

Having learned from previous attempts of establishing methodologies for design research, European and North American design researchers around the Finn Ilpo Koskinen heavily extended Frayling's basic idea of "Research through art and design" (1993). In turn, they conceived *Constructive Design Research (CDR)* as a flexible research methodology, applicable for an immense variety of design research projects (Koskinen et al. 2011). *CDR* pivoted from the purely rationalistic models and is inspired by diverse trades like engineering, science, social science, design and art. Corresponding multidisciplinary work has been undertaken at universities like *Carnegie Mellon University,* technical universities in *Delft* and *Eindhoven, Politecnico di Milano* and the former *University of Art and Design Helsinki,* as well as companies like *Microsoft, Nokia, Intel* and *IDEO* (Koskinen et al. 2011).

As previously mentioned in the *Context* section *Constructive Design Research* (see page 17), in contrast to some of the before-mentioned approaches, *CDR* embraces the manifold constructive process of design and acknowledges its knowledge creating nature, as well as the knowledge inherent in the developed artifacts (Koskinen et al. 2011). In fact, its central focus lies on constructing designs in the form of prototypes and/or products and communicating these works may be done in textual form, but also through exhibitions (Koskinen et al. 2011). Regarding this research, it provides a good and suitable balance between adaptability and guidance. Furthermore, *CDR* can be regarded as an encompassing "umbrella" or "meta-methodology" (Markowski 2016), as it is based on so many diverse trades. These also provide the toolset for an individual *CDR* approach (Markowski 2016 and Koskinen et al. 2011), which may partly overlap with some methods from the before-mentioned methodologies.

Still, *CDR* generally proposes a flexible and adjustable iterative cycle roughly outlined as: defining an objective, creating a concept, developing prototypes or products, performing studies and evaluating them (Szymanski and Whalen 2011, de Ruyter and Aarts 2010 and Koskinen et al. 2011).

As previously mentioned in the *Context* section *Constructive Design Research* (see page 17), the *CDR* approach categorizes very different projects in the three loose groupings called *"Lab", "Field"* and *"Showroom"* (Koskinen et al. 2011). These will be further elaborated on in the following.

Although, the *Lab* may be the closest form of evaluating designs in a scientific laboratory-like manner, nevertheless, inspiration for these projects may come from practical knowledge instead of preliminary user studies (Frens 2006a, 2006b and Koskinen et al. 2011). Jerald argues that experiments for creating *VR* applications are mostly "less formal than the extensive research methods performed by researchers more interested in scientific inquiry than creating *[VR]* experiences." (2016). This statement seems to describe a *Lab* approach similar to the one of *CDR.* Hence, I argue that *CDR Lab* experiments are specifically suitable for researching *VR* experiences. Jerald furthermore describes rigorous academic experiments as often being "overkill" for developing experiences, though he also states the usefulness of having an understanding of the basic concepts of formal investigation to design more informal experiments (Jerald 2016). I agree with Jerald, that knowledge on more formal experimental designs is surely helpful, but also that an extremely strict laboratory-like strategy seems inadequate to evaluate *VR* experiences in a more holistic way. Regarding the investigation of *VR* related games in this research, a tenacious focus on e.g. a statistically dogmatic experimental design for user tests likely would have resulted in examining aesthetically underdeveloped prototypes, providing little depth in content, a usage atmosphere unlike one in a real-world application and shallow and probably uninspired gameplay mechanics. On the contrary, it seems especially important to provide content in certain minimum depth, aesthetic and gameplay quality, to be able to properly analyze the mechanics of an experience. Nevertheless, I argue that evaluating selected aspects of *VR* experiences and games can benefit from a still formal experimental design, to gather specific insights, while maintaining relation to the real world in terms of aesthetics, gameplay and depth of content. Hence, three *Lab* experiments were conducted throughout the overall study.

As previously mentioned in the *Context* section *Constructive Design Research* (see page 17), the *Field* makes use of techniques, mostly used in social sciences like *Ethnography.* Co-design and co-creation in the *Field* opens the design process up to other stakeholders and users (Koskinen et al. 2003 and Mattelmäki et al. 2010), which can sometimes blur the line between designers and non-designers (Koskinen et al. 2011). This category of evaluation was not applied in the overall study though.

Leaning heavily on practices in design and art, in the *Showroom* the production of a replicable process is less important, then the articulation of an idea through a working design (Koskinen et al. 2011). Furthermore, this strategy seems to "allow ... designers to approach topics that seem inaccessible to science – topics such as aesthetic pleasure on the one hand, and cultural implications on the other." (Gaver 2001). Jerald sees "demos" critical in creating deeper quantitative insights when not combined with a data-focused approach (2016). He nevertheless states the importance of often giving demos, to stay in contact with the audience, to get "a general feel of others' interest" and "to understand real users, to receive fresh ideas, and to market the project." (Jerald 2016). I agree with Jerald, that *Showroom* demos need to be specifically prepared, if one wants to establish quantitative understanding of certain aspects. However, in my opinion, *Showroom* demos are far more suited to collect great amounts of diverse qualitative feedback from users in a short time frame with relatively little work on preparation, except for getting the experience itself presentable. In turn, several *Showroom* demos of different iterations of the artifacts of this research were conducted during diverse events and occasions.

These *CDR* categories must not be seen as strict containers to place projects into though, but as different toolkits, which can be recombined and used to create individual approaches instead of a strict standardized methodology. Supporting this argument, Markowski for example used a hybrid *Showroom* and *Field* approach in her *PhD* studies on "Designing online social interaction for and with older people" (2016). She applied a combination of the narrative of her design journeys, additional inspirational sources and co-design approaches and named it the *"extended Showroom"* (Markowski 2016).

Finally, *CDR* does not have to, but can lead to research projects as precedents rather than resulting in abstracted theories (Koskinen et al. 2011). Using these precedents or case studies as inspiration or as other forms of knowledge foundations is a common technique in other well respected fields of learning (e.g. humanities, clinical medicine, law etc., Lawson 2004), as it encourages creativity for further developments, which is also the case in design practice (Koskinen et al. 2011).

Referring to the research questions and aims of this research (see from page 7ff.), using *CDR* in particular was the right choice to achieve those aims and answer those research questions.

Due to *CDR's* focus on the constructive aspect of design, it was possible to develop three different sophisticated digital gaming artifacts as precedents for design and research. During the development of these, reflection on their various iterations was an essential part of the research process. Hence, this led to the *Hybrid Journaling Technique using Versioning Repositories* and answering the research question **"In which ways can versioning repositories, used in software developments, contribute to journaling aimed for reflection?".**

The in *CDR* inherent iterative and reflective process was furthermore fundamental in defining and answering the research question **"In which ways may *VR* game interfaces affect *Rollenwahrnehmung, Perspective* and *Space* for the player?"** and its three sub questions.

The multidisciplinary nature of the digital games and their evaluations (i.e. visual design, game design, *UX* design, software development, *Showroom* demos and scientific *Lab* experiments with artifact iterations) was well supported by *CDR's* flexible umbrella approach. In turn, by using a combination of *Showroom* demos and *Lab* experiments, it was possible to develop more advanced artifacts, leading to more relevant results. By constantly iterating on the basis of user feedback, gathered during *Showroom* events, the quality of the digital games and their interfaces improved drastically over time. In turn, the *Lab* experiments were then based on already more elaborate artifacts, being further evaluated in a non-dogmatic and more holistic way, including their context, environment and treating their users as experiential beings. This made answering partly technical but also experiential research questions possible, like e.g. **"In which ways can *3D Stereoscopy* affect *Immersion* for the player of a *Local Multiplayer* game?", "In which ways can *3rd Person VR* games work for a broad audience?"** or **"In which ways can *VR Locomotion* mechanics affect the *User Experience* of a player?".**

3.3 CDR CRITIQUE

This section will discuss some of the critique towards *CDR* (Koskinen et al. 2011) as a methodology.

I agree with Markowski, when she argues that *CDR* has yet to reach full maturity, by further establishing itself among design researchers (2016). Its biggest advantage of being flexible and open leads also to its arguably biggest vulnerability at the same time. Although being a lot more confined than Frayling's "Research through art and design" (1993), it still offers room for different interpretations (Markowski 2016). On the one side, this lets it capture diverse design related research projects, but on the other side, it opens up points for discussion. Originating from design practice, to me though, this is not an actual disadvantage, but an inherent feature of design in general. So, I disagree with Zimmerman et al. (2010) and Basaballe and Halskov (2012) that more "formalization" of design research beyond what *CDR* proposes is needed. Instead, it seems more applicable for design research to take a step back and keep "the research approach on general terms" (Markowski 2016) as corresponding projects may differ substantially in terms of e.g. research context (Bang et al. 2012). Hence, I argue to simply communicate original knowledge coming from design research in a way, which is "defined and executed in a manner that is commonly agreed." (Candy 2006). Or in other words, one needs to supply an artifact or documented process in combination with an exegesis, which includes defining and addressing research questions or problems to enhance knowledge, illustrating a research context and elaborating on the applied research methods (AHRC 2015). Not a stricter set of rules, but the reviewing and publishing of more *CDR* research projects as precedents may provide this methodology with more clearly defined paths for research and contribute to its role as an inspirational guideline in the corresponding community.

I further agree with Markowski in her argument, that "it depends on the design context whether more or less structure in the design process can or shall be applied." (2016). Nevertheless, I disagree with her breakdown between design research on "engineered" products or services, which concentrate "on improved efficiency and effectiveness" and "dialogue-orientated design research", which focuses on "gaining insights, the process and reflections" (Markowski 2016). The former should supposedly be more prone to a "more structured design process", whereas the latter needs more "freedom and exploration" (Markowski 2016). On the basis of the overall study described in this thesis, I would argue, that the creation of effective artifacts, regarding their *UX,* was among its main goals. However, acquiring unforeseeable insights, exploration and reflection strongly contributed to achieving this goal.

Markowski further considers the differentiation between the *Field* and the *Showroom* to be slightly vague (2016). She describes her understanding of the *Field* with "whether a design researcher learns first from the target audience and the context before designing" and the *Showroom* with "whether the design researcher puts something together to express their thinking based on inspirations & insights and then gets people to reflect on it" (2016). I agree that there is a certain overlap between the two toolkits and would extend Markowski's description by also highlighting the more obvious differentiation based on the actual scenarios in which a product or service is tested or consumed by an audience. In my opinion, the *Field* also suggests a more independent and unguided real-world interaction of an audience with the product or service. Whereas a

Showroom demo also implies at least some form of introductory presentation of the product or service to the audience and any interactions are related to the context of the event, which likely does not represent a real-world scenario.

Overall though, in my opinion for the reasons I have described here, the downsides of *CDR* are clearly outweighed by its upsides. Hence, it was selected for this research, due to its balance between flexibility and guidance, which fitted the prospected research process during an early phase of the overall study. As a methodology, *CDR* furthermore allowed the integration of additional, originally not listed, research methods and methodologies without causing conflict regarding the overall epistemological approach.

3.4 INDIVIDUAL CONFIGURATION OF CDR

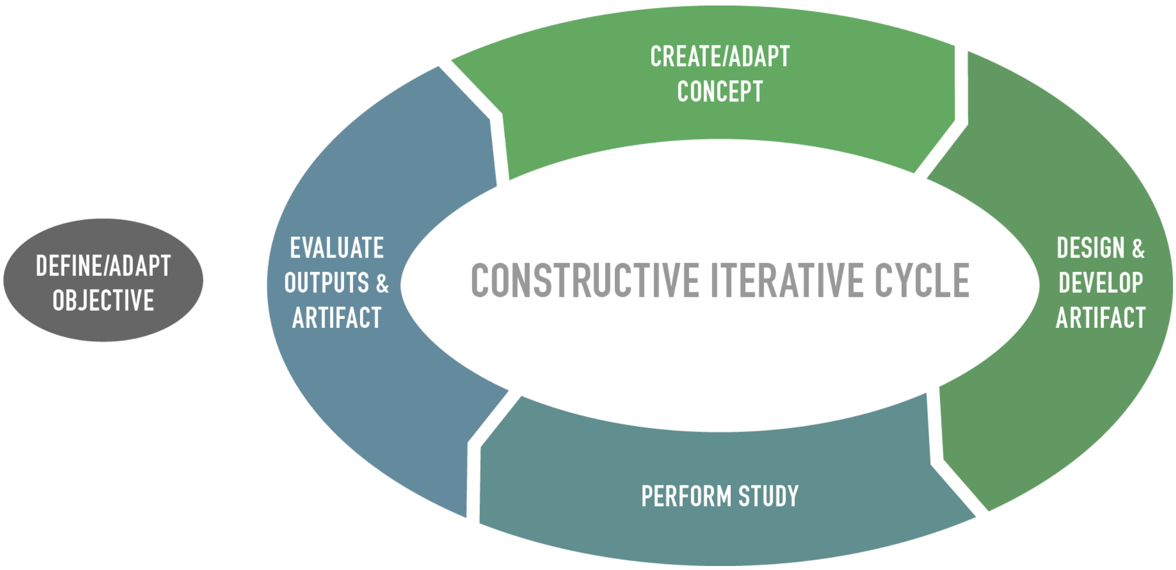


Figure 26: Constructive Iterative Cycle of this research

The following will elaborate on how *CDR* was applied as an overarching methodology and explain its individual configuration for this research.

The previously mentioned iterative cycle proposed by *CDR* (see section *The Constructive Design Research Approach* from page 59ff.) was slightly adjusted to the needs and the flow of the overall study (see Figure 26). Due to its focus on creating artifacts, defining a clear research objective strictly speaking was not part of the cycle. The research objective of an artifact in most cases only arose over time. I.e. the design, development and evaluation of early prototypes would uncover e.g. interface issues or other peculiarities, which in turn could be selected for more thorough investigations.

Other than that, the *Constructive Iterative Cycle* was applied pretty much in its straightforward way: A concept or idea would be developed (or adapted, if it was not the first iteration of the cycle) and based on that concept/idea an artifact would be designed and developed. Subsequently, one or more studies would be performed to test this prototype iteration with users, either via *Showroom* demos or *Lab* experiments. Finally, the diverse outputs of the different test sessions and the artifact itself would be evaluated. After that, the cycle could start again, by adapting or extending the previous concept.

Minor elements of the *Field* (e.g. free text user feedback on artifacts) can be found in the overall study. Nevertheless, artifact evaluation via user testing sessions in the form of more informal *Showroom* demos and rather controlled *Lab* experiments in combination with a reflective design and development process form the core of the selected *CDR* toolkit for this research.

The sometimes local, sometimes international *Showroom* demo events included gaming parties, game and technology meetups, game and technology jams, game pitches, game festivals, science fares and academic conferences. This diverse collection of events provided a huge amount of qualitative feedback from potential consumers, professional specialists and academics of various ages, genders and nationalities. The mostly verbal and informal feedback covered the areas of design, development, *UX* and *HCI* and was complemented with my personal observations of play test sessions. Although this kind of evaluation method might not conform to scientific standards, it still led to invaluable knowledge and ideas in the fields above. Other advantages of these events are their relatively little preparation effort and the access to great numbers of diverse participants in a short amount of time.

For more details on the different *Showroom* demos see the corresponding sections for *Nicely Dicely* from page 85ff., for *LizzE* from page 111ff. and for *Gooze* from page 145ff.

The *Lab* experiments on the other hand, required much effort in preparation and logistics, but led to very specific, retraceable and detailed qualitative and quantitative insights. Although the three artifacts of the overall study varied a lot regarding content and technology, a general methodological pattern can be identified for the three corresponding experiments (one per artifact). All experiments started with a verbal and textual disclaimer, which described the academic background of the study, the rough outline of the procedure, the types of data which would be collected, the ethical and confidential usage of any raw collected data, the possibilities for publishing strictly anonymized data, where information on actual publications could be accessed, the health and safety issues, the option to stop the examination at any time, the minimum age and health requirements, the possibility to withdraw from the study and the contact information for any enquires. Via pre-test questionnaire, each participant specifically gave consent to the terms of usage of his or her data and accepted the health and safety issues. Additionally, relevant personal information was gathered on e.g. age, gender, subjective experience with digital games and *VR* (or *Stereoscopic 3D* respectively) and how often the participant played digital games. Then, the specific study procedure and the participants tasks would be explained in more detail and the play test session would begin. Each session would typically go through several time limited modes (conditions like *Non-3D Monoscopic* and *3D Stereoscopic),* which would be compared by different measures, either in complete at the end of the session or in part after each mode. The collected data included pre and post-test participant questionnaires (mostly Likert-scale and free text field questions), automatically tracked in-game parameters and video recordings of the sessions for documentation and to retrace any peculiarities during later analysis. All post-test questionnaires asked the participant to give a rating for *Simulator Sickness,* decide on a generally preferred mode/sub mechanic and freely describe how a mode/sub mechanic affected gameplay and what other thoughts or feelings it may have triggered. The experiments with *LizzE* and *Gooze* both also asked for ratings on *Player Enjoyment* and *Support of Gameplay,* either per mode or per sub mechanic. Additionally, the experiments with *Nicely Dicely* and *Gooze* also included either partial or complete *IPQs.*

For more details on the methodological specifics of the three different *Lab* experiments see the sections *Lab Experiment: Local Multiplayer Immersion Affected by 3D Stereoscopy* (from page 91ff.), *Lab Experiment: Virtual Reality 3rd Person Camera Behavior Modes* (from page 119ff.) and *Lab Experiment: UX Evaluation of VR Locomotion & Virtual Object Interaction Mechanics* (from page 150ff.).

The participants of *Showroom* demos and *Lab* experiments did not receive any compensation whatsoever and the participants of the *Lab* experiments confirmed, that they were all at least 16 years old, not pregnant and did not have epilepsy. Although the latter experimental requirements could not always be met or confirmed during the informal *Showroom* demos, the specific focus of an event (e.g. a gaming festival vs. an academic conference) would of course also set the context in which the games were played. Although none of the artifacts displays e.g. extreme violence or sexuality, it needs to be noted, that one could assume from the context of the event that some sort of guardian is close by for children below the age of 16.

3.5 REFLECTION BASED ON HYBRID JOURNALING TECHNIQUE

Another important aspect of *CDR* is the evaluation of an artifact or process based on the reflection of the researcher. Though, in the case of *PhD* research, the overall study likely spreads over several years. So, to actually reflect thoroughly on a topic which takes that long, memories alone seem prone to fade and are likely insufficient to provide a rich base for reflection. Hence, it is common practice to maintain some kind of research journal.

During my research, aside from noting more overarching and general aspects of the overall study in a manual journal, I also realized the value of the structured content of my "commit" messages, which I regularly entered in a *git* (git 2019) versioning repository during the software development phases. To track changes in code and other files and to make them reversible, it is common practice in software development to use versioning repositories. This process encourages the developer to regularly verbalize the changes, which have been made and any issues or ideas surrounding them. Furthermore, all commits can be clearly retraced down to a single character change in code and are automatically timestamped. Hence, to achieve a richer base for later reflection, I extended my commit messages with streams of thought concerning research, design and development, which were accessible through a central interface and did not interfere with the actual code files.

This *Hybrid Journaling Technique*, using a more general manual journal in combination with the structured and extended commit messages was a great help during the reflections phase. It simplified the retracing and understanding of problems, design and development decisions and corresponding timeframes. Finally, this technique enriched the base for reflection with more details, due to its regular usage deeply integrated in the development workflow. Although this depends on the researcher's preferences, my base for reflection certainly would have been shallower without the extended commit messages.

3.6 METHODOLOGY SUMMARY

The previous sections elaborated on *CDR* as a methodology for this research and outlined what it is comprised of. Some of the advantages and disadvantages of research supported by design practice were discussed, as well as a critique on *CDR* specifically. Additionally, its three toolkits *Lab*, *Field* and *Showroom* and their flexible application were illustrated. In turn, the overall study's individual configuration of *CDR* was specified, which heavily leans on a combination of the *Constructive Iterative Cycle*, *Showroom* demos, *Lab* experiments and reflective artifact evaluations. In addition, the general procedure of the three *Lab* experiments was outlined. Finally, the applied *Hybrid Journaling Technique* using extended commit messages in versioning repositories was elaborated on.

4 CRITICAL REFLECTION: ARTIFACTS & STUDIES

This research aimed to explore *VR* and gaming by creating individual and exemplary artifacts, which led to different types of contributions to the overlapping areas of: *HCI,* design research, *VR* research, games research, interaction design, game design and game development.

Nevertheless, only after evaluating the first artifact iterations and while being guided by technological developments and an enthusiasm to investigate and develop diverse designs, it became clear in which directions these center-staged artifacts would develop. A collection of transferrable specific insights related to digital games and *VR,* grounded in the design and development of these artifacts is the result.

Hence, the following chapter will elaborate and critically reflect on the three different artifacts of the overall study within three corresponding subchapters: *Nicely Dicely* (see from page 71ff.) – a *Stereoscopic 3D Local Multiplayer* game based on physics, *LizzE – And the Light of Dreams* (see from page 104ff.) – a vrified *3rd Person 3D Hack and Slay* game and *Gooze* (see from page 130ff.) – a *1st Person VR* puzzle horror game. They were not developed in this order. Instead the design and development of iterations switched back and forth between the artifacts and sometimes overlapped to some degree, as some gained insights were affecting multiple games in parallel. The timeline in Figure 27 gives a chronological overview of relevant events and the different development phases, which resulted in several versions or iterations of the artifacts.

As part of *CDR's Constructive Iterative Cycle* (see Figure 26 on page 64), each artifact's section will illustrate several logically separated artifact iterations. However, it needs to be mentioned that these iterations were not always developed linearly until an "end" was reached. Instead, sometimes smaller optimizations and adjustments of design and implementation have been made between studies. Further conforming to the *CDR* approach, each artifact section will elaborate on related *Showroom* demos and one individual *Lab* experiment (see from page 59ff.). Each *Lab* experiment subsection will explain its individual experiment methodology, as well as its results and will finish with an individual experiment conclusion. Finally, again following the *CDR* methodology, a reflective discourse to each artifact will be illustrated, as well as its individual contribution to the overall study.

Although various support material was already moved to the *Appendices* (see from page 197ff.), the condensed content of this chapter still spans over a considerable length for several reasons: The involved practical work of this research was substantial and the amount of conducted studies were numerous. The created artifacts themselves are very different from each other in terms of genre, gameplay, social game type, content, design, technology stack and interaction methods. Thus, they do not represent iterations of the same application, but instead dedicated artifacts. Hence, they furthermore required individual testing strategies and tools, which only to a certain degree overlapped between the games. Finally, due to its length and complexity, the chapter also needed additional guidance and wayfinding for the reader.

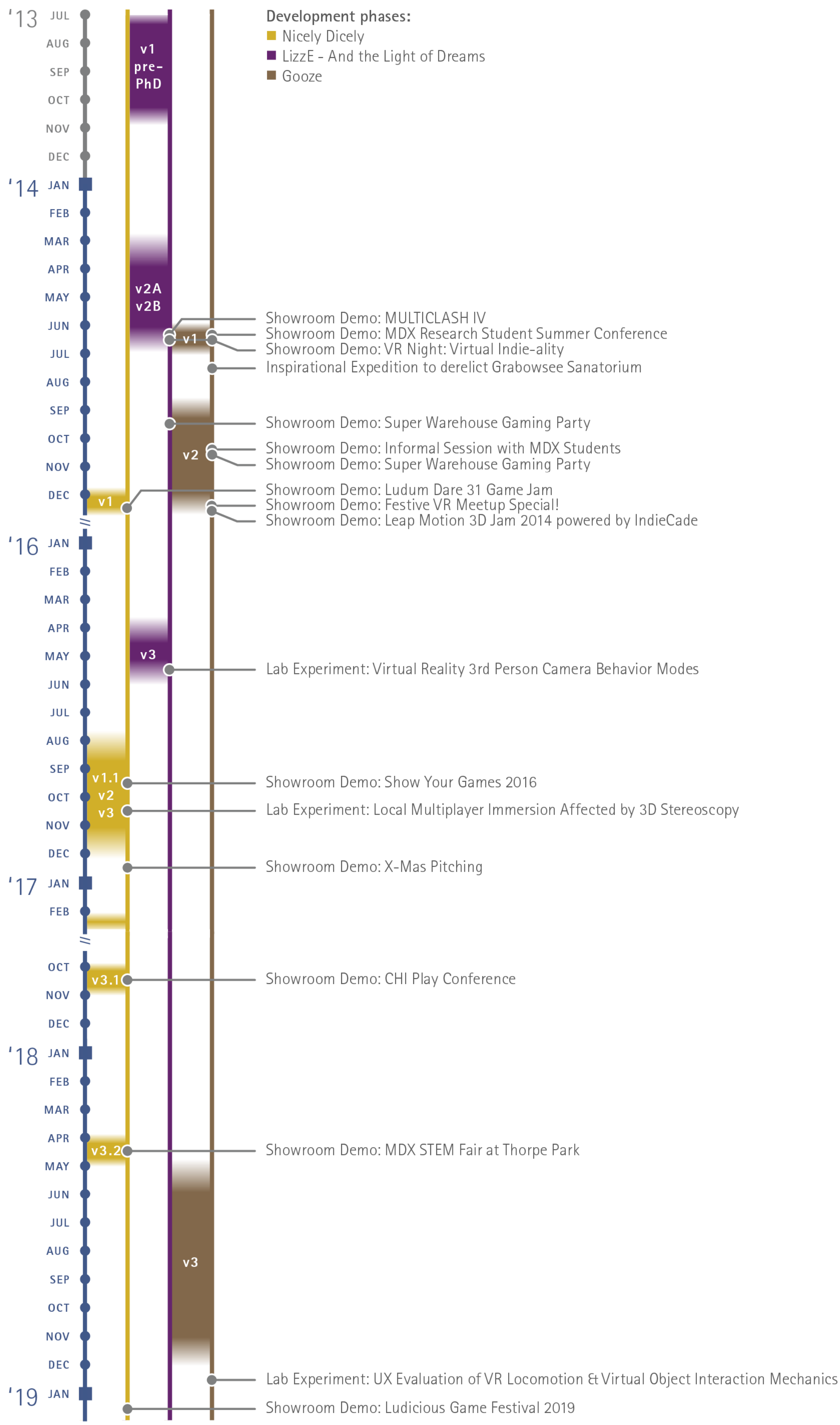


Figure 27: Research timeline showing development phases of artifact iterations and events

4.1 NICELY DICELY

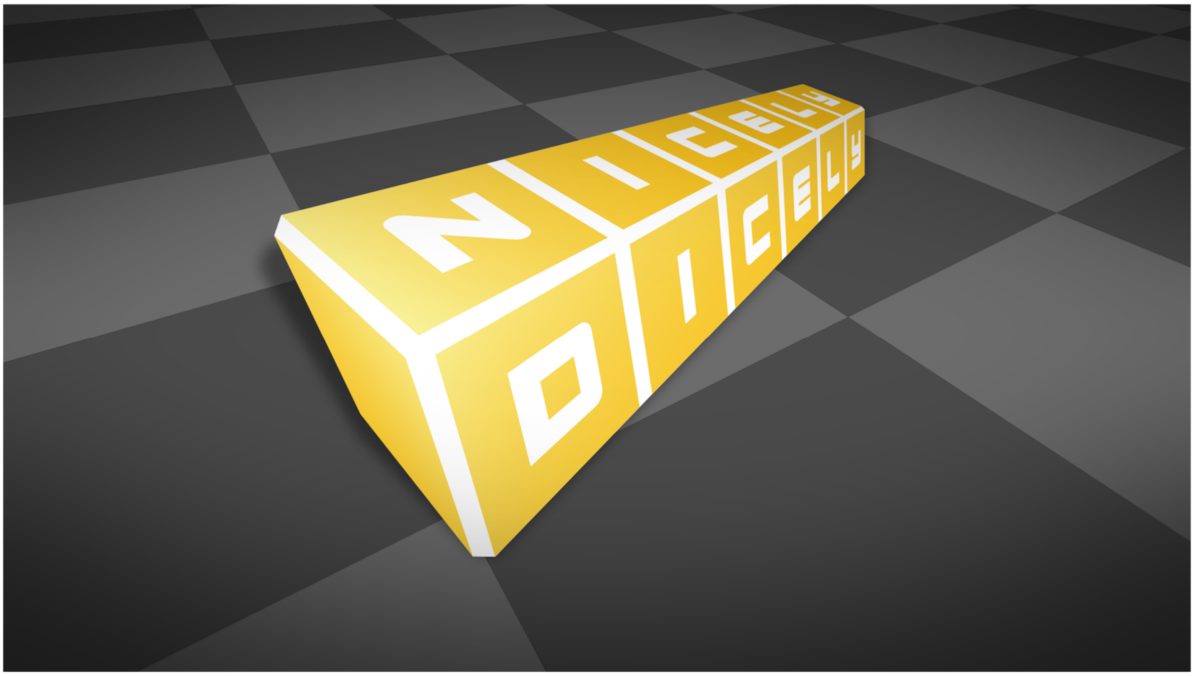


Figure 28: Nicely Dicely key visual

For a video presenting the game see *Appendix F.1.1* on page 263.

The following subchapter will outline the concept and the attributes of the artifact *Nicely Dicely.* Relating to *CDR's Constructive Iterative Cycle,* it will further elaborate on various iterations, which the game went through over its development time. Subsequently, corresponding studies will be illustrated, i.e. *CDR* conform *Showroom* demos and a *Lab* experiment. The latter section will elaborate on the experiment's modes, methodology, results and conclusion, regarding how *Local Multiplayer Immersion* is affected by *3D Stereoscopy.* Finally, as part of the *CDR* approach, a reflective discourse on the artifact will be held and its contribution to the overall study will be summarized.

4.1.1 THE GAME

> *Nicely Dicely* [see Figure 28] is a fun *3D Local Multiplayer* game based on physics, for up to four simultaneous players. The whole game takes place on one screen.
> (Wiedemann et al. 2017c)

Players can decide, if they want to compete against all other players or in teams of up to two players.

> Each player controls the movement and certain actions of one special player cube [see numbered cubes in Figure 31] on a floating and dynamically changing playing board. Additionally to the player cubes, there are also passive score cubes (golden at the beginning), explosive mines and from time to time a *"Mystery*

> *Crystal"* [see Figure 31].
>
> The goal is to score as many points as possible during a match and the player with the highest score at the end wins. Each match consists of a minimum of three rounds of new score cubes and mines. A new round gets triggered once all score cubes have been removed from the board.
>
> There are several ways of affecting one's score count. By touching a score cube, it gets tinted with the color of the player touching it [see un-numbered blue cubes in Figure 31]. If this score cube gets pushed off the board or otherwise falls off it, the player [or team] with that color scores a point. If a player cube for some reason falls off the board itself, one score point gets subtracted.
> (Wiedemann et al. 2017c)

To provide a more direct way to compete between players and enforce interactions between them, it is also possible to paralyze another player and in turn steal one of his or her points.

> Technically, because of its reduced visual design, *Nicely Dicely* is rather performance efficient. The game can be played on *macOS* with up to four common game controllers, but is optimized for the use with *Xbox* controllers, including their rumble functionality. Furthermore, *Nicely Dicely* can either be played in *Monoscopic* or *Stereoscopic 3D Mode (Side-by-Side 3D),* if a compatible *3D TV* or *3D Projector* is used [see Figure 13].
> (Wiedemann et al. 2017c)

> Optimized for *3D,* the game takes place on one screen, omitting any drastic depth animations, and is visually positioned 'behind the screen', to reduce any eye strain.
> (Wiedemann et al. 2017c)

All used audio assets for background music and effects are license free.

The game was chosen as an artifact for the overall study, because with v1 a prototype was already available and "internal testing showed, that the game's fundamental gameplay principle seemed to provide great fun among players, especially due to its *Local Multiplayer* concept." (Wiedemann et al. 2017c). Furthermore, because of its one screen design meant for *Multiplayer* gaming, it seemed a suitable candidate for testing the effects of *3D Stereoscopic Vision* on *Immersion* in a *Local Multiplayer* situation (see from page 91ff.).

4.1.2 ITERATIONS

As part of the *CDR* approach, the following will elaborate on the different iterations of *Nicely Dicely,* to provide an overview on the progress the game has made over various design and development phases and to illustrate its corresponding features.

4.1.2.1 Nicely Dicely v1

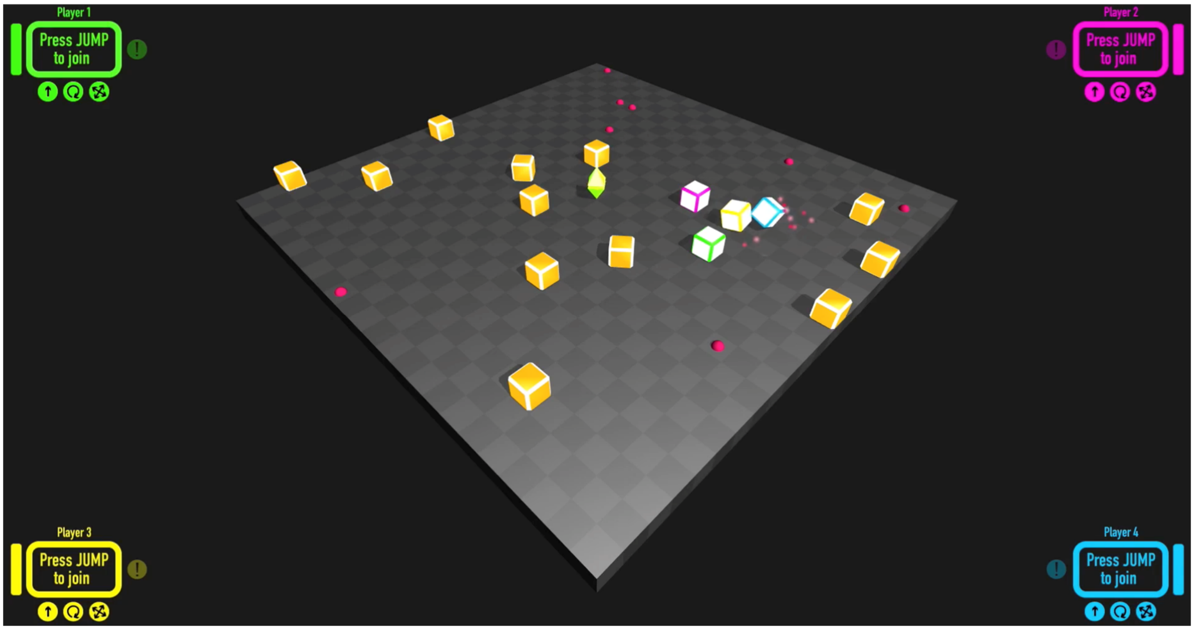


Figure 29: Nicely Dicely v1

The very first version of *Nicely Dicely* (see Figure 29) was conceived and developed during the two-day *Ludum Dare 31 Game Jam* (see from page 86ff.).

The game's board consisted of 24 x 24 separately addressable cubes and was procedurally generated for easy manipulation. Three special scenarios were implemented additional to its neutral condition. *Nicely Dicely* v1 actually used a slightly different wording for these board states (i.e. *Mysteries),* which was adjusted during later iterations to accelerate the understanding in players. The following will use the improved wording.

In *"Inverted Controls"* (see Figure 48), the whole board was turned by 180 degrees on the y-axis and thus players had to use inverted controls, as suddenly up was down and left was right. In *"Board Displacement"* (see Figure 49), a random selection of cubes was temporarily moved upwards, thus creating a sort of maze, which could block players from each other and from targeted score cubes. In *"Board Deletion"* (see Figure 50), a random selection of cubes was temporarily scaled down to zero, so the board would be filled with holes, into which players and score cubes could fall. The mechanic of the *Mystery Crystal* to actually trigger these features in-game in random order could unfortunately not be implemented in time for v1.

A number of score cubes and mines were randomly placed on the board with each start of the application. When a mine (see pink spheres in Figure 29) was touched by either a score or a player cube, a light explosion would spread the surrounding cubes, also possibly over the board.

First attempts in implementing multiple player actions (additional to controlling movement) were made. However, jumping was the only one, which was properly integrated (see Figure 40).

A crude counter for the scores was implemented, but a player-respawn, when falling off the board was not. So, the demo ended once a player fell off.

Additionally, it was experimented with a very crude *AI* controlled version of the score cubes, so *Singleplayer* gaming would be possible. The general idea of a *Singleplayer* mode was never discarded, but due to its complexity, the functionality got never developed to a point were actual gameplay would arise.

The *HUD GUI* elements could not be made functional in v1.

Finally, though an intermediate version of the demo made multiple controllers and thus multiple players possible, this functionality unfortunately broke during further development and was not recovered for v1. Hence, the decision was made to not send out v1 as a submission for the game jam.

4.1.2.2 Nicely Dicely v1.1

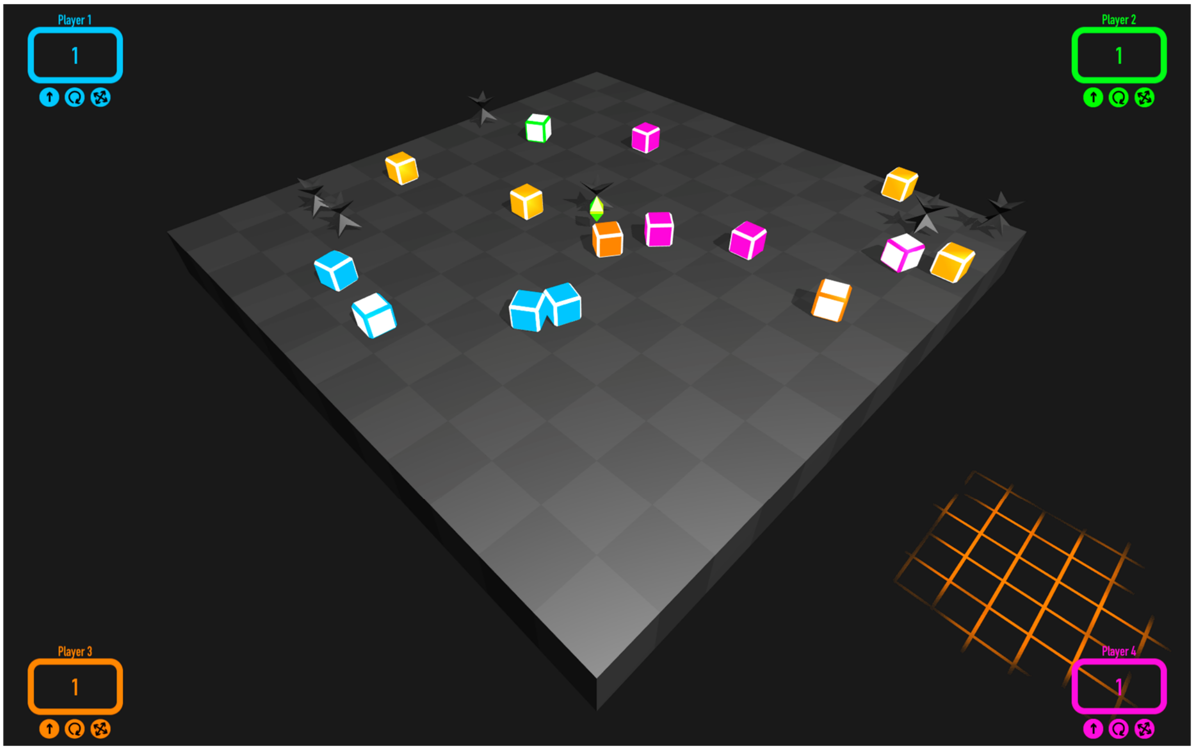


Figure 30: Nicely Dicely v1.1

Regarding this research, *Nicely Dicely* was chosen for further development as an artifact, because with v1 an early prototype was already available, the inherent basic gameplay principle seemed appealing and its *Local Multiplayer* aspect promised a diversification of the portfolio of games. Due to its rather simple one screen design, it further seemed an interesting candidate for testing the effects of *3D Stereoscopic Vision* on *Immersion* in a *Local Multiplayer* situation, as *3D Stereoscopy* and *Immersion* are important aspects of *VR.*

Nicely Dicely v1.1 (see Figure 30) was an intermediate alpha version of the game. Though not all needed game elements for a proper run-through were implemented, it was presented at the *Show Your Games 2016 Showroom* event (see page 87), to gather further insights on game mechanics and design.

In v1.1 the board was reduced to include only 12 x 12 separate but bigger level cubes. Like this, score or player cubes could not get stuck in small crevices anymore (during *Board Deletion)* and *Board Displacement* would actually result in a maze with obstacles of increased size.

The *"Mystery Crystal"*, which spawned after a certain amount of time in the center of the board, was introduced for the board states and further temporary *"Mysteries"* later on. By touching the crystal these *Mysteries* would be triggered in random order.

The mines were completely redesigned and animated to better visually express their function and fit the rest of the game's design (see grey spikey objects in Figure 30).

The *HUD GUI* elements in each corner of the screen, linked to each player, were redesigned and made functional. Each one would correctly count the actual score. The lower circle icons would inform on the state of action cooldown times in a radially animated way, when player actions were triggered.

The performable player actions were: *Jump, Burst* and *Dash*, though this improved wording was introduced in a later version, to increase understanding in players. *Burst* (formerly *Bounce)* would perform a light explosion originating from the player's position, which would give surrounding cubes an outwards push. The *Dash* (formerly *Spin)* action would quickly roll the player cube in the direction currently aiming. Each action would be accompanied by an appropriate visual effect (see Figure 40, Figure 41 and Figure 42).

To create a more visually dynamic game, a parameterized *Screen Shake* effect was added. Performing a *Burst* would trigger a shorter and subtler shake, whereas the explosion of a mine would trigger a stronger effect etc. For more details see *Appendix C.1.1 Screen Shake* from 243ff.

These visual effects and even mere cube collisions were enhanced by adding correspondingly configured controller vibrations for compatible gamepads. This should make the most of the interface hardware and most importantly add an immersive haptic element to the game.

Finally, to better illustrate which player actually scored a point, corresponding score cubes got tinted in the color of the last player affecting them (e.g. by touch or by triggering a mine). Additionally, a respectively colored visual grid effect was introduced (see orange grid in Figure 30), to visualize when a score was made and by which player. This further visually enhanced the understanding of the space around the board and also defined the depth in which score and player cubes would be erased.

4.1.2.3 Nicely Dicely v2 (Experiment Version)

Figure 31: Nicely Dicely v2

Nicely Dicely v2 (see Figure 31) was specifically prepared for the *Lab* experiment on *3D Stereoscopy* affecting *Immersion* (see page 91ff.).

A game start up sequence for logos and the control scheme was added, as well as a menu, to start, restart and configure "Single vs" and "Team vs" game matches with varying numbers of connected gamepads and players (see Figure 32, Figure 33 and Figure 34).

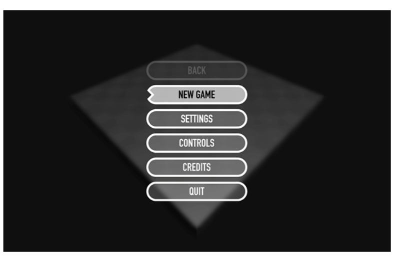


Figure 32: Nicely Dicely main menu

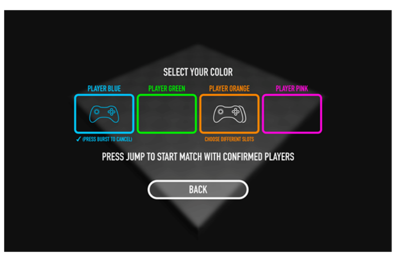


Figure 33: Nicely Dicely Single vs mode player selection menu

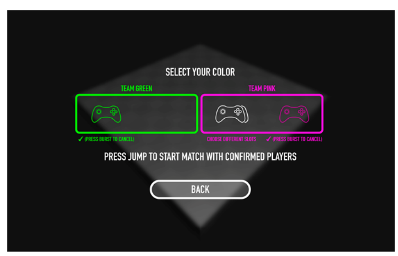


Figure 34: Nicely Dicely Team vs mode player selection menu

Multiple previously discovered technical and design related issues were mitigated or solved in v2.

E.g. a system of two light sources was implemented. One light is intended to preserve the angled shading of the game and its objects but does not influence drop shadows. The second one is positioned directly above the center of the board and influences almost only the shadows. This massively enhanced correctly orienting player cubes flying over the board, by casting object shadows directly below them (see drop shadow under green player cube in Figure 31).

To better settle the floating game board in its reference space, a subtle but constantly visible grey grid was added visualizing the "floor" (see Figure 31), where scores would be made and player cubes would die.

The perspective of the camera was slightly optimized, to reduce the possibility of player cubes being able to leave the viewport and to simplify playing in the far back compared to playing in the front. Nevertheless, as player cubes were in some situations still able to leave the viewport, respective *GUI* indicators were only later implemented in v3 (see Figure 46).

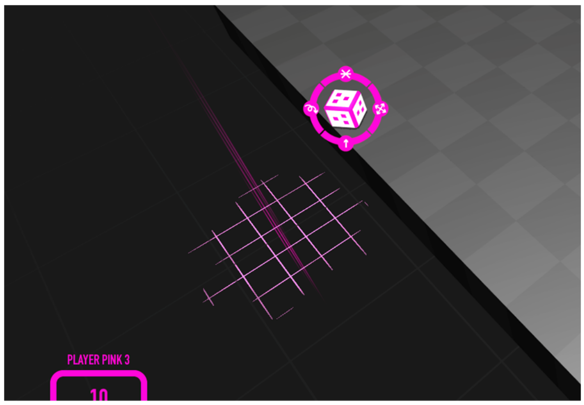


Figure 35: Nicely Dicely score effect with additional uprising particle effect (screenshot of v3)

Furthermore, to improve the understanding of when a score happens, the colored grid effect was visually expanded by an equally colored uprising particle effect to better highlight the positively counting up of score points (see Figure 35).

To accelerate the comprehension of several aspects of the game, including fast happening *Mysteries* and the general goal to push score cubes over board, a sophisticated headline element was developed (e.g. see Figure 48). For more details see *Appendix C.1.2 Animated Headline* from 244ff.

The initially planned permanent death of a player, triggered when falling too deep from the board, was replaced with an automatic respawn of the player after a certain time penalty. This reduced the entry barrier for new players and further promoted the party game usage of *Nicely Dicely*, providing quick matches amongst friends.

The whole color scheme of the game was adjusted in an attempt to better differentiate the four player colors and to provide a better experience for players with color differentiation disorders. Only more user testing led to the conclusion that an option to choose from multiple different "color-blind" friendly color schemes would be required to mitigate the various color-blindnesses. As the issue was beyond the scope of this research and due to time constraints, a corresponding implementation was omitted.

Nevertheless, additionally to the different colors, to better differentiate player cubes, each player cube's 3D model received one to four notches on all six sides, showing the player's ID (see Figure 31 and Figure 35 for a close up).

Figure 36: Nicely Dicely v2 Stereoscopic 3D simulation

Figure 37: Nicely Dicely v2 Stereoscopic 3D cooldown GUIs

The first experiences with *Stereoscopic 3D* were made by using a third-party *Side-by-Side 3D (SBS3D)* plugin during the development of *LizzE* v2A (see from page 108ff.). Unfortunately, using the same plugin was not possible for *Nicely Dicely,* as its support had ended, and it did not provide all targeted features for this project (e.g. conveniently handling overlaying *GUI* elements). Hence, a custom *SBS3D* solution was implemented (see Figure 36 and Figure 37), providing options for defining the zero-parallax distance from the camera (the focal point), the *IPD* and a parallax multiplier. It further supports automatically handling *UI Canvas* objects and offers a *3D Simulation Mode* to accelerate adjusting *3D* parameters without the need of an actual *Stereoscopic 3D* setup. For more details see *Appendix C.1.3 3D Stereoscopy System* from page 245ff.

The unintended but critical issue with a 45-degree angled movement control has been fixed. So, when the gamepad analogue stick gets pulled down, the player cube correctly follows that route on the screen as well.

To enhance the visibility of player action cooldowns, circular *GUI* elements were added around the player cubes (see Figure 31 and Figure 37 for a close up). In v2 each ring around a player cube would consist of three arches, which also showed the corresponding player action icons. Once an action is triggered the arch would shrink and over time "load" up again. Once fully loaded, the action would be available to the player again.

The *Dash* action was reworked, in that the player cube would push along the movement direction but would spin opposing to that. This behavior improved the usability of the action by far and made it a viable option during gameplay, to quickly kick score cubes overboard, instead of over rolling them.

Finally, the whole application was redesigned for the use in an experiment. Hence, unneeded menus and functionality were hidden or disabled, and a clear and comprehensible procedure was added, guiding the participants through the whole experiment.

4.1.2.4 Nicely Dicely v3

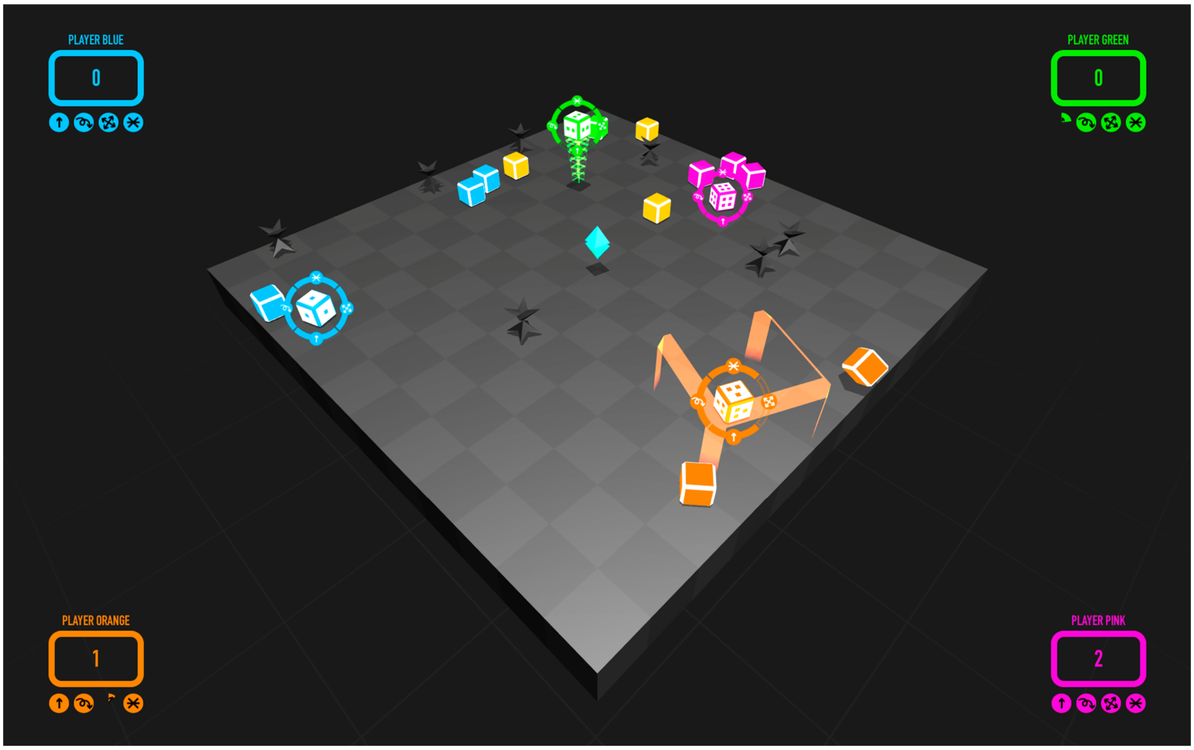


Figure 38: Nicely Dicely v3

Based on the gained insights of the previous studies, *Nicely Dicely* v3 (see Figure 38) was developed, including several new features and optimizations.

In general, the controls were tightened and the "floatiness" of the cubes was decreased by adjusting various physics parameters. Values for gravity, general movement and jumping were optimized for a more settled feeling during gameplay, though only to some degree to retain the original feeling of the game.

In the same process, further parameters concerning all player actions, their cooldown times and related amounts of physical forces were calibrated for a more balanced experience.

For instantiating objects, like score and player cubes, as well as mines and the *Mystery Crystal*, subtle animations were implemented, to create a generally more sophisticated and pleasing visual appearance of the game.

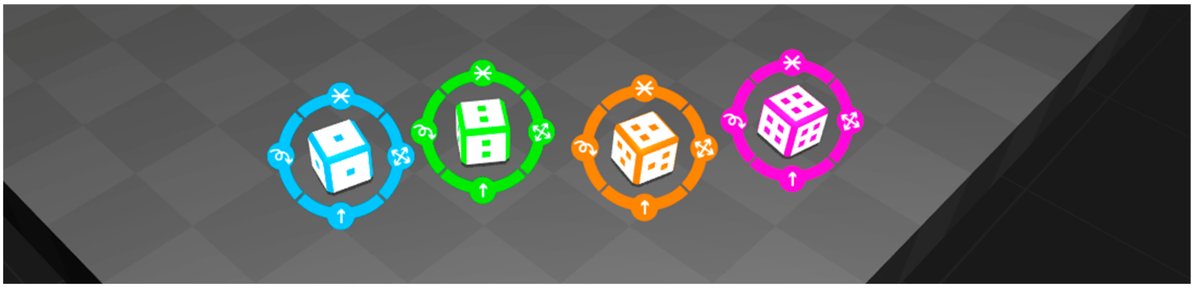


Figure 39: Nicely Dicely v3 player cubes and surrounding cooldown GUIs

All cube colors have been adjusted again, including the main player colors, for a better differentiability (see Figure 39). Nevertheless, a solution similar to the *Witcher 3's* color-blind friendly option (Makuch 2015) was not implemented for reasons already explained.

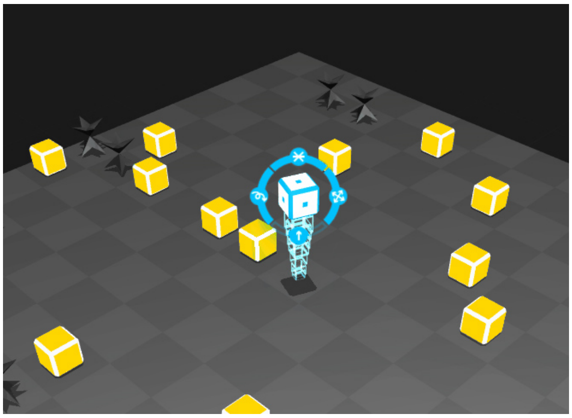


Figure 40: Nicely Dicely player Jump

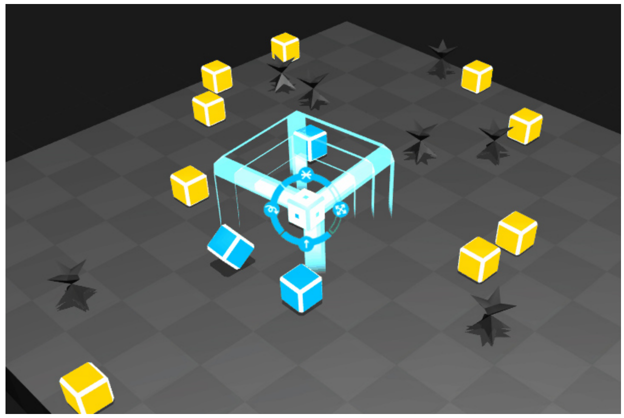


Figure 41: Nicely Dicely player Burst

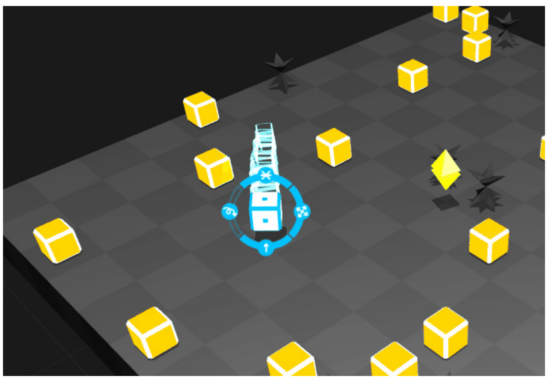


Figure 42: Nicely Dicely player Dash

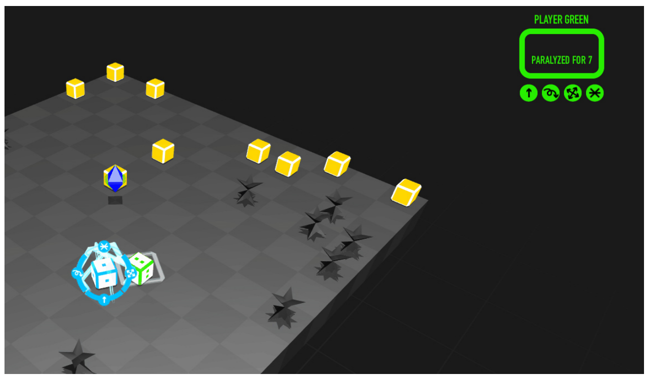


Figure 43: Nicely Dicely blue player paralyzes green player and steals one point

In v3 there are four different player actions: *Jump*, to fly over obstacles or return to the board when falling off (see Figure 40), *Burst*, to spread flocks of cubes possibly off the board (see Figure 41), *Dash*, to perform a forceful push in a directed manner (see Figure 42) and *Paralyze & Steal*, to directly apply a time and score punishment to other players in reach (see Figure 43). The latter wording including the term *Steal* was introduced in a later version.

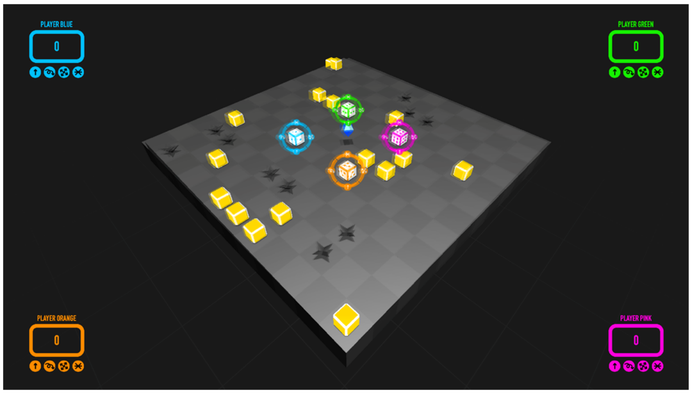


Figure 44: Nicely Dicely v3 Stereoscopic 3D simulation

Figure 45: Nicely Dicely v3 Stereoscopic 3D cooldown GUIs

Figure 39 also shows the completely rebuilt cooldown *HUD* around the player cubes. The thicker circle now consists of four arches (one was added for the *Paralyze & Steal* action), positioned like the four action buttons on a gamepad. Instead of the previous *UI Canvases*, textured 3D planes and a special overlay shader are used. Like this, the *HUDs* are technically handled as regular 3D objects and thus can be spatialized at the depth of the player cubes. In turn, this is far more pleasant for the eyes, when playing in *3D Stereoscopic Mode*, as users can focus on one distance (compare Figure 36 and Figure 37 with Figure 44 and Figure 45).

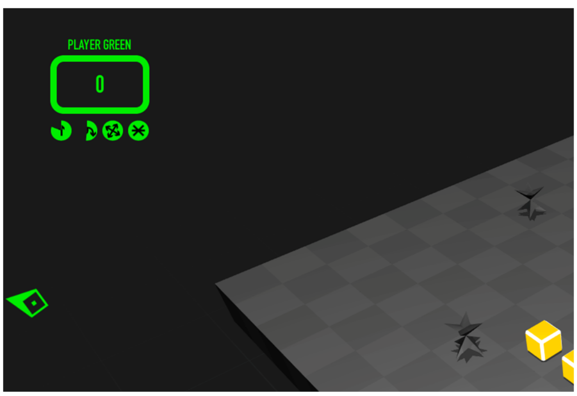


Figure 46: Nicely Dicely GUI player cube indicator, when out of viewport (see green arrow at the left screen edge)

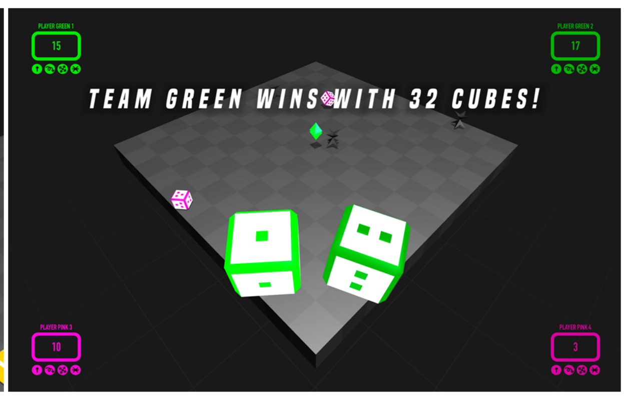


Figure 47: Nicely Dicely team match winners screen

In case player cubes leave the viewport, corresponding player indicators were implemented in v3 (see Figure 46). Respectively colored and using the right number of dots, these indicators are designed as arrows, pointing in and following the direction of corresponding player cubes, once they are not on screen.

For when a match is won by a player or team, a special screen was introduced, highlighting the winning cube/s and presenting the winning score (see Figure 47).

Figure 48: Nicely Dicely Mystery: Inverted Controls

Figure 49: Nicely Dicely Mystery: Board Displacement

Figure 50: Nicely Dicely Mystery: Board Deletion

Figure 51: Nicely Dicely Mystery: Shrinkage

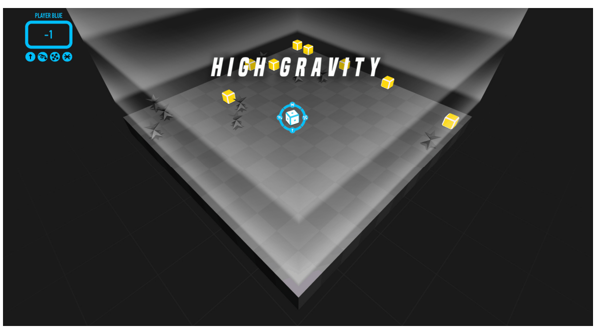


Figure 52: Nicely Dicely Mystery: High Gravity

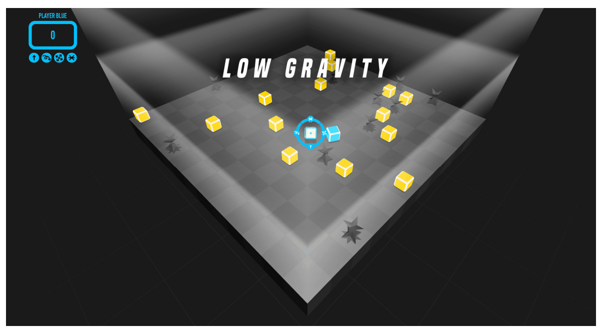


Figure 53: Nicely Dicely Mystery: Low Gravity

In v3 the *Mysteries* included six different temporary conditions. To the already mentioned *Inverted Controls* (see Figure 48), *Board Displacement* (see Figure 49) and *Board Deletion* (see Figure 50) three further *Mysteries* were added. In *"Shrinkage"* player cubes get shrunken in size and strength (see Figure 51). *"High Gravity"* and *"Low Gravity"* adjust the corresponding physics parameter, resulting in very differently feeling controls (see Figure 52 and Figure 53).

4.1.2.5 Nicely Dicely v3.1

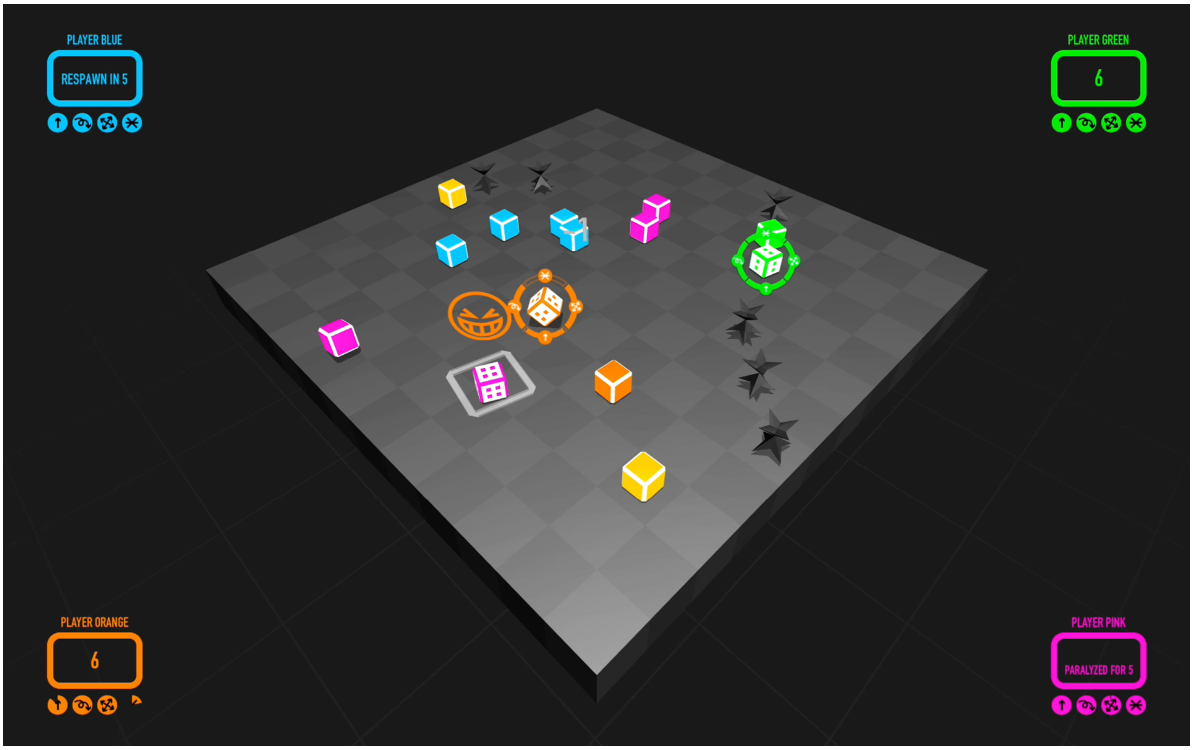


Figure 54: Nicely Dicely v3.1

In *Nicely Dicely* v3.1 experiment features were completely removed and several smaller adjustments in gameplay and effects were implemented.

To enforce more direct player vs. player action and lessen the gameplay during which players would interact more with score cubes than other players, the *Paralyze & Steal* action was strengthened visually and in terms of its parameters. An evil smiley effect was added, hovering over the paralyzed (see Figure 54), to increase the emotional charging of these “Gotcha!” and “Damn!” moments. Due to the smiley being colored as the paralyzing player, the paralyzed one is constantly reminded who to possibly take revenge on. Additionally, the reach of the action was increased and the cooldown time was slightly decreased, so it would be easier to paralyze other players.

Further highlighting the collecting and losing of score points, quickly animated “+1” and “-1” effects were added for when a player scored, died or paralyzed another player and stole a score point.

Finally, the *Roundhouse Push Mystery* was introduced to add a strictly beneficial option for the activating player to the randomly chosen *Mysteries* and thus motivate players to trigger the crystal. If the *Roundhouse Push* gets activated, several “ghost duplicates” of the triggering player cube automatically push outwards from the center in a star-shaped manner and thus possibly take multiple score cubes off the board (see Figure 55).

Figure 55: Nicely Dicely Mystery: Roundhouse Push

4.1.2.6 Nicely Dicely v3.2

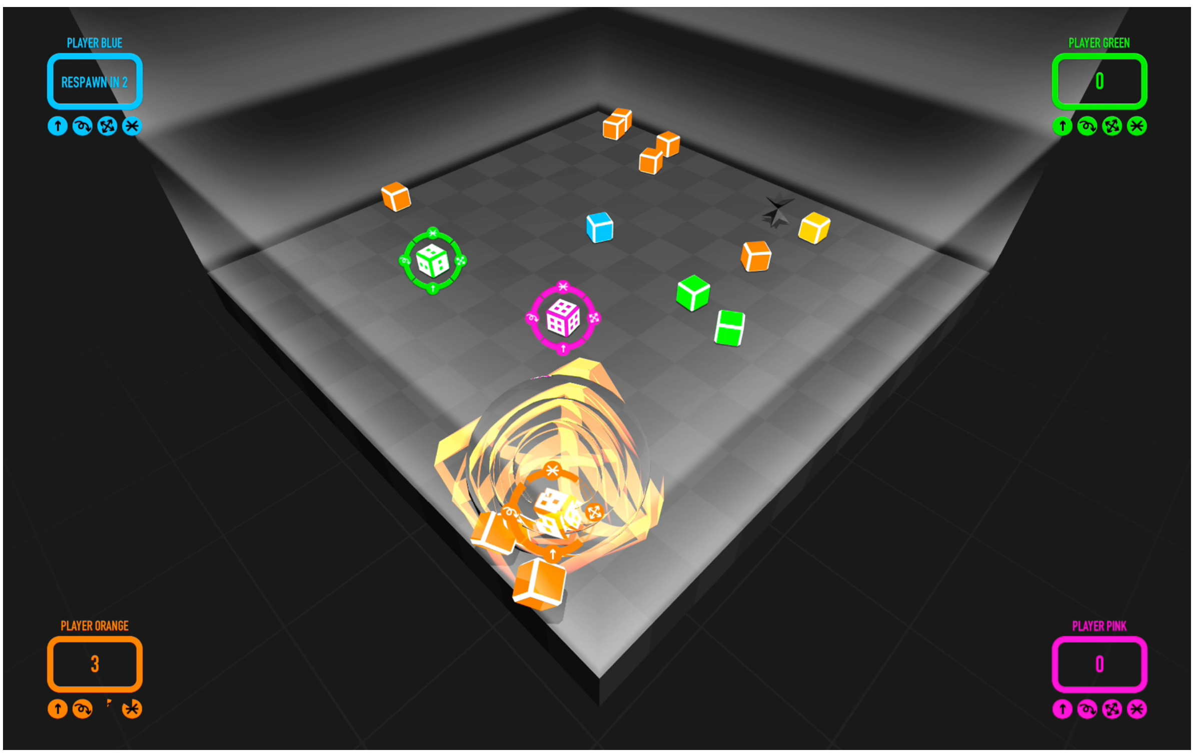


Figure 56: Nicely Dicely v3.2

Nicely Dicely v3.2 included further smaller gameplay optimizations and bug fixes.

The *Paralyze & Steal* action received its final wording and the control scheme visualization was adjusted accordingly (see Figure 57).

Figure 57: Nicely Dicely control scheme

To weaken the negative score punishment when falling off the board and to mitigate score differences between players, negative score counts were precluded. In turn, keeping score counts at zero and above should increase the motivation amongst players to fight until the end of a match and simplify getting into the game for new players.

Finally, a shockwave effect was added for mine explosions and *Burst* actions to further refine the visual style of the game (see *Burst* in Figure 56).

For a video outlining the game see *Appendix F.1.1* on page 263.

4.1.3 STUDIES

As part of the *CDR* approach, the following section will elaborate on the various studies conducted with *Nicely Dicely.* The public and informal *Showroom* demos are presented, providing an outline of the events which greatly helped iterating the design of the game. Finally, the *Lab* experiment conducted with the game illustrates the scientific investigation of *Local Multiplayer Immersion Affected by 3D Stereoscopy* (see from page 91ff.).

4.1.3.1 Showroom Demos

During six different *CDR Showroom* presentation events (see timeline in Figure 27), *Nicely Dicely* was presented to approximately 1000 people with different ages, genders and backgrounds including around 180 active play testers, whose informal feedback significantly influenced adjusting and designing various aspects of the game.

4.1.3.1.1 Ludum Dare 31 Game Jam

Figure 58: Ludum Dare 31 International Game Jam (Ludum Dare 2014)

Held in December 2014, the *31st International Ludum Dare Game Jam* provided a friendly development community and the topic "A game in one screen" as the foundation for getting together and creating games within roughly 48 hours (Ludum Dare 2014).

At *Google Campus London*, *Nicely Dicely* actually started off as a helpful demonstration to other developers, showing how quickly one could utilize the *Unity 3D* engine to create interactive and physics-based applications. A simple setup was created, consisting of a "floor" and several cubes on top. Applying a bit of scripting, the crude movement of one of those cubes could be controlled via a gamepad and the other passive cubes could be pushed over the edge of the floor. Once a second player was able to control a different cube, a competitive element between the players immediately established on its own. Thus, the basic principle of a game was born.

Once the above topic of the game jam was revealed and as the crude demonstration project luckily fitted the theme, it was decided to develop this further as the project for the game jam. Unfortunately, it was not possible to finish a working and playable version of the game in the required time frame of the event, so no actual submission was made. Nevertheless, an intermediate version of the demo, played by several other developers, already showed the inherent fun of the concept and its great potential.

4.1.3.1.2 Show Your Games 2016

Figure 59: Show Your Games 2016 (Werk1 2016)

Held in September in *Munich*, the *Show Your Games 2016* event provided a platform for presenting *Nicely Dicely* v1.1 to approximately 60 people from the indie game development industry (Werk1 2016). Around 15 of them were informally testing the game and giving vital constructive feedback on it. Once playing, the gameplay principle of *Nicely Dicely* clearly established fun and competition amongst the players and various up and downsides of the game could be observed.

4.1.3.1.3 X-Mas Pitching 2016

Figure 60: X-Mas Pitching 2016 (@UXsue 2016)

The *X-Mas Pitching Showroom* event held in December 2016 in *Munich* provided an audience of approximately 80 people from the gaming industry (Games Bavaria 2016). *Nicely Dicely* v3 was generally well accepted by observers.

A jury of professionals from the industry and around ten informal play testers provided great constructive feedback and inspiration for further fine-tuning or extending the established gameplay principle.

The three main areas for feedback were concerned with further strengthening the direct competition between players, somehow emotionally charging this competition, although the visual style of the game is very reduced and finally adding more and more varied *Mysteries* or game modes.

4.1.3.1.4 CHI PLAY Conference

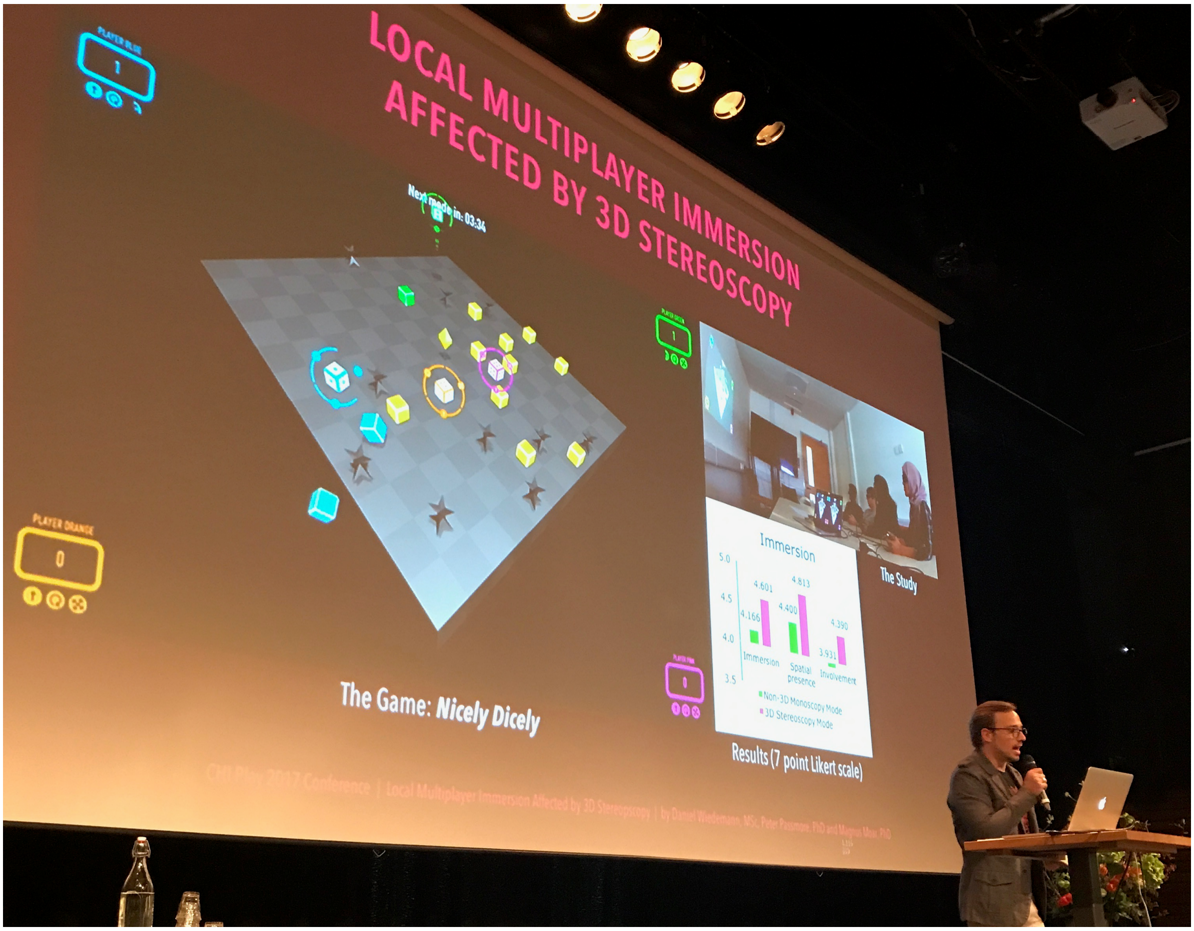


Figure 61: CHI PLAY Conference 2017

During the *CHI PLAY* conference in *Amsterdam* in October 2017 (CHI PLAY 2017) the outcomes of the *Lab Experiment: Local Multiplayer Immersion Affected by 3D Stereoscopy* (see from page 91ff.) were presented to approximately 150 people from games, play and *HCI* research.

In a demo area *Nicely Dicely* v3.1 was played by around 15 informal testers, coming from said research areas. It was interesting to get feedback from a rather academically focused audience and to see that the game was also well accepted in this environment.

4.1.3.1.5 MDX STEM Fair at Thorpe Park

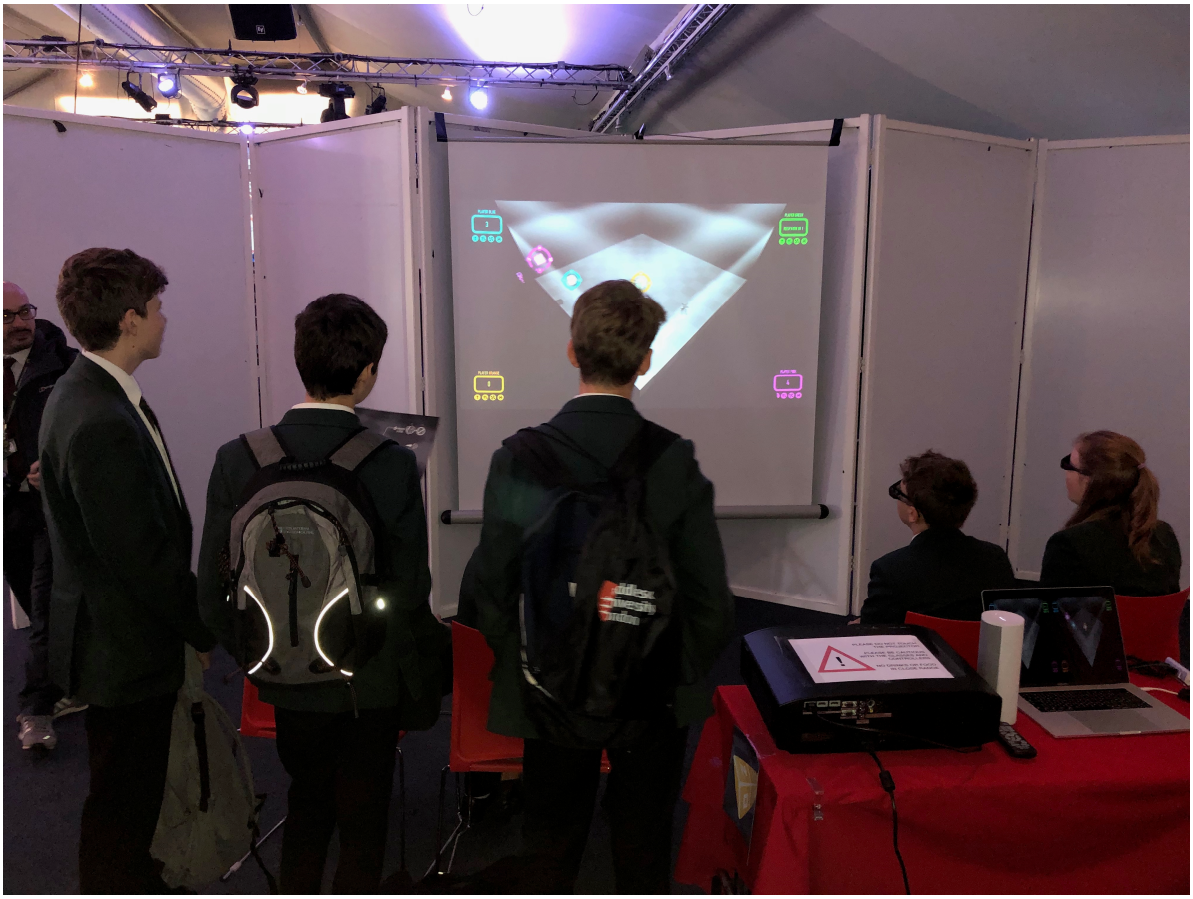


Figure 62: MDX STEM Fair at Thorpe Park

At the *MDX STEM Fair at Thorpe Park* near *London* in April 2018 (Middlesex University London 2018) *Nicely Dicely* v3.2 was presented to approximately 500 school children. Around 100 players from this young audience tested the game in a rather unguided and informal atmosphere and it was very informative to observe the dynamics in groups of pupils and what they thought would be good extensions to the game.

Additionally, it was very satisfying to see how quick the controls and the gameplay were understood and how well the game was generally accepted by children, which was highlighted by crowds of them queuing up to play the game.

4.1.3.1.6 Ludicious Game Festival 2019

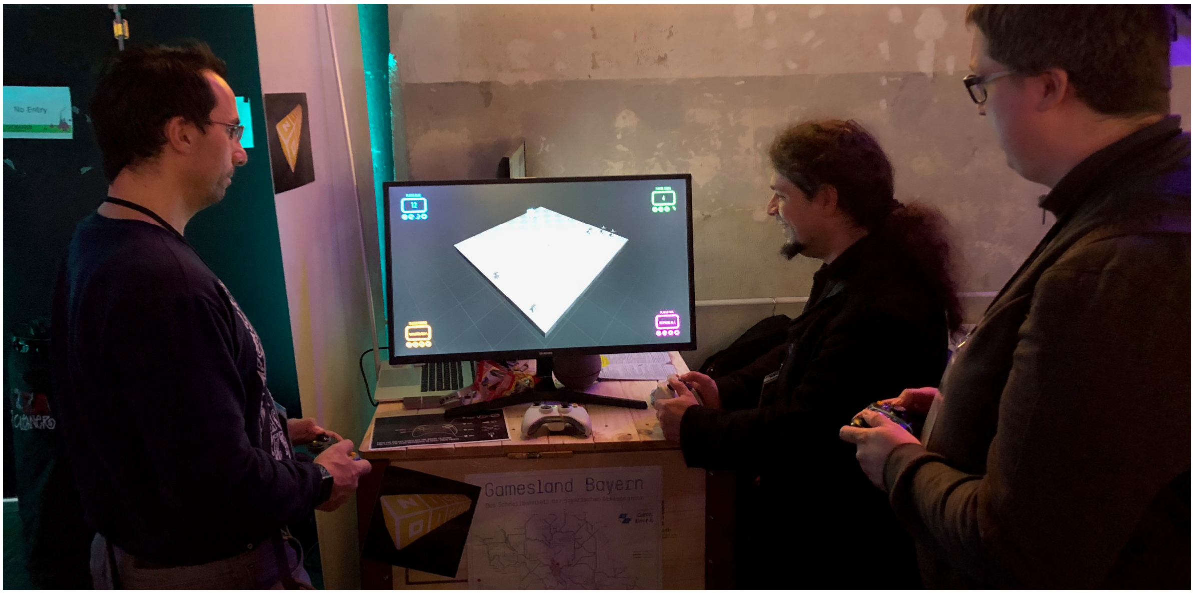


Figure 63: Ludicious Game Festival 2019

The *Ludicious Game Festival* in *Zurich* in January 2019 provided a great platform to present *Nicely Dicely* v3.2 to a crowd of approximately 200 gaming affine people with varying ages and backgrounds (Ludicious 2019). The game was played by around 50 informal testers. Especially as there was great competition in attracting players, due to the large number of further game demos, it was great to see that groups of young and old people wanted to play the game and sometimes even came back for additional matches. Most of the given feedback was already known, although it nevertheless further highlighted certain priorities.

As the audience also included several professionals from the industry, the game was also individually presented to two *Nintendo* representatives during a meeting and it was recommended for a release on the *Nintendo Switch* console. Though, one important feedback was, that the game would likely need some form of *Singleplayer* mode apart from the *Local Multiplayer* to justify a price tier around 12€, which seemed to be their recommendation.

4.1.3.2 Lab Experiment: Local Multiplayer Immersion Affected by 3D Stereoscopy

Figure 64: Nicely Dicely experiment setup

One immersive aspect, that *VR HMDs, 3D Cinema* and *3D TVs* and *Projectors* have in common, is *3D Stereoscopy.* Refraining from evaluating *VR* as a whole and instead looking at available *3D* devices and their great potential for gaming, the following respective *CDR Lab* experiment using *Nicely Dicely* v2 was conducted in *London* in October 2016 with 31 participants.

> [This study investigates] if and how *Stereoscopic 3D Vision* can affect *Immersion,* a crucial aspect of gaming experiences. Furthermore, it is going to do that in the context of a *Local Multiplayer* game. By concept, this leads to several players being present in the same room and thus a possibly very distracting gaming experience, due to chatting and banter, which happened in varying degrees during [the] experiment sessions. *Local Multiplayer* and the game being specifically developed for *3D*, differentiates this study from others. Thus, [the] main hypothesis is: ***"3D Stereoscopic Vision* increases *Player Immersion,* even in a possibly distracting *Local Multiplayer* game.".**
>
> To evaluate this relation, [I] developed the game *Nicely Dicely* from scratch, while being compatible to *Stereoscopic 3D,* right from the start [see *Appendix C.1.3 3D Stereoscopy System* from page 245ff.]. Optimized for *3D,* the game takes place on one screen, omitting any drastic depth animations, and is visually positioned slightly "behind the screen", to reduce any eye strain. Internal testing showed, that the game's fundamental gameplay principle seemed to provide great fun among players, especially due to its *Local Multiplayer* concept.
>
> (Wiedemann et al. 2017c)

4.1.3.2.1 Experiment Methodology

“ The hardware setup for the experiment included an *Apple MacBook Pro* (Mid 2012), four *Xbox* controllers, a *Panasonic PT-AT6000E 3D Projector* and four pairs of *Panasonic TY-EW3D3ME 3D IR* active *Shutter Glasses.* All user test sessions were video recorded (see Figure 64), to capture verbal remarks and gaming behavior.

By filling out the consent form, the participants agreed to the experiment terms and provided basic information about themselves and their experience with digital games and *3D Stereoscopy.* The main goal for the subjects was communicated as achieving the highest score possible, by pushing the golden score cubes off the game board, while themselves not falling off the board and thus losing score points. Each mode and thus each match would end after five minutes.

The procedure of the user test is explained to participants as followed: The experiment will go through three different phases. Each will last for 5 minutes and reset the game automatically afterwards, resulting in a total play session duration of ~15 minutes (see Figure 65 and Figure 66).

Figure 65: Nicely Dicely experiment phases

The first phase will be *Monoscopic* like in any other regular flat game, so subjects can generally make themselves familiar with the game first. In the subsequent phases, two modes will be tested, one again *Monoscopic* and the other in *3D Stereoscopic.* The order of these two modes will be pseudo random, to counterbalance any order effects. While playing, a countdown is visible, showing the remaining time of the current mode (see Figure 31).

(Wiedemann et al. 2017c)

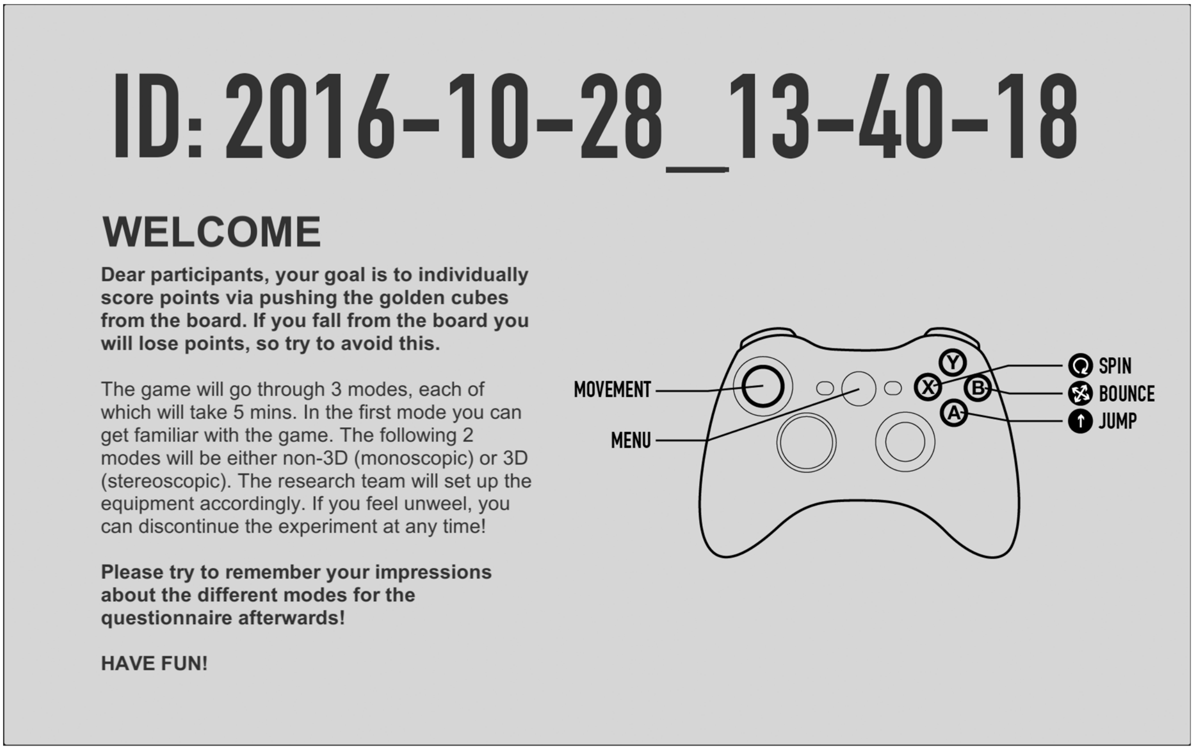


Figure 66: Nicely Dicely experiment application's first screen

Based on the two *Immersion* concerning sub scales *"Spatial Presence"* and *"Involvement"* of the *IPQ* [Schubert et al. 2001 and igroup 2016], a questionnaire specific to the experiment was developed, which would be filled out after the play testing phases. Separated into three sections, the participants were asked to evaluate their gaming experience in the *"Non-3D Monoscopy Mode", "3D Stereoscopy Mode"* and in "General". Based on the *IPQ* [igroup 2016], to assess mode related *Player Immersion*, the first two sections each provide the following statements, to be rated by subjects on a 7-point Likert scale from "Strongly disagree" to "Strongly agree": "Somehow I felt that the virtual world surrounded me.", "I felt like I was just perceiving pictures.", "I did not feel present in the virtual space.", "I had a sense of acting in the virtual space, rather than operating something from outside.", "I felt present in the virtual space.", "I was completely aware of the real world surrounding while navigating in the virtual world (i.e. sounds, room temperature, other people, etc.).", "I was not aware of my real environment.", "I still paid attention to the real environment." and "I was completely captivated by the virtual world.". Relating to the earlier discussed connection between *Presence* and *Immersion* [Slater and Wilbur 1997 and Jerald 2016], and as the experiment is assessing a change caused by *3D Stereoscopy*, which drastically affects the perception of virtual space, [I] chose to additionally combine the two *IPQ* sub scales *Spatial Presence* and *Involvement* to an overall *"Immersion"* scale for this investigation. This arguably enhances capturing the effect of *3D Stereoscopy* on *Immersion*, instead of only relying on the involvement sub scale.

In the third section, participants are asked for their personal *Mode Preference* and their reasoning for their decision. Two further free text questions gave subjects space for concrete and individual feedback.

Besides, the experiment application tracked the following in-game parameters for each player per mode: *Player Score, Player Deaths* and *Player Performance* for analysis [see *Appendix D.1 XML Excel Export of In-Game Parameters* from page 257ff.]. *Player Performance* is the calculated ratio between *Player Score* and *Player Deaths*.
(Wiedemann et al. 2017c)

Furthermore, participants were asked "Did you feel any nausea during the test, or right afterwards?" on a scale from 0 ("No nausea at all") to 10 ("I feel extremely sick"). This simple *Simulator Sickness* rating could not be evaluated separately for each mode, because of the experiment's design. This aspect and available data on a scale from 0 to 10 from previous user test sessions resulted in using this trivial *Simulator Sickness* evaluation, instead of using for example the rather complex *Simulator Sickness Questionnaire* (Kennedy et al. 1993). Finally, subjects were asked to answer, "Though feeling nauseated, would you keep on playing?" on a 7-point Likert scale.

For a video outlining the experiment procedure, the *Monoscopic* and *Stereoscopic Modes* and a selection of edited recordings of participant sessions see *Appendix F.1.2* on page 263.

4.1.3.2.2 Experiment Results

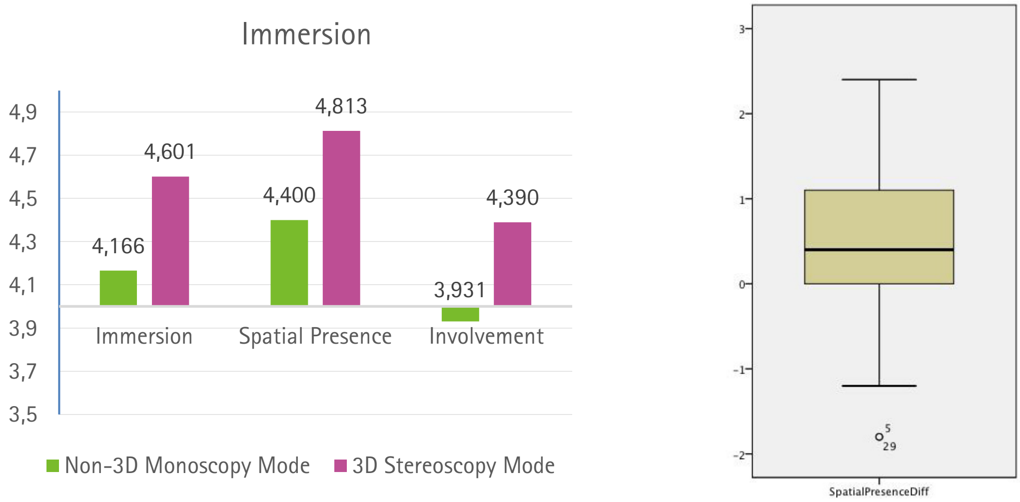
The experiment was conducted with 31 participants (total n = 31), partly knowing each other, of which 24 were male and 7 were female. Ages ranged from 18 to 57 years and averaged at 22 years. According to the statement "I am an experienced digital game player", 4 were rather inexperienced (< 4 on 7-point Likert scale) and 27 rather experienced (>= 4) subjects, with a total mean of 5.68. Rather little experience with *3D Stereoscopy* noted 8 (< 4 on 7-point Likert scale) and rather more experience was noted by 23 (>= 4) of the participants, with a total mean of 4.71. 4 subjects noted, they were playing digital games between "less than once a year" and "once every some months", one single participant noted she was playing "once a month" and 26 marked they would play digital games between "once or twice a week" and "every day".

	a) *Immersion*		b) *Preference*	c) *Player Performance*	
	Spatial Presence	*Involvement*		*Player Score*	*Player Deaths*
Non-3D Monoscopy Mode	4.166 ± 0.923		42% (13)	5.040	
	4.400 ± 0.788	3.931 ± 1.498		29.94 ± 14.938	5.94 ± 5.285
3D Stereoscopy Mode	4.601 ± 0.887		58% (18)	5.001	
	4.813 ± 0.879	4.390 ± 1.237		29.10 ± 13.524	5.81 ± 4.370

Table 1: a) Immersion: Means ± Standard Deviation of Immersion, Spatial Presence and Involvement on a 7-point Likert scale. b) Preference: Percentages (subject count) of directly chosen Presentation Mode Preference. c) Player Performance: Means ± Standard Deviation of Player Score, Player Deaths and the subsequently calculated Player Performance

(Wiedemann et al. 2017c)

4.1.3.2.2.1 Immersion, Spatial Presence and Involvement



a) b)

Figure 67: a) Diagram for Immersion and b) Spatial Presence data Tukey boxplot (whiskers showing 1.5 IQR)

> Three separate *Paired-Samples t-tests* (Laerd Statistics 2015a and d) were used to determine whether there were statistically significant mean differences on the *Immersion, Spatial Presence* and *Involvement* 7-point Likert scales between presenting the game in *3D Stereoscopic Mode* compared to *Non-3D Monoscopic Mode.* To preserve easy comparability with the original 7-point Likert scale format, the means (not sums) of item scores were used to calculate the resulting scales, before performing the *t-tests.*
>
> There were no outliers in the overall *Immersion* data, as assessed by inspection of a boxplot.
>
> (Wiedemann et al. 2017c)

A normal distribution of the data is required for this statistic. To test the data for normality based on objective numerics, an analysis of skewness and kurtosis was performed (Laerd Statistics 2015g, see *Appendices A.57* and *A.106* on pages 204 and 209 for a description of these terms). Corresponding z-values are acquired by dividing the skewness/kurtosis values by their *Standard Errors (SEs).* If these are within the conservative threshold of ± 2.58 (corresponds to significance level of 0.01), the data can be regarded as normally distributed (Laerd Statistics 2015g).

> Scores were normally distributed with a skewness of -0.305 (SE = 0.401) and kurtosis of 0.052 (SE = 0.821). Data are mean ± *Standard Deviation,* unless otherwise stated. Participants experienced stronger *Immersion* when the game was presented in *3D Stereoscopy* (4.601 ± 0.887) as opposed to *Non-3D Monoscopy* (4.166 ± 0.923). The *3D Stereoscopic Mode* compared to the *Non-3D Monoscopic Mode* elicited a statistically significant mean increase on the *Immersion* scale of 0.435 (95% CI, 0.089 to 0.781), t(30) = 2.565, p = 0.016 and d = 0.461 (small to medium effect size).
>
> Two outliers were detected in the *Spatial Presence* data, that were more than 1.5 times the *Inter-Quartile Range (IQR)* from the edge of the box in a boxplot (see Figure 67b). Inspection of their values did

not reveal them to be extreme (< 3 *IQR)* and they were kept in the analysis. Scores were normally distributed with a skewness of -0.350 (SE = 0.421) and kurtosis of -0.222 (SE = 0.821). Data are mean ± *Standard Deviation*, unless otherwise stated. Participants experienced stronger *Spatial Presence* when the game was presented in *3D Stereoscopy* (4.813 ± 0.879) as opposed to *Non-3D Monoscopy* (4.400 ± 0.788). The *3D Stereoscopic Mode* compared to the *Non-3D Monoscopic Mode* elicited a statistically significant mean increase on the *Spatial Presence* scale of 0.413 (95% CI, 0.021 to 0.805), t(30) = 2.150, p = 0.040 and d = 0.386 (small to medium effect size).

There were no outliers in the *Involvement* data, as assessed by inspection of a boxplot. Scores were normally distributed with a skewness of -0.029 (SE = 0.421) and kurtosis of –0.862 (SE = 0.821). Data are mean ± *Standard Deviation*, unless otherwise stated. Participants experienced stronger *Involvement* when the game was presented in *3D Stereoscopy* (4.390 ± 1.237) as opposed to *Non-3D Monoscopy* (3.931 ± 1.498). The *3D Stereoscopic Mode* compared to the *Non-3D Monoscopic Mode* elicited a statistically significant mean increase on the *Involvement* scale of 0.457 (95% CI, 0.016 to 0.898), t(30) = 2.118, p = 0.043 and d = 0.380 (small to medium effect size).

The statistically significant increases in the quantitative data on *Spatial Presence*, *Involvement* and *Immersion* (see Table 1a and Figure 67a), relating to the *3D Stereoscopic Presentation* of the game, contribute to qualitative feedback and the following further comments: "*3D* felt like I was in the actual game (inside)" [P14, participant ID], "It felt more interactive [in *3D Mode]*" [P5] and "I preferred the *3D Mode* because it was more engaging and also captured my attention more" [P24].
(Wiedemann et al. 2017c)

Except for *Involvement* during the *Non-3D Presentation* of the game, female participants generally registered higher values on the previous scales, as their male counterparts. The corresponding mean differences in *Immersion* are 0.011 *(Non-3D)* and 0.363 *(3D).*

Subjects who preferred the *3D Stereoscopic Mode* also showed higher scores on *Spatial Presence*, *Involvement* and thus *Immersion*, compared to those who preferred the *Non-3D Monoscopic Mode.* The corresponding mean difference in *Immersion* is 0.466.

4.1.3.2.2.2 Mode Preference

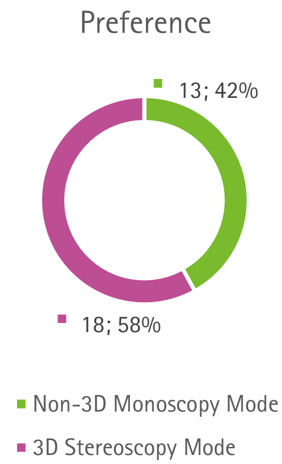


Figure 68: Diagram for Preference

The answers to the direct question "Which mode did you prefer?" ranked the *3D Stereoscopic Mode* on the first place with 58% and the *Non-3D Monoscopic Mode* on the second place with 42% (see Table 1b and Figure 68). A *Chi-Square Goodness-of-Fit* test (Laerd Statistics 2015a and b), with a minimum expected frequency of 15.5, indicated that the distribution of *Mode Preference* by participants in this study was not statistically significantly different ($\chi2(1) = 0.806$, $p = 0.369$).

Nevertheless, by investigating the free text answers of participants, the following insights were extrapolated, in relation to the subjects' chosen *Preferences.*

Five subjects, which preferred *Non-3D,* commented that this presentation was not straining their eye sight as much as it did in *3D.* Also, an additional effort in concentration was noted, when playing in *3D.* Others who preferred *Non-3D* additionally mentioned not perceiving a great difference at all between the two modes. These attitudes could be noticed as well in corresponding subjects commenting on how gameplay was affected: *"3D* was more obstructive. I found it more difficult to navigate the map." [P03], "It made me think what I had to do to overcome the problem" [P12] and "I did not notice much difference" [P27].

On the other hand, participants who preferred the *3D Stereoscopic Presentation* of the game highlighted the following positive aspects. Relating to the previous results on increased *Immersion* in *Stereoscopic 3D,* corresponding subjects clearly emphasized this mode's positive effect: "I found it more captivating" [P01], "[I preferred *3D* because of the] *Immersion* into the world" [P10] and "with the glasses you make your brain just focus on the screen and everything else loses importance" [P13]. This aspect was amplified by the perceived "realness" of the game through *3D Stereoscopy:* "Putting on *3D* glasses felt more real!" [P06] and "everything felt like it had a real impact, both my actions and the cubes" [P11]. Contributing to an increased graphical attractiveness participants furthermore highlighted: "The *3D* mode was more visually appealing" [P23] and "In the *3D* mode, the effects were a lot more enhanced." [P24]. Furthermore, *3D Stereoscopic Presentation* of the game also seemed to enforce more fun: "Fun, interactive" [P16] and "It was more fun in the *3D Stereoscopic*" [P15]. Finally, the *Stereoscopic Vision* seemed to improve controls: "You have more attachment with the movement of the dice as perspective works well." [P01] and "The objects featured in the game seemed to 'pop out' more, and perceiving the 3D world was easier in *3D.*" [P02]. Adding to this aspect of affecting gameplay, subjects further commented this mode in the following: "The game was a little easier to play with *3D* enabled, as you could see the '3D-ness' of the world better." [P02], "I found it much easier to control my dice, because it helped me understand the perspective better." [P01] and *"3D* was better … because it's easy to judge the environment space." [P18].

In terms of enhanced *Immersion* by *3D Stereoscopy* affecting gameplay, participants noted the following: "More concentration with *3D* then *[Non-3D]"* [P06] and *"3D-Stereoscopy* made me tunnel vision the game, like I lost all my awareness of my surrounding and everything [else] came black" [P13].
(Wiedemann et al. 2017c)

4.1.3.2.2.3 In-Game Parameters

"

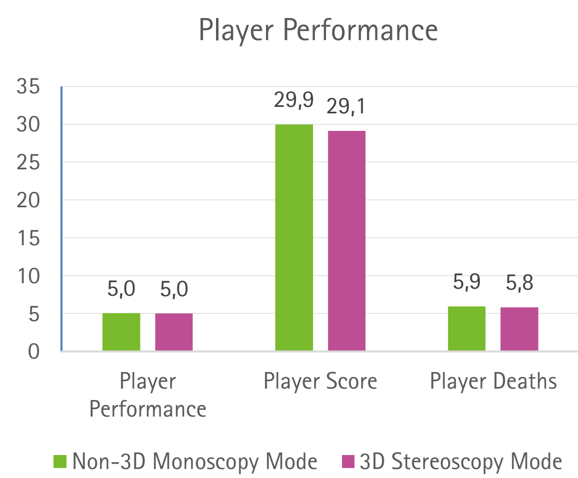


Figure 69: Diagram for Player Performance

Two *Paired-Samples t-tests* (Laerd Statistics 2015a and d) were used to determine whether there were statistically significant mean differences in the tracked in-game parameters *Player Score*, *Player Deaths* and the subsequently calculated *Player Performance*, when presenting the game in *3D Stereoscopic Mode* compared to *Non-3D Monoscopic Mode* (see Table 1c and Figure 69). *Player Scores* were normally distributed with a skewness of -1.011 (SE = 0.421) and kurtosis of 1.962 (SE = 0.821), but did not show a statistically significant difference between means ($p > 0.05$). *Player Deaths* were normally distributed with a skewness of -0.878 (SE = 0.421) and kurtosis of 1.505 (SE = 0.821), but did not show a statistically significant difference between means ($p > 0.05$).

> The increases and decreases in *Player Performance* relating to the two different modes show the same tendency as the chosen *Mode Preference.* Subjects who preferred the *Non-3D Monoscopic Mode* also showed a decrease in *Player Performance* in *3D Stereoscopic Mode*, with a mean difference of −2.161. Whereas, subjects who preferred the *3D Stereoscopic Mode* also showed an increase in *Player Performance*, while playing in *3D Stereoscopic Mode*, with a mean difference of 1.009.
> (Wiedemann et al. 2017c)

Reflecting the difference in spending time on playing digital games and their experience with them, female participants scored less than half of the tracked *Player Performance* of male participants in both presentation modes. The corresponding mean differences in *Player Performance* are 3.258 *(Non-3D)* and 3.6 *(3D).*

As could be assumed, subjects who played digital games at least "once or twice a week", were able to show over three times the *Player Performance* in *Non-3D Mode* and over four times in *3D Mode*, compared to other subjects playing "once a month" and less. The corresponding mean differences in *Player Performance* are 4.113 *(Non-3D)* and 4.836 *(3D).*

4.1.3.2.2.4 Simulator Sickness

Due to optimizing the application for *3D Stereoscopy*, registered *Simulator Sickness* levels were very low (see Table 2). Participants who registered any amount of nausea after their session were rather less experienced with *3D Stereoscopy*, with a mean of 3.6 on the *3D Stereoscopy* experience scale and a mean difference of 1.323 to the rest of the participants. Finally, no female participants did register any Simulator Sickness at all.

	Mean ± SD
Simulator Sickness (scale from 0 to 10)	.452 ± 1.387
Motivation to keep playing, though feeling nauseated (7-point Likert scale)	4.290 ± 1.953

Table 2: Means ± Standard Deviation of Simulator Sickness and Motivation to keep playing, though feeling nauseated

4.1.3.2.3 Nicely Dicely and the Next Iteration

> “ In general, *Nicely Dicely* received really positive feedback and seemed to provide a lot of fun for participants. Its potential as a great party or couch game was highlighted by around a third of the subjects. A later version of *Nicely Dicely* provided tighter controls (by adjusting physics parameters), more mysteries (e.g. high gravity, low gravity and player cube shrinkage) and a fourth player action "paralyze", to temporarily paralyze other players in close range [and steal one of their points]. The latter added a more direct competitive element and another way for scoring. Internal testing showed, that these additions positively influenced gameplay and fun, by making the game more versatile.
> (Wiedemann et al. 2017c)

4.1.3.2.4 Experiment Limitations

The experiment had several limitations. Though it was possible to retrieve statistically significant results (e.g. on *Immersion),* the sample size of 31 is relatively small. In the case of observed *Mode Preference,* this likely caused not being able to present statistical significance. Furthermore, the small sample size did not permit reliable significance analysis of the cross-referenced results (e.g. on gender, gaming or *3D* experience), as sub samples did not provide enough subjects. Finally, the experiment was conducted in a laboratory like manner and thus cannot reflect the exact same situation as playing *Nicely Dicely* in a more natural gaming environment.

4.1.3.2.5 Experiment Conclusion

> “ Relating [the] experiment's results to the initial hypothesis *"3D Stereoscopic Vision* increases *Player Immersion,* even in a possibly distracting *Local Multiplayer* game.", [I] can make the two statements. Indeed, *3D Stereoscopic Vision* significantly increases *Player Immersion* (including *Involvement* and *Spatial Presence),* compared to *Non-3D Monoscopic Vision.* As different evaluation tools were used, [the] results strengthen the primary outcomes of studies by Mahoney et al. (2011) and Schild et al. (2012). Additionally, [the] study has expanded these outcomes by illustrating, that the increase in *Player Immersion* also applies in a possibly very distracting *Local Multiplayer* situation with up to four players. Furthermore, subjects' comments on an increased realness and graphical attractiveness, as well as a subjectively better gameplay, caused by an improved depth perception, are adding to the advantages of *Stereoscopic 3D.* As such, [I] argue for the potential that *Stereoscopic 3D* holds for digital games in general, but also for party and couch games with multiple parallel players.
>
> Nevertheless, [I] agree with Mahoney et al. (2011), that games need to be specifically designed for *Stereoscopic 3D,* to deliver an enjoyable and superior experience to users. Providing meta information via overlaying *HUDs* for example, needs to be designed with great care. The version of *Nicely Dicely* tested in the experiment, spatially placed all *HUDs* (including the cooldown rings around the player cubes) at the zero-parallax distance in the front. Reviewing some participants' comments on eye strain and an increased demand for player concentration in *Stereoscopic 3D,* [I] think this and the only slightly higher direct *Preference* for *3D* were caused by not spatially placing the ring *HUDs* at the same distance as the player cubes. In a later version of the game, the ring *HUDs* were completely redeveloped to be able to render with the same parallax shift as the corresponding player cubes. Internal testing showed, this relieved eye strain drastically, as users would not need to constantly readjust their focus distance between the player cube and its surrounding ring *HUD.*

> Similar to the study of [Litwiller and LaViola] (2011), [I] could not find any effect on in-game *Player Performance*, related to the two different presentation modes. Nevertheless, there was an undetermined correlation between subjective direct *Mode Preference* and objective *Player Performance.* Subjects who preferred one mode, most likely also showed better *Player Performance* in this mode, compared to the other one.
> (Wiedemann et al. 2017c)

In terms of gender specific outcomes, it can be stated that female subjects generally scored considerably less in in-game *Player Performance* and expressed overall higher *Immersion*, than their male counterparts. The latter two aspects likely resulted, because female subjects spent less time on playing digital games and noted a diminished experience with digital games and *Stereoscopic 3D* in general.

4.1.4 REFLECTIVE DISCOURSE

As part of the *CDR* approach, the following section will reflect more thoroughly on some of the aspects of the artifact's development and its corresponding studies.

Nicely Dicely is likely the most successful artifact of the three games regarding its development and design progress. Due to its relatively simple gameplay and limited scope of content, I was able to gradually refine its gameplay and polish its visuals, step by step leading to an improved *UX.* This resulted in the most "complete" game in the portfolio, which is in a state very close to being released to the public. This is also supported by the positive player feedback gathered through the various *Showroom* demos and the *Lab* experiment.

The chronologically earlier developments of the *Stereoscopic 3D* and *VR* versions of *LizzE* (see v2A and v2B from page 104ff.) significantly helped to implement a *Stereoscopic 3D Mode* in *Nicely Dicely.* Especially the previously gathered experience on handling *GUI* elements in a *Stereoscopic* environment not only accelerated the development process of *Nicely Dicely,* but also made its custom *Stereoscopic 3D* system more versatile and developer friendly.

On the other hand, *Nicely Dicely* explores "only" the, nevertheless essential, *3D Stereoscopy* aspect of *VR,* but it is not a *VR* game per se. Its *Local Multiplayer* gameplay concept would have made a *VR* version significantly harder to develop and conducting corresponding user tests with it, would have required substantially more complex logistics.

Regarding the *Lab* experiment on *Immersion being Affected by 3D Stereoscopy* (see from page 91ff.), making the respective preparations (e.g. choosing a *UX* aspect to investigate and developing the questionnaire) could have benefited from a more thoroughly planned approach. The unique feature of the study – *Local Multiplayer* and the corresponding possibility of distractions through banter and chatting – was established only after the study. The anticipatory way the experiment was conducted and data was collected, nevertheless very much helped with converging on this topic in the postprocessing of the experiment.

Due to its *Local Multiplayer* concept and its rather abstract style, *Nicely Dicely* provides a platform, which lets players easily and quickly immerse themselves into a group of competing users. Hence, the players' *Rollenwahrnehmung* in *Nicely Dicely* is not concerned with a very strong and serious bond between a user and his or her player cube. Instead, the rather abstract and loose connection supports the uncoerced party game concept, as new players can quickly join the game without the need for much exercise in gameplay mechanics. Likewise, if a player wants or needs to stop playing, no severe repercussions are expected. In turn, this provides a subliminal freedom while playing, which benefits direct communication with the other human beings, including the occasional friendly banter.

In contrast to e.g. a multi split screen design, *Nicely Dicely's* single screen design provides one visual *Perspective* on the game, shared by all players, similar to a traditional board game. This characteristic of the game again strengthens the party game concept, as all players are physically and virtually sharing the same *Perspective.* This makes the game more easily accessible, as there is no split of the *VE* and thus, there is no need to overcome the corresponding abstraction hurdle to reconnect several *Perspectives* to a single *VE.* Switching between *Non-3D Monoscopic* and *3D Stereoscopic Vision* obviously also applies a change in the visual *Perspective* for all players.

Closely related to the shared *Perspective* is the transformation of the whole physical environment around the game including the present people, into a shared gaming *Space* for players and observers. This is even more intensified, when the *Stereoscopic 3D Mode* is activated, as this more closely connects the game with the physical environment by visually extruding the screen in depth. In turn, the virtual *Space* in *Nicely Dicely* and the physical *Space* visually merge into a single one, encompassing the people within it.

4.1.5 CONTRIBUTION TO OVERALL STUDY

The artifact *Nicely Dicely,* its various iterations and the *Showroom* and *Lab* investigations provide several contributions to the overall study.

A general know-how for implementing *3D Stereoscopy* was established and a corresponding custom *Unity* tool was developed, which may rather easily be implemented in other projects.

The *Showroom* demos resulted in several informal, but nevertheless important and easy to gather understandings on general aspects of the artifact, leading to a fun and well-balanced *Local Multiplayer* gameplay and a well-integrated *3D Stereoscopy Mode.* The *Lab* experiment, with a refined gameplay concept and a working *Stereoscopic 3D Mode* provided a deeper investigation of the relation of *3D Stereoscopy* and *Player Immersion* in a possibly distracting *Local Multiplayer* gaming environment. This led to optimizations of the *3D Stereoscopy* implementation and a better understanding of its effect on *Player Immersion.* This eventually also benefits *VR* development, as both topics are rather important aspects of it.

Regarding the investigation of the three guiding key areas, *Nicely Dicely* provides its individual take on these. The *Rollenwahrnehmung* is purposefully kept loose and easy, to support the party game concept of the game. Further supporting this, it uses a single *Perspective* shared by all players, making it more accessible. Switching between *Non-3D Monoscopic* and *3D Stereoscopic Vision* also applies a change in visual *Perspective*. Additionally, the *Local Multiplayer* aspect transforms the *Space* around the game and its players to a shared and communicative gaming *Space.* This gets even further connected by visually merging the physical with the virtual *Space* through *3D Stereoscopy.*

Finally, the artifact *Nicely Dicely* and its documented iterations act as an individual precedent for design, development and research and thus add significant elements to the overall precedent, i.e. the portfolio of artifacts.

4.2 LIZZE – AND THE LIGHT OF DREAMS (LIZZE)

Figure 70: Illustration of Lizze and Ezzil, the two playable main characters of the game (Wiedemann 2013)

For a video presenting the game see *Appendix F.2.2* on page 264.

The following subchapter will outline the concept and the attributes of the artifact *LizzE – And the Light of Dreams.* Relating to *CDR's Constructive Iterative Cycle,* it will further elaborate on various iterations, which the game went through over its development time. Subsequently, corresponding studies will be illustrated, i.e. *CDR* conform *Showroom* demos and a *Lab* experiment. The latter section will elaborate on the experiment's modes, methodology, results and conclusion, regarding *VR 3rd Person Camera Behavior Modes.* Afterwards, distinctions related to the artifact will be outlined. Finally, as part of the *CDR* approach, a reflective discourse on the artifact will be held and its contribution to the overall study will be summarized.

4.2.1 THE GAME

> “ *LizzE – And the Light of Dreams* is a *[3rd Person] 3D Hack and Slay* video game, that adapts its experience to the user’s performance and immerses him [or her] in its fantastic storyline. Furthermore, to its *Singleplayer* mode the game features also a *Multiplayer* cooperation mode.
>
> Technically *LizzE* combines several common interaction methods like the keyboard or an *Xbox 360* game controller, with the more recent multitouch capabilities of an *iPad* and the … motion sensing technology of the *Leap Motion* controller.
>
> (Wiedemann 2013)

The game was chosen as an artifact for the overall study, because the base version of the game (v1) was already developed prior to this research, with working gameplay and a diverse feature set. In the context of the overall study it was used as a platform to test various techniques (e.g. *3D Stereoscopy* and *VR)* and to explore different research routes. Finally, due to its *3rd Person Perspective*, it was a great case to investigate corresponding *VR* camera behavior modes (see from page 114ff.). During these explorations, different features of the original version of the game needed to be adjusted, deactivated or removed to focus on the actual research. This will be further explained later on.

4.2.2 ITERATIONS

As part of the *CDR* approach, the following will elaborate on the different iterations of *LizzE*, relevant to this research, to provide an overview on the progress the game has made over various design and development phases and to illustrate its corresponding features.

4.2.2.1 LizzE v1 (pre-PhD)

Figure 71: LizzE v1 (pre-PhD): Lizze getting attacked by a Bonemage and Imp (FIERY THINGS 2013)

Figure 72: LizzE v1 (pre-PhD): Ezzil spreading a bunch of Imps with spherical blast special attack (FIERY THINGS 2013)

The first version of *LizzE – And the Light of Dreams* was originally implemented as the final project accompanying my *Master of Science* thesis in 2013, prior to this *PhD* research. As I had complete control over all aspects of the game and its source code, this version of *LizzE* built the foundation for further developments and investigations.

Though *LizzE* v1 does not form part of the overall study, for the sake of understanding and completeness, the following will describe relevant aspects of the game's content, gameplay and feature set.

> [Explained in an intro video, the] storyline of *LizzE* includes a little orphan girl called *Lizze* (short for *Elizabeth*), with a yet unknown background history and an almost psychopathic habit for knifes, and a beast called *Ezzil.*
>
> *Ezzil* (spells *"Lizze"* backwards) from the beast world was send out by *Bethara,* an old mighty sorceress and ruler of this parallel world. Like many others, he was ordered to collect the *Light of Dreams,* a magical kind of energy source, that gets fueled with varying powers by dreaming humans. …
>
> Though this time as *Ezzil* feels the immense power of *Lizze's Light of Dreams,* he refuses to collect the light. *Bethara* gets so furious about this, that she casts a mighty spell on him. But the spell has a side effect. *Lizze* gets sucked into the world in between and somehow merged with *Ezzil* into one being. …
>
> As they have no other choice, they decide to work together, to find a way to split themselves again.
>
> [For the intro video see *Appendix F.2.1* on page 264.]
>
> (Wiedemann 2013)

> The *LizzE* universe consists of three parallel worlds, the human world, the beast world and the "world in between". The … available level only takes place in the world in between and only with a reduced range of level elements. … [It] included two different enemy types and a mini boss.
>
> (Wiedemann 2013)

Figure 73: LizzE control scheme

> The player controls either *Lizze* or *Ezzil* [see Figure 71 and Figure 72] from a third person point of view. He [or she] can actively switch between the two characters and perform the currently available corresponding actions like melee attacks, combos, spells and special attacks. … In case of *Lizze* this is a distance attack spell, whereas *Ezzil* offers a magical close combat special attack blast [see Figure 73]. …
>
> The player is supposed to run around the level geometry, jump over obstacles, collect the *Light of Dreams*, fight against *[AI* controlled] enemies and switch between the two protagonists.
>
> (Wiedemann 2013)

For a video outlining the game see *Appendix F.2.2* on page 264.

Because of presentational and experimental reasons, some of the v1 features were disabled in the following iterations. This included the intro video, dynamic difficulty (Hunicke and Chapman 2004), the cooperative *Multiplayer* mode, other input modes than the *Xbox 360* controller, support for *Windows* and *iOS* platforms and any randomization of parameters, e.g. when inflicting damage on an enemy.

4.2.2.2 LizzE v2A

Figure 74: LizzE v2A: First attempt in adding Side-by-Side 3D support to LizzE

In *LizzE* v2A (see Figure 74) I first attempted in adding *Stereoscopic 3D* support to a game by implementing a corresponding third-party plugin, which offered a *Side-by-Side 3D* mode *(SBS3D,* see Figure 74). At that time this plugin easily created a two-camera setup for *SBS3D* rendering that most *3D TVs* and *Projectors* can turn into a *3D Stereoscopic* image.

Although it was relatively trivial to render the three-dimensional parts of the game in *SBS3D* mode, fixing two-dimensional *GUI* elements to properly work in this setup was not. Especially the relatively complex *HUD*, providing information on player health and the mini map etc., was important to the gameplay. So, to avoid re-developing features, a practical implementation was needed to adapt a greater part of the *GUI* to the *Stereoscopic Vision* setup. The solution was to render the *HUD* into a render texture and place that onto a semi-transparent plane in front of the camera. Nevertheless, this trade-off resulted in needing to disable some features (e.g. the mini map and enemy health bars), as they were not easily transferrable to this approach. For more details see *Appendix C.2.1 Spatialized HUD* from page 246ff.

4.2.2.3 LizzE v2B

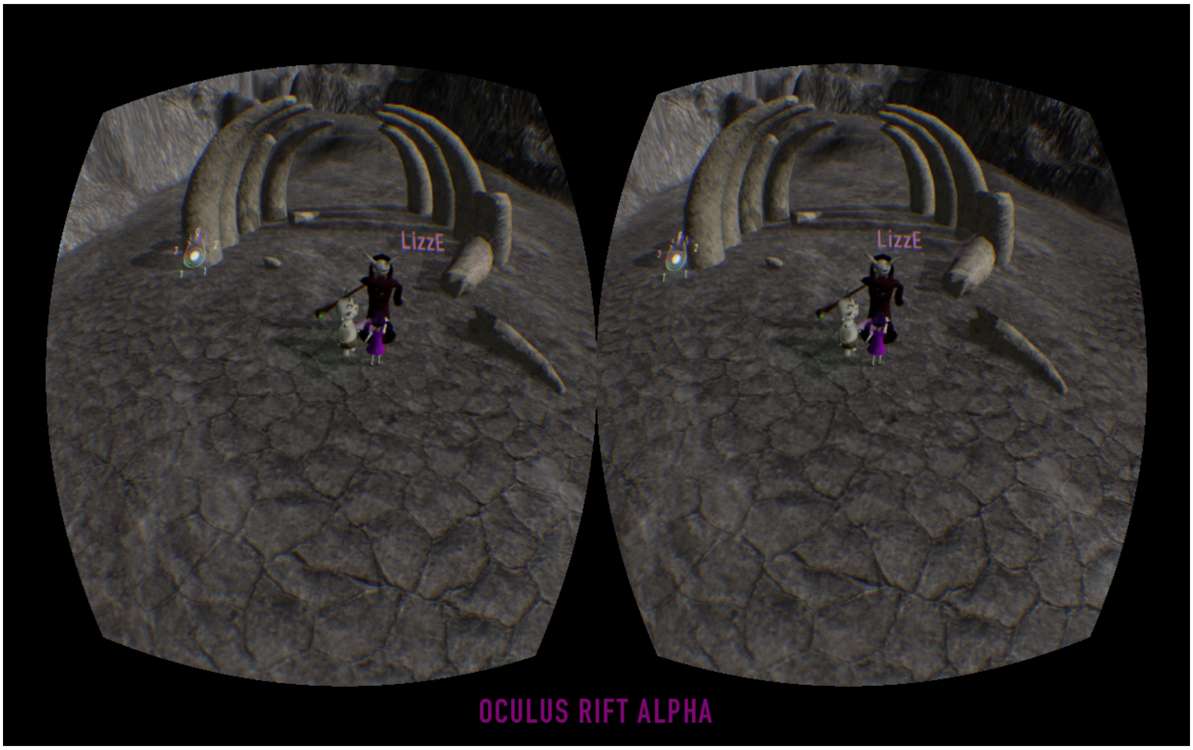


Figure 75: LizzE v2B: First attempt in adding VR support to LizzE

LizzE v2B (see Figure 75) was developed parallel to v2A and was my first attempt in adding *VR* support to a game using the *Oculus DK1* (see *Appendix B.2.1* on page 218). At the time of this writing, *3rd Person VR* games are rather exotic, which was even more so during the development of v2B.

Though by no means optimized, this version already provided several different camera behavior modes, which could simply be cycled through via a hot key. These included first versions of the *Fast, Lazy* and *No Circling* modes (see section *Camera Behavior Modes* for more details on optimized implementations from page 115ff.), as well as a *Stereoscopic Only* mode that completely disabled head tracking and used the *DK1* just for displaying.

At that time, the importance of design and development focusing on minimizing *Simulator Sickness*, was not as apparent. It was also not as clear that very high frame rates are one key aspect to achieving this. The mostly short play testing sessions with v2B during *Showroom* demos (see from page 113ff.) did not uncover this issue. Thus, v2B was not particularly optimized in terms of performance and ran with around 30 FPS.

In contrast, cycling through the available camera behavior modes, an immediate negative impact on *Simulator Sickness* could easily be recognized. The *Stereoscopic Only* mode caused nausea in users very quickly, which made it unusable. Additionally, it became clear, that *Simulator Sickness* increased with the speed of circling around the character, but that no circling at all did not support the freely explorable level design of a game like *LizzE.* Furthermore, people's individual sensitivity to *Simulator Sickness* in general varied greatly from "None at all" to "I need to take the headset off right now".

Implementing *VR* with the *Oculus SDK* in v2B was similar to implementing *Stereoscopic 3D* in v2A. Adding the basic functionality was rather trivial, whereas the *GUI* issues were basically the same as in v2A, due to the two-camera setup. In turn, the same trade-off solution from v2A (see page 108) was applied in v2B, which required disabling some features like enemy health bars and the mini map. For more details see *Appendix C.2.1 Spatialized HUD* from page 246ff.

"Vrifying" this *3rd Person* game in v2B uncovered another interesting effect, which I named the *"Entity Split"* (Wiedemann et al. 2017). It is concerned with switching from directly identifying with the playable character to separating oneself as an independent entity from the playable character. Because, "Without looking through a viewport and seeing what surrounds the screen, but instead feeling completely encapsulated in the virtual world and in natural control of the camera(s), the player acknowledges her or himself as a distinct entity." (Wiedemann et al. 2017).

4.2.2.4 LizzE v3 (Experiment Version)

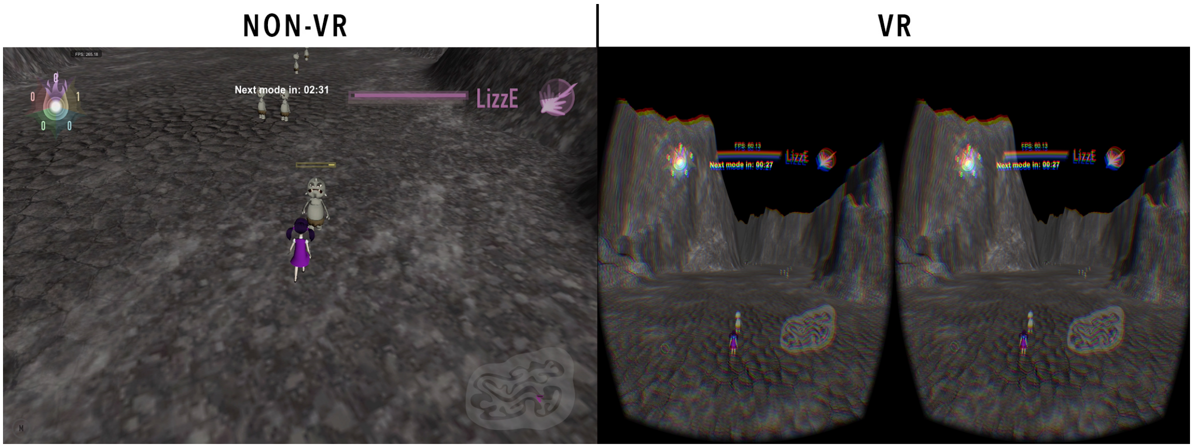


Figure 76: LizzE v3: Screenshots of LizzE – And the Light of Dreams,
Non-VR version (left) and VR version (right) (Wiedemann et al. 2016)

LizzE v3 was specifically adjusted and optimized for the *Lab* experiment on *Virtual Reality 3rd Person Camera Behavior Modes* (see from page 114ff.) using the *Oculus DK2* (see *Appendix B.2.2* on page 218).

At this point, it was clear that achieving a high framerate was crucial to minimizing *Simulator Sickness.* Nevertheless, even though the *DK2* could support up to 75 Hz, the game was optimized to run at 60 FPS. Running the game at this framerate was a technical requirement, so it could be mirrored to a separate screen and thus the experiment participant's gameplay could be recorded and analyzed.

The performance relevant optimizations were mostly leaning on insights from developing for mobile platforms and included: simplifying and reducing the number of terrain textures, removing initially distributed collectable *Light of Dream* objects and respective light sources, optimizing the level of distance rendering parameters and removing for the experiment unneeded elements like physics *Collider*-based audio effects and realtime lighting.

Nevertheless, this was an act of balance as the original look and feel of the game should be retained, it should steadily run above 60 FPS and the whole process should not require massive redevelopments.

In a second attempt, the mini map feature could be revived. Nevertheless, the enemy health bars stayed disabled in *VR,* as they would have needed to be completely redeveloped.

Another issue was concerned with the *Level of Detail (LOD)* adjustment of *Unity's* terrain system. Due to using two slightly differently positioned cameras for *Stereoscopic 3D Vision,* it was possible that one eye was presented a different *LOD* version of the terrain then the other one. As this problem could not be easily fixed and because it rarely occurred at all and only for a short period of time, it was ignored. Nevertheless, it is clear, that this behavior could cause eye strain and definitely should be fixed for a commercial application.

Furthermore, in v3 the existing *3rd Person* camera behavior modes were adjusted based on the insights from v2B, the rather unusable *Stereoscopic Only* mode was removed, and the two new modes *Blink Circling* and *Buffered Pulling* were added as further alternatives. For more details see section *Camera Behavior Modes* from page 115ff.

Finally, the whole application was redesigned for the use in an experiment. Hence, unneeded menus and functionality were hidden or disabled, and a clear and comprehensible procedure was added, guiding the participants through the whole experiment.

4.2.3 STUDIES

As part of the *CDR* approach, the following section will elaborate on the various studies conducted with *LizzE.* The public and informal *Showroom* demos are presented, providing an outline of the events which greatly helped exploring different interface routes and iterating the design of the game. Finally, the *Lab* experiment conducted with the game illustrates the scientific investigation of *Virtual Reality 3rd Person Camera Behavior Modes* (see from page 114ff.).

4.2.3.1 Showroom Demos

During three different *CDR Showroom* presentation events (see timeline in Figure 27), *LizzE – And the Light of Dreams* was presented to approximately 350 people with different ages, genders and backgrounds including around 50 active play testers, whose informal feedback significantly influenced adjusting and designing various aspects of the game.

4.2.3.1.1 MULTICLASH IV

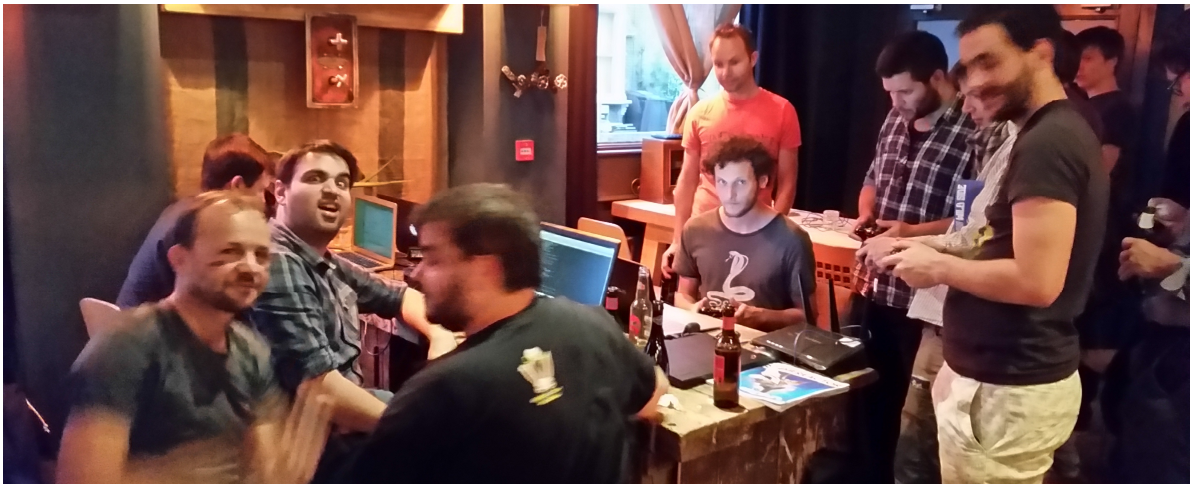


Figure 77: MULTICLASH IV (Meetup 2014)

Held in June 2014, during the *MULTICLASH IV Meetup* event in *London* (see Figure 77) I was able to present *LizzE* v2A in *Stereoscopic 3D,* by installing the *Panasonic PT-AT6000E 3D Projector* and providing four pairs of *3D Shutter Glasses.* From a general audience of around 50 people, mostly coming from the game development scene, around 20 of them actively play tested the game and provided informal feedback. The *3D* effect was immediate and mostly perceived as pleasant, especially by those who liked to watch *3D* movies in cinemas.

4.2.3.1.2 VR Night: Virtual Indie-ality

Figure 78: VR Night: Virtual Indie-ality

The *VR Night Meetup* event in *London* (see Figure 78), held in June 2014, provided over 100 participants, of which around 15 actively play tested *LizzE* v2B. *Gooze* v1 was also presented at the same event (see page 145). Although mostly coming from the game development scene, the audience also included simply *VR* interested visitors. All other *VR* demos at this event were providing some forms of *1st Person* experience. Hence, being the only *3rd Person VR* game, *LizzE* received great attention. During the play testing sessions, first insights were acquired on how the different available camera behavior modes were accepted by users and feedback was given on what worked well and what did not.

4.2.3.1.3 Super Warehouse Gaming Party

Figure 79: Super Warehouse Gaming Party overview (@Kris and the team 2014)

Figure 80: Super Warehouse Gaming Party LizzE stand (@NintendoGBR 2014)

The *Super Warehouse Gaming Party* in *London* (see Figure 79 and Figure 80) was a paid entrance event held in September 2014, during which I could present *LizzE* v2B. It combined partying and indie and retro gaming and provided several hundred visitors. Most of the audience had a general affinity for gaming and even a background in game development.

Around 15 play testing sessions confirmed most of the previously gathered insights on the *3rd Person* camera behavior modes of *LizzE* v2B and additionally provided further feedback.

4.2.3.2 Lab Experiment: Virtual Reality 3rd Person Camera Behavior Modes

Figure 81: LizzE experiment setup

VR games in *3rd Person Perspective* offer great opportunities for gameplay but designing and implementing a camera behavior which feels good for a majority of players and supports the game design is a challenge. In turn, the following corresponding *CDR Lab* experiment on *Virtual Reality 3rd Person Camera Behavior Modes* was conducted in *Munich* in May 2016 with 33 participants using *LizzE – And the Light of Dreams* v3 as a platform.

> " When conceiving a *Virtual Reality (VR)* game, one might quickly think of digital games in *1st Person Perspective* because of the fundamental properties of *VR Head Mounted Display (HMD)* technologies. At this point the essential properties focus on translating the natural movement and rotation of the human head into the application. But *VR* games offer more than just the ability to intuitively move the head of the playable main game character. Among other possible game genres, *3rd Person Perspective* games bring up interesting gameplay and design opportunities (e.g. having to look around a corner for the main character or various forms of communication between characters and the player entity/the stereo camera rig). However, *3rd Person Perspective VR* also poses significant challenges in terms of camera behavior. The critical need to avoid nausea or *Simulator Sickness* opposes most formerly traditional techniques of moving the camera in relation to the main character. Getting the camera movement and rotation right (Hurd and Bettner 2014) for the majority of players is crucial for engaging them in the game and prolonging play in the *Virtual Environment.* This becomes even more important when developing games for *VR,* as people tend to experience nausea more quickly and with increased intensity when wearing an *HMD.* For these reasons [I] wanted to explore the question: **"In which ways can *3rd Person VR* games work for a broad audience?"**
>
> To evaluate different camera behavior approaches in *3rd Person VR* in a "lifelike" manner, [I] decided to utilize a realistic use case. As complete source code access was a requirement, [I] chose *LizzE – And the Light of Dreams* as [the] primary game platform (see Figure 76) (FIERY THINGS 2013). To provide reliable and reproducible results in terms of damage points inflicted by attacks, [I] modified this *Hack and Slay* game to resign of any corresponding random range behaviors.
>
> For *VR* applications, it is important to provide a high and steady frame rate. By removing some effects and lowering the default rendering quality, [I] achieved steady 60 FPS *[Frames per Second]* in *VR* mode, with enough buffer to cope with any possible spikes in performance usage. Though relatively low at this point *(Oculus* recommends 90 FPS for their … *CV1 HMD),* this frame rate also made screen mirroring and thus the parallel video recording of the user and the game possible for [the] experiment setting. Furthermore, the camera behavior modes [I] wanted to explore in this experiment, should be level design independent and only relying on their algorithms and not manually placed waypoints or similar strategies. Hence, the relatively unrestricted, in all directions explorable level design was kept for the user test as is.
>
> (Wiedemann et al. 2016)

4.2.3.2.1 Camera Behavior Modes

> " All tested camera behavior modes are level independent and thus only relying on their individual algorithm. Due to the nature of the game *LizzE – And the Light of Dreams,* a reduction of depth animation, as described

by Schild et al. (2014) was not feasible.

The following illustrations and visualizations will describe the different modes on the X-Z coordinate plane.

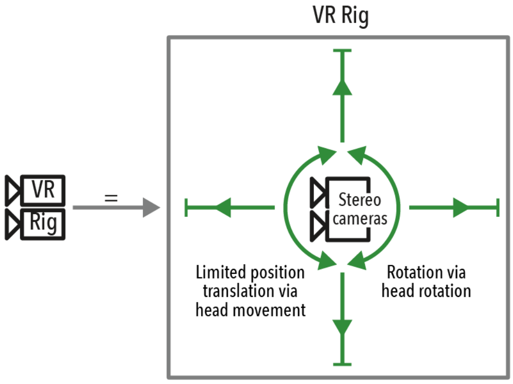


Figure 82: Explanation of VR Rig symbol

To simplify visualizations, a *VR Rig* symbol was used, which stands for two cameras that render a *stereoscopic* and for *VR* optimized image to the screen (see Figure 82). The *VR Rig* also generally supports and handles 360° X-Y-Z head rotation and X-Y-Z head position translation (limited by the *DK2's* position tracking camera's frustum and distance). The playable main character is symbolized by the *Char* figure and looks into the direction its arrow is pointing to on the X-Z plane.

(Wiedemann et al. 2016)

4.2.3.2.1.1 Mode A: Fast Circling

“

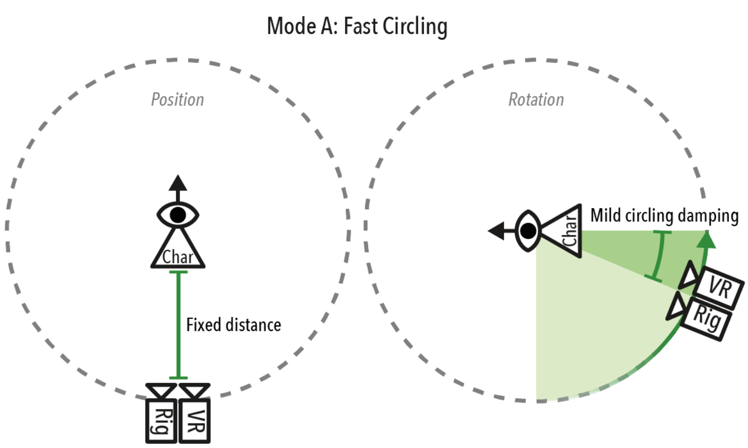


Figure 83: Mode A: Fast Circling visualization

Fast Circling, which is also the default camera behavior mode of the original *Non-VR* game, is based on *Unity's* standard asset *ThirdPersonCamera* controller from 2013. The *VR Rig* is attached to the main character in a fixed distance. Moving the character into any direction immediately pulls or pushes the *VR Rig* with it. Turning the character will quickly circle the *VR Rig* in an animated way behind the character

again with a mild damping (see Figure 83).
(Wiedemann et al. 2016)

4.2.3.2.1.2 Mode B: Lazy Circling

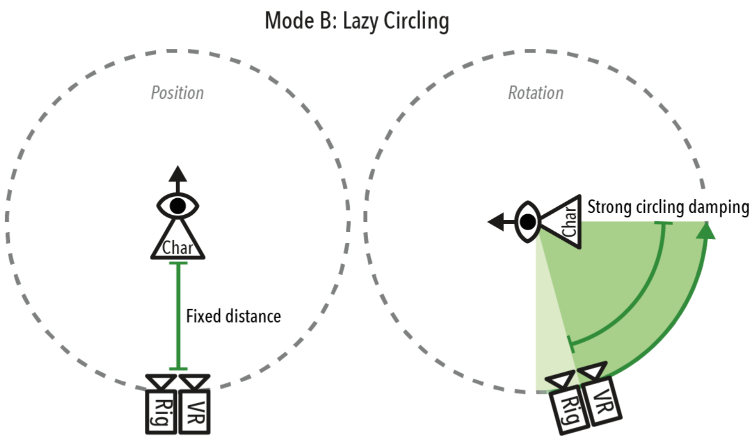


Figure 84: Mode B: Lazy Circling visualization

Lazy Circling uses the same algorithm as *Fast Circling*, only with partly different parameters. When rotating the character, the *VR Rig* circles slowly behind the character again. This is accomplished by adjusting the parameters *angularSmoothLag* from 0.2f *(Fast Circling)* to 2.8f and *angularMaxSpeed* from 100f *(Fast Circling)* to 18f. This results in a clearly stronger circling damping (see Figure 84).
(Wiedemann et al. 2016)

4.2.3.2.1.3 Mode C: No Circling

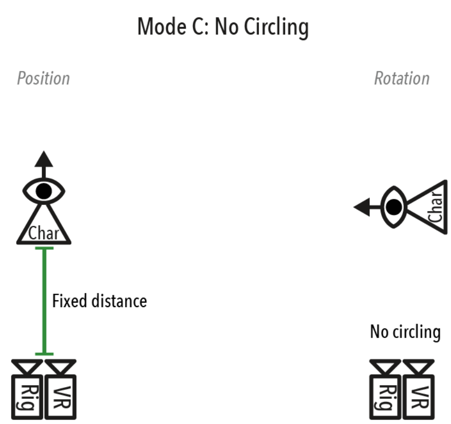


Figure 85: Mode C: No Circling visualization

No Circling has the same fixed distance and position translation behavior to the main character as modes *A* and *B* do. The difference is the *VR Rig* does not circle around it, when turning the character (see Figure 85).
(Wiedemann et al. 2016)

4.2.3.2.1.4 Mode D: Blink Circling

“

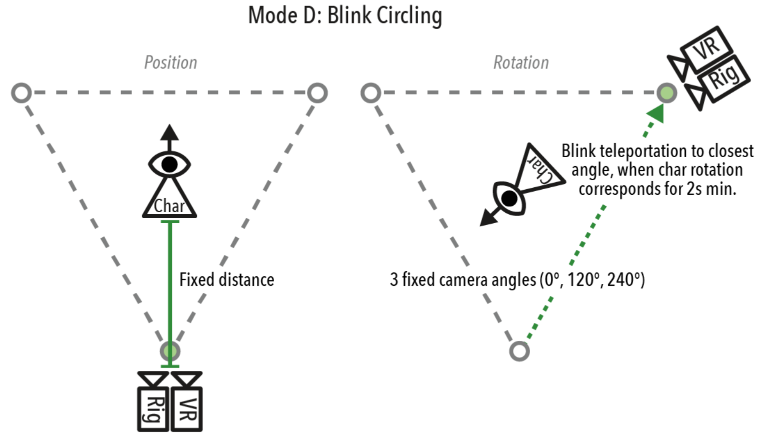


Figure 86: Mode D: Blink Circling visualization

Blink Circling as the modes *A*, *B* and *C* keeps the same fixed distance and position translation behavior to the main character. The circling is restricted to three evenly distributed and fixed camera angles around the main character at 0°, 120° and 240°. When turning the character, no immediate circling is performed. Only after the character's rotation corresponds to a new angle for more than 2 seconds a blink will be performed. In a blinking manner, the screen will very quickly fade to black. Then the *VR Rig* will be teleported in a non-animated way to the corresponding position and turned in the corresponding direction (see Figure 86). Afterwards the screen will very quickly fade back to the game environment. The complete duration of this process takes 0.25 seconds and feels very much like a blink.

(Wiedemann et al. 2016)

4.2.3.2.1.5 Mode E: Buffered Pulling

“

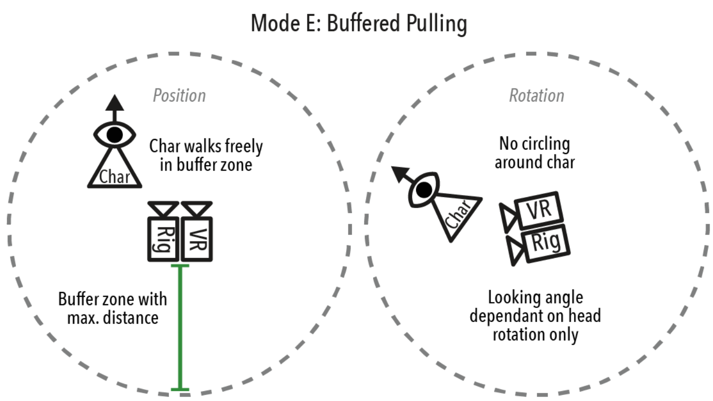


Figure 87: Mode E: Buffered Pulling visualization

Buffered Pulling uses a very different approach. The character does not keep a fixed distance to the *VR Rig* *but* can instead walk freely inside a buffer zone around the *VR Rig* without pulling or pushing it. Once the

> character reaches the border of the buffer zone, the *VR Rig* will get pulled with it, like on a leash. Turning the character has no effect at all on the rotation of the *VR Rig.* The user needs to physically turn (e.g. preferred in a swivel chair or standing), in order to look at the character, when it walks into a very different direction (see Figure 87).
> (Wiedemann et al. 2016)

4.2.3.2.2 Experiment Methodology

> “ The experiment hardware setting consisted of one *Apple MacBook Pro* (Mid 2012) with 2.6 GHz *Intel Core i7 CPU,* 16 GB *RAM* and *NVIDIA GeForce GT 650M* graphics card. As the primary input device [I] used a *Microsoft Xbox 360* controller and for the *HMD* the *Oculus Rift Developer Kit 2 (DK2)* and corresponding position tracking camera. The experiment software was using the *Oculus Runtime* and *SDK* for *OS X* v0.5.0.1-beta and was running on *OS X* v10.11.5. Furthermore were all user test sessions video recorded with a common video camera.
>
> The subjects were verbally and textually informed of possible health and safety issues, as well as the ethical usage of their data in the context of this research. By filling out the first part of a questionnaire, the participants agreed to the experiment terms and provided basic information about themselves and their experience with digital games and *VR.*
>
> The main goal for the subjects was communicated as eliminating as many enemies as possible, while themselves maintaining as much health as possible (see Figure 88). Furthermore, it was made clear that for experimental reasons, the participants could not die in game.

Figure 88: LizzE experiment application's first screen

The procedure of the user test is explained to users as following: The experiment will go through six different modes. Each will last for 3.5 minutes and reset the game automatically afterwards, resulting in a total session duration of ~21 minutes.

The first mode will be *Non-VR* and use the default camera behavior, so subjects can make themselves familiar with the original game first. Subsequently the five different camera behaviors will be tested in *VR*. The order of these modes will be pseudo random after a Latin square sequence for each participant. Between each mode, users are presented a screen showing the identifying character and title of the mode about to start (e.g. *"Mode A: Fast Circling")*. Additionally, while playing, a countdown is visible, showing the remaining time of the current mode. Once all modes are finished, participants take off the *HMD* and are presented with the session specific order of the modes. This helped the subjects remind themselves when filling out the remainder of the questionnaire. …

In the questionnaire, subjects were asked about all *VR* modes on a 7-point Likert scale if they enjoyed e.g. *"Mode A: Fast Circling"* and in a separate question if it supported their gameplay. Furthermore, they had to directly specify their preferred mode for the game *LizzE – And the Light of Dreams* and their *Preference* "in general". Two free text questions asked about "How did certain *VR* camera behaviors affect the way you played the game?" and "Any thoughts about the different *VR* camera behaviors?". Finally, subjects were asked "Did you feel any nausea during the test, or right afterwards?" on a scale from 0 to 10. Due to the experiment design, nausea could not be ranked separate for each mode directly. This and the availability of previous data on a scale from 0 to 10 resulted in using this simpler nausea evaluation, compared to using the more complex *Simulator Sickness Questionnaire* (Kennedy et al. 1993).

Additionally, participants and their gameplay were video recorded during their session to capture any verbal remarks and gaming behavior.

Furthermore, aside from the mode order, the experiment application tracked the following in-game parameters for each session per mode: *Dealt Damage*, *Lost Health*, *Dealt Damage/Lost Health Ratio*, *Kills*, *Pseudo Deaths and Kills/Pseudo Deaths Ratio* [see *Appendix D.1 XML Excel Export of In-Game Parameters* from page 257ff.]. From this data the following variables were extrapolated: *1st Best VR Mode in Dealt Damage/Lost Health*, *2nd Best VR Mode in Dealt Damage/Lost Health*, *Worst VR Mode in Dealt Damage/Lost Health*, *1st Best VR Mode in Kills/Pseudo Deaths*, *2nd Best VR Mode in Kills/Pseudo Deaths* and *Worst VR Mode in Kills/Pseudo Deaths.*
(Wiedemann et al. 2016)

For a video outlining the experiment procedure, the different camera behavior modes and a selection of edited recordings of participant sessions see *Appendices F.2.3* and *F.2.4* on page 265.

4.2.3.2.3 Experiment Results

“ The experiment was conducted with 33 participants (total n = 33), from which 23 were male and 10 were female. Ages ranged from 26 to 76 years and averaged at 31 years. According to the statement “I am an experienced digital game player”, 19 were rather inexperienced (< 4 on 7-point Likert scale) and 14 rather experienced (>= 4) subjects, with a mean of 3.39. Rather little experience with *VR* noted 27 (< 4 on 7-point Likert scale) and rather more experience with *VR* only 6 (>= 4) of the participants, with a mean of 2.33. 17 subjects noted, they were playing digital games between “less than once a year” and “once every some months”, whereas 16 noted they would play digital games between “once a month” and “every day”.
(Wiedemann et al. 2016)

4.2.3.2.3.1 Preferences

“

	LizzE	In general
Mode A: Fast Circling	30.3% (10)	24.2% (8)
Mode B: Lazy Circling	18.2% (6)	18.2% (6)
Mode C: No Circling	9.1% (3)	18.2% (6)
Mode D: Blink Circling	15.2% (5)	15.2% (5)
Mode E: Buffered Pulling	27.3% (9)	24.2% (8)

Table 3: Directly chosen camera behavior Mode Preference

Two *Chi-Square Goodness-of-Fit* tests (Laerd Statistics 2015a and 2015b) were conducted to determine whether an equal number of participants would choose either *Mode A*, *B*, *C*, *D* or *E* as their *LizzE* specific and general *Preference.* The minimum expected frequency was 6.6 in both cases. The *Chi-Square Goodness-of-Fit* tests indicated that the distributions of *Mode Preference* by participants in this study were not statistically significantly different (*LizzE* specific: $\chi^2(4) = 5.030$, $p = .284$, general: $\chi^2(4) = 1.091$, $p = .896$).

Two additional *Chi-Square* tests were conducted with combined data of *Mode A + B*, because of their similarity and *Mode C*, *D* and *E* against a distribution of equal proportions for *LizzE* specific and general *Preference*. The minimum expected frequency was 8.3 in both cases, due to the reduction from 4 to 3 degrees of freedom. In the case of *LizzE* specific *Preference*, the *Chi-Square Goodness-of-Fit* test indicated that the distribution of *Mode Preference* in this study (with combined *Mode A + B* data) was statistically significantly different ($\chi^2(3) = 11.970$, $p = .007$). In the case of general *Preference*, the *Chi-Square Goodness-of-Fit* test indicated that the distribution of *Mode Preference* in this study (with combined *Mode A + B* data) was not statistically significantly different ($\chi^2(3) = 5.909$, $p = .116$).
(Wiedemann et al. 2016)

“ The answers to the direct question “Which *VR* camera behavior did you prefer (specific for the game *LizzE)?*” ranked *Mode A: Fast circling* on the first place with 30.3% and *Mode E: Buffered pulling* on the second place with 27.3%. Whereas the answers to the direct question “Which *VR* camera behavior did you prefer (in general)?” ranked *Mode A* and *E* together on the first place with 24.2%. As will be described later on, these results need to be interpreted with great care though. For a full comparison of the answers to these two questions see Table 3.
(Wiedemann et al. 2016)

4.2.3.2.3.2 Player Enjoyment & Support of Gameplay

“

	Enjoyment	*Support of Gameplay*
Mode A: Fast Circling	3.15 ± 1.906	3.90 ± 1.860
Mode B: Lazy Circling	4.09 ± 1.627	4.15 ± 1.482
Mode C: No Circling	3.64 ± 1.966	3.15 ± 1.679
Mode D: Blink Circling	3.73 ± 1.825	3.61 ± 1.580
Mode E: Buffered Pulling	4.48 ± 1.805	4.27 ± 1.663

Table 4: Means ± [SD] of camera behavior mode Enjoyment and Support of Gameplay on a 7-point Likert scale

A *One-Way Repeated Measures ANOVA* (Laerd Statistics 2015a and 2015c) was conducted to determine whether there were statistically significant differences in *Enjoyment* between the five different modes.
(Wiedemann et al. 2016)

As with the statistical treatment in the previous study, a normal distribution of the data is required for this test and a numerical and objective analysis of skewness and kurtosis was performed (Laerd Statistics 2015g, see *Appendices A.57* and *A.106* on pages 204 and 209 for a description of these terms). Corresponding z-values are acquired by dividing the skewness/kurtosis values by their *Standard Errors (SEs).* If these are within the conservative threshold of ± 2.58 (corresponds to significance level of 0.01), the data can be regarded as normally distributed (Laerd Statistics 2015g).

> “ There were no outliers and the data was normally distributed, as assessed by boxplot and skewness and kurtosis analysis, respectively. *Enjoyment* scores were normally distributed for *Mode A* with a skewness of .433 (SE = .409) and kurtosis of -1.354 (SE = .798), for *Mode B* with a skewness of -.202 (SE = .409) and kurtosis of -.946 (SE = .798), for *Mode C* with a skewness of .125 (SE = .409) and kurtosis of -1.185 (SE = .798), for *Mode D* with a skewness of -.094 (SE = .409) and kurtosis of -1.118 (SE = .798) and for *Mode E* with a skewness of -.687 (SE = .409) and kurtosis of -.679 (SE = .798). *Mauchly's* test of sphericity indicated that the assumption of sphericity had not been violated, $\chi^2(9) = 8.347$, $p = .50$. *Enjoyment* scores were statistically significantly different between the different modes, $F(4, 128) = 2.725$, $p = .032$, partial $\eta^2 = .078$ and partial $\omega^2 = .040$.
>
> Another *One-Way Repeated Measures ANOVA* (Laerd Statistics 2015a and 2015c) was conducted to determine whether there were statistically significant differences in *Support of Gameplay* between the five different modes. There were no outliers and the data was normally distributed, as assessed by boxplot and skewness and kurtosis analysis, respectively. *Support of Gameplay* scores were normally distributed for *Mode A* with a skewness of -.138 (SE = .409) and kurtosis of -1.604 (SE = .798), for *Mode B* with a skewness of -.645 (SE = .409) and kurtosis of -.459 (SE = .798), for *Mode C* with a skewness of .463 (SE = .409) and kurtosis of -.674 (SE = .798), for *Mode D* with a skewness of .248 (SE = .409) and kurtosis of -.422 (SE = .798) and for *Mode E* with a skewness of -.160 (SE = .409) and kurtosis of -.627 (SE = .798). *Mauchly's* test of sphericity indicated that the assumption of sphericity had not been violated, $\chi^2(9) = 12.550$, $p = .185$. The analysis could not lead to any statistically significant changes in *Support for Gameplay* scores between the different modes, $F(4, 128) = 2.417$, $p = .052$, partial $\eta^2 = .070$ and partial $\omega^2 = .033$.
>
> (Wiedemann et al. 2016)

4.2.3.2.3.3 Combined Results

> “ Though *Fast Circling* was ranked very high as a directly chosen *Preference*, it scored last rank with a mean of 3.15 on a 7-point Likert scale, when asked if participants actually enjoyed using it. Some subjects specifically noted increased *Simulator Sickness*, the need for heavy concentration, the need to actually close the eyes while circling and avoidance of rotation altogether. Furthermore, one participant had to completely discontinue the experiment while playing in *Fast Circling.* Other subjects described it with the following words: “extremely nauseating, after this mode all other modes were affected” [P09, participant ID], “is nearly impossible to play for a longer time (motion sickness).” [P14], “very unpleasant.” [P03] and “was 'too fast' / confusing for an inexperienced player” [P27]. Only four participants noted something positive for this behavior mode, mostly because it was similar to traditional *Non-VR* behavior. *Fast Circling* was also clearly ranked last in in-game *Performance* when comparing the *Dealt Damage/Lost Health Ratios* (by 42.42%) and

Kills/Pseudo Deaths Ratios (by 36.36%).

Lazy Circling ranked better than *Fast Circling* in terms of *Enjoyment* (mean of 4.09) and *Support of Gameplay* (mean of 4.15). Though some described it as pleasant, still similar sometimes strongly nauseating effects were observable during other user sessions. One subject described it with the following words: "I didn't like *Lazy Circling* and I see no use for this mode, especially while playing a fast game like hack&slay" [P05].

The data shows that participants with *VR* experience (>= 4 in 7-point Likert scale; n = 6) were more likely to directly choose *Fast* or *Lazy Circling* as *Preference* for *LizzE* (83.33%) and in general (66.66%). The same is true, when looking at the direct choice of *Preference* for *LizzE* (64.29%) of participants with gaming experience (>= 4 in 7-point Likert scale; n = 14).

In the context of an, in all directions freely explorable level, *No Circling* understandably ranked last in *Support of Gameplay* (mean of 3.15). Subjects mention the uselessness of this mode when in need of turning, because of the level design: "made it nearly impossible to play the game properly, because you can't always see the enemies / bullets" [P14], "I was a bit lost in no circling camera view because I couldn't see the way. So I tried more to focus [on] the way than on the enemy." [P21], *"Mode C* is unplayable" [P29] and "bad for orientation. Couldn't see the enemy." [P21].

Blink Circling leads the ranking in in-game *Performance.* With 27.27% each, it scored the best and second best rank in *Dealt Damage/Lost Health Ratios* and with 36.36% the best rank in *Kills/Pseudo Deaths Ratios.* Opinions about this mode were mixed: *"Blink Circling* was most comfortable as I didn't feel dizzy." [P04] and *"Blink Circling* was the most comfortable" [P23]. But subjects also mentioned disorientation through blinking, the need for heavy concentration and blinks feeling too random: "seemed more like a handicap to me, because it seemed to happen randomly" [P18], "The blinking-mode was ok at some spots but worst at others." [P12], "I did not like and understand the *Blink Circling* because it didn't feel natural to me. The game just forced a different camera angle on me, abruptly." [P13], "spontaneously switching the point of view. That was absolutely weird." [P24] and *"Blink Circling* very abrupt, unexpected change of view" [P26]. Because of the orientation problems, it does not come unexpected that *Blink Circling* ranked second last in *Support of Gameplay* (mean of 3.6), one rank above *No Circling.*

Buffered Pulling clearly scored first ranks in *Player Enjoyment* with a mean of 4.48, as well as *Support of Gameplay* with a mean of 4.27. Most participants mention their delight about the need to physically turn. Participants mostly described this camera behavior mode as very pleasant and really enjoyable. Some furthermore noted: "The *Buffered Pulling* mode seemed more intuitive to me" [P18] and *"Buffered Pulling* was the most realistic one" [P23]. The more critical participants mentioned sometimes losing sight of the main character and the inherent issues of physically turning, like pulling cables and the requirement for either a swivel chair or to stand up: "a little obstructive because I ran out of my field of view sometimes" [P07], "Having to stand up and completely turn around to make the camera turn was gameplay wise rather hard to do since I just sat on a couch." [P13], "With *[Mode] E* the gaming experience was different and not so easy." [P25], *"Buffered Pulling* [was] only bad when [the] character is in the center and one has to look downwards." [P26], *"Buffered Pulling* was much more difficult, as I always had to look around to find the character and the cable of the glasses as well as sitting on a [swivel] chair was not optimal." [P04] and "Freedom of movement was limited by the cables." [P19]. In terms of in-game *Performance*, it scored the first rank in second best mode in *Kills/Pseudo Deaths Ratios* with 42.42%. Additionally 44.44% of subjects with stronger nausea (>= 7 on a 0 to 10 scale; n = 9) preferred *Buffered Pulling* specifically for *LizzE.*

For a full comparison of the results in *Enjoyment* and *Support of Gameplay* see Table 4. No gender specific results could be extrapolated.
(Wiedemann et al. 2016)

4.2.3.2.4 Experiment Limitations

The experiment had several limitations. Though it was possible to retrieve some statistically significant results (e.g. on *Enjoyment),* the sample size of 33 is relatively small. This did not permit reliable significance analysis of cross-referenced data (e.g. on gaming or *VR* experience), as sub samples did not provide enough subjects.

The concept of the experiment application and its automated procedure, leading through all five camera behavior modes in succession, intended to provide a *Lab* session with as little influence as possible from the researcher towards the participant. Nevertheless, this resulted in the disadvantage that participants needed to fill out the questionnaire after finishing all five modes. The within-subjects design and the timing for the questionnaire at the end may have possibly affected participants' self-reports. E.g. they may have been influenced by "carry-over" effects, including mixing up or forgetting parts about their different experiences (Greenwald 1976, Price et al. 2017 and Rölfing et al. 2019), as well as "peak-end" effects (Schreiber and Kahneman 2000), which may affect experiential ratings globally per session. This was mitigated though through several means: the individual mode order was supplied at the end as a memory aid for the participant, the provided questionnaire was relatively simple and quickly filled out and the individual mode orders were pseudo randomization after Latin square.

4.2.3.2.5 Experiment Conclusion

" **In which ways can *3^rd^ Person VR* games work for a broad audience?** Though this might be similar for all *VR* applications, to keep a broad audience playing a *3rd Person VR* game, it is essential to eliminate causes for nausea and *Simulator Sickness* as much as possible, while still maintaining an attractive gameplay. Utilizing a well-accepted camera behavior mode in terms of *Enjoyment* and *Support of Gameplay* seems to be one of the most important steps. Conceiving and implementing individual viable solutions still pose significant challenges, but some approaches tested in this study clearly show great potential, whereas others seem incompatible for a broad audience in *VR.*

Though this study could not always elicit statistically significant quantitative data, in combination with the qualitative and observational results [I] extrapolated the following relevant conclusion.

When looking at the experience levels of subjects in gaming and *VR*, [I] argue that *Preferences* to *Fast* and *Lazy Circling* might be related to the already established familiarity to traditional camera techniques used in popular *Non-VR* games like *Super Mario 64* [Nintendo 2020a], *World of Warcraft* [World of Warcraft 2017] and *Banjo-Kazooie* [Nintendo 2020b]. Simple acclimatization with other camera behavior modes over some time might change their opinion.

The *No Circling* approach, though reducing the vection effect, was clearly unusable for a level design that encourages exploration into all directions. A more linear level design like in *Lucky's Tale* (Hurd and Bettner 2014 and Hurd and Reiland 2016) can make it a viable approach though.

In the case of *Blink Circling*, nausea did not seem to be a significant problem compared to other modes, as it drastically reduces the vection effect. Furthermore, it offers a way of playing without requiring a swivel chair or physically standing up. It seems reasonable to expect better acceptance by users of this approach, once players have spent a longer time using it and were getting a better feel for when blinks will occur. As subjects were kept naive about the different camera behavior modes (except for their titles), some sort of explaining visualization and/or subtle tutorial could also help.

In this study, the *Buffered Pulling* approach showed the greatest potential. The vection effect was reduced to a minimum through requiring natural movement (Riecke and Feuereissen 2012) and utilizing the buffer zone. Thus, participants felt little to no nausea. Even though this is not true for all subjects, physically moving delighted the majority of them and increased their feeling of realism and *Presence* (Lombard and Ditton 1997) in the game.

This collection of camera behavior modes is not at all exhaustive, but coming from the gathered findings of this experiment, when developing a *3rd Person VR* game with a freely explorable level design, [I] recommend implementing fine-tuned versions of *Buffered Pulling* (default) and *Blink Circling* (optional). This gives the users the possibility of playing the game either through physical movement or more stationary on a couch for example. Adding some sort of optional *Fast* or *Lazy Circling* mode for traditionalists might be alluring, but a clearly visible warning of highly possible *Simulator Sickness* would be strongly recommended.
(Wiedemann et al. 2016)

4.2.4 DISTINCTIONS

The work on *LizzE – And the Light of Dreams* and the respective research with it, led to the following distinctions.

4.2.4.1 NOISE Festival – Awards

Both, the first version of the game and its animated intro video received *Excellent* awards in the category *Games & New Media* (see *Appendix E.1* on page 261), among others presented by the highly distinguished British game developer *Ian Livingstone CBE* (Livingstone 2014).

4.2.4.2 Game-On'2016 – Best Paper of Conference Award

The corresponding paper to the before-described experiment on *Virtual Reality 3rd Person Camera Behavior Modes* (see from page 114ff.) was awarded with the *Best Paper of Conference* award for the international *Game-On'2016* conference in *Lisbon, Portugal* (see *Appendix E.2* on page 261).

4.2.5 REFLECTIVE DISCOURSE

As part of the *CDR* approach, the following section will reflect more thoroughly on some of the aspects of the artifact's development and its corresponding studies.

Due to its first version having been developed before starting this *PhD* research, *LizzE – And the Light of Dreams* is the game in the portfolio with the largest amount of content and artworks. This provided several advantages and disadvantages. As previously mentioned, I had full access to all elements of the already working game. Hence, I was immediately able to start experimenting with incorporating different novel technologies, like *3D Stereoscopy* and *VR.*

Chronologically being the first artifact of the overall study, it also meant I had little to no experience in these areas. Beginning development from an already working game, also meant I had to work with an, in this case, outdated codebase and programming language (*LizzE* was developed in *Unity Script* and not in the better supported *C#).* Additionally, already implemented features like the *HUD* were hard to properly port to a *stereoscopic* environment. To me, this uncovered how challenging and maybe even inappropriate the *"VRification"* of some *"Former-Non-VR"* games may be (Wiedemann et al. 2017a).

Nevertheless, the rather surprising uncovering of the *Entity Split*, showed the huge potential of *3rd Person VR* games and *VRification* in general.

LizzE as the previously described research project also takes a special place amongst the artifacts in the portfolio. It was not laid-out to be a *VR* game from the beginning, but rather a platform for experimentation and investigation. It very much fulfilled this purpose, being a prototypical *VR* artifact and its experimentations led to an extensive understanding of: *VR* development in general (benefiting all later developments), the potential of *3rd Person VR* and different approaches on how *3rd Person VR* and corresponding camera behaviors can be designed to be attractive and comfortable at the same time.

Regarding the latter, the corresponding *Lab* experiment on *Virtual Reality 3rd Person Camera Behavior Modes* (see from page 114ff.) was conceived through early experimentations and several camera behavior modes naturally evolved when trying to integrate *VR*. Nevertheless, the most successful *Buffered Pulling* approach was conceived only through another iteration of thinking through camera behaviors, because of the preparations for the experiment.

The observed *Entity Split*, taking place when *vrifying* a *3rd Person* game (Wiedemann et al. 2017a), clearly affects the player's *Rollenwahrnehmung:*

> In the game's *Non-VR* version, the player looks through the screen into the game world and [mostly] identifies her or himself with the player character, as she or he controls the character's movement and actions. Playing the *VR* version of the game, the *Entity Split* becomes perceptible. Without looking through a viewport and seeing what surrounds the screen, but instead feeling completely encapsulated in the virtual world and in natural control of the camera(s), the player acknowledges her or himself as a distinct entity. Dynamically hovering over the player character, she or he feels more like a god that rather guides the player character than actually identifies with it.
> (Wiedemann et al. 2017)

In turn, this not only means a change in the obvious visual *Perspective,* but also in the metaphorical one.

> [The *Entity Split]* raises lots of gameplay possibilities, like looking around corners, uncovering for the player character unreachable spaces and objects, but also new kinds of communications and interactions between player, player character, *Non-Player Characters (NPCs)* and the game world. Interesting questions arise through this, like for example "Why is it, that I can control character XY?", "Am I perceptible to *NPCs?"* and "Could character XY turn against me at some point?".
> (Wiedemann et al. 2017)

The game's different camera behavior modes also investigated different ways of approaching the visual *Perspective* in *3rd Person VR* and how it should behave to support an attractive gameplay, while at the same time providing a comfortable player experience.

Looking at the *VRification* of *LizzE* in a more general context, adding *VR* support also caused a transformation in the perception of the virtual *Space.* Although not specific to this game alone, this means a fundamental shift from looking through a rather small window into a *VE,* still surrounded by everyday objects in the room, to diving into a completely encompassing virtual experience with little to no reference to the physical world.

4.2.6 CONTRIBUTION TO OVERALL STUDY

The artifact *LizzE,* its various iterations and the *Showroom* and *Lab* investigations provide several contributions to the overall study.

A general know-how for implementing *3D Stereoscopy* and *VR* was established, which benefited the design and development of the other two artifacts *Nicely Dicely* and *Gooze.* Especially designing and integrating *GUI* elements from the ground up for these cases, was heavily supported by the insights gathered with *LizzE.*

The *Showroom* demos resulted in several informal, but nevertheless important and easy to gather understandings on general aspects of the artifact and especially the different *3rd Person* camera behavior modes. The *Lab* experiment, with refined versions of previous camera behavior modes and additional ones, then supported these understandings via a deeper investigation. This led to establishing design guidelines for *3rd Person VR* camera behavior modes, including recommending the *Buffered Pulling* (default) and *Blink Circling* (optional) approaches, based on the experiment's results.

Regarding the investigation of the three guiding key areas, *LizzE* provides its individual take on these. The *Rollenwahrnehmung* is clearly affected by the *Entity Split,* meaning the player does not directly identify anymore with the player character, but instead feels as a separate and independent entity. In turn, not only an obvious change in visual *Perspective* is connected, but also one in the metaphorical sense, which raises new communication and interaction possibilities between player, player character, *NPCs* and the game world. The game's diverse camera behavior modes further approach the visual *Perspective* in *3rd Person VR* in different ways. Furthermore, a general aspect of *VRification* is concerned with the transformation of *Space*, as the look through a small window into a *VE* shifts to an encompassing virtual experience for the user instead.

Finally, the artifact *LizzE* and its documented iterations act as an individual precedent for design, development and research and thus add significant elements to the overall precedent, i.e. the portfolio of artifacts.

4.3 GOOZE

Figure 89: Key visual of Gooze's intro video

For a video presenting the game see *Appendix F.3.2* on page 266.

The following subchapter will outline the concept and the attributes of the artifact *Gooze*, as well as its storyline. Relating to *CDR's Constructive Iterative Cycle*, it will further elaborate on various iterations, which the game went through over its development time. Subsequently, corresponding studies will be illustrated, i.e. an inspirational expedition to a derelict asylum, as well as *CDR* conform *Showroom* demos and a *Lab* experiment. The latter section will elaborate on the experiment's modes, methodology, results and conclusion, regarding the *UX* evaluation of *VR Locomotion* and *Virtual Object Interaction* mechanics. Afterwards, a distinction related to the artifact will be outlined. Finally, as part of the *CDR* approach, a reflective discourse on the artifact will be held and its contribution to the overall study will be summarized.

4.3.1 THE GAME

Gooze is a *1st Person VR* horror game, based on a real derelict asylum (see Figure 89). The experience is about solving puzzles to flee from scary creatures from room to room. The player will not be provided with any weaponry, but instead is required to utilize items in the surrounding to find a way out, while living through a horrifying atmosphere of decay and uncertainty (for an intro video see *Appendix F.3.1* on page 266). In other words, the player needs to grab and inspect interactive objects and use them to solve puzzles. To do that, he or she needs to move through the *VE* and explore the respective surrounding.

The player character is conceived to be as feature-less as possible to act as a blank slate for the player (e.g. character thought subtitles were used instead of voice over samples). So, he or she can fill out this role with his or her own character instead. Thus, the game would supposedly provide a deeper and more individual experience for each player.

Technically *Gooze* uses the *Oculus SDK* for *VR* and provides several input options including gamepad, *Leap Motion* controller, *Oculus Touch* controllers and the *Wizdish ROVR 1 Omnidirectional Treadmill* for *Locomotion.*

4.3.2 STORYLINE

Although no implemented iteration of *Gooze*, discussed in this thesis, included any scary *NPC* entities and detailed story elements, the game's background concept does provide a narrative. It needs to be mentioned though, that neither did the one playable prototype level go beyond teasing story elements, nor were *NPCs* actually implemented in it. Thus, participants of the studies and especially the corresponding *Lab* experiment (see from page 150ff.) did not experience these contemplated elements. Nevertheless, to provide a more exhaustive description of the game, its storyline will be illustrated in the following.

The storyline, as well as the rationale of the game will not be clear to the player from the beginning but will evolve over time and finally will be completely uncovered at the end.

At the start, the player gets dropped into an unknown derelict environment, trapped in a single room. Textual streams of thought hint that he or she needs to find a way out and flee. Objects in the surrounding (e.g. photographs, a diary etc.) give ambiguous indications on what could have happened in this rotten place and what the player's function is in all of this. While trying to figure out what to do, he or she will be visited several times by surreal and frightening creatures. This is supposed to build up pressure in the player to move on quickly, as there is no way of defending oneself against them. As the user tries to flee from room to room, solving various puzzles on the way, it becomes clear, that these creatures while looking somewhat different also share certain visual similarities.

The final clue of the storyline will be revealed in the last room. In it, the player will find a mirror, where he or she can look at him or herself. Instead of seeing a human being though, another similarly looking version of the previous creatures is visible. In the spirit of movies like *Fight Club* (IMDb 1999) and *Identity* (IMDb 2003), this last scene finally gives meaning to the previous endeavors. Eventually, a stream of thought describes the realization that all this time the player character was actually trapped in his or her own rotten mind and that the creatures seen before, were competing multiple identities, which the player was trying to overcome.

4.3.3 ITERATIONS

As part of the *CDR* approach, the following will elaborate on the different iterations of *Gooze*, to provide an overview on the progress the game has made over various design and development phases and to illustrate its corresponding features.

4.3.3.1 Gooze v1

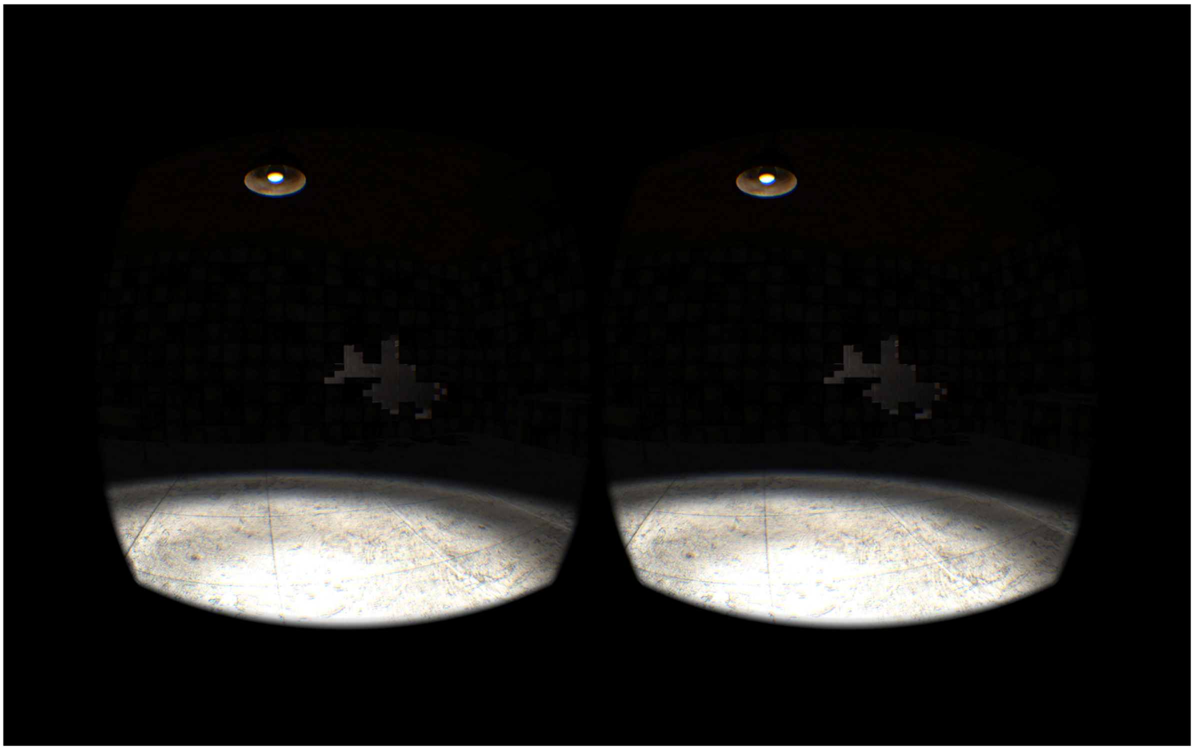


Figure 90: Gooze v1 with early Oculus SDK implementation and gamepad support only

The first version of *Gooze* (see Figure 90) was an initial prototype of a *1st Person VR* experience, to gather basic insights in designing and developing artifacts for *VR* from the ground up. Its basic concept of slowly walking around finite rooms and interacting with objects to solve puzzles, was among other things conceived to explore different available interface technologies in a *1st Person* scenario.

I chose to place the look and feel of the game into the horror genre for several reasons. First of all, very fast paced gaming in *VR* seemed counterproductive in terms of minimizing possible *Simulator Sickness,* which was confirmed by ongoing research. On the other hand, using slow movements rather contributed to the horrifying vision of the game. Secondly, though horror surely is not everyone's taste, the related powerful emotions were likely going to contribute to the feeling of *Presence*. Thirdly, other game developments in the market seemed to head a similar way, e.g. *Grave* (2014), *Slender: The Arrival* (n.d.), *Alien Isolation* (2014) and more recently *Resident Evil 7* (Capcom 2016). Fourthly, personally having an affinity for the genre and some experience with it, supported me to design a more convincing gaming experience. Only further development would more clearly settle the game into its genre. Nevertheless, through its scarce and dim lighting and the derelict texturing, v1 already hinted in this direction, without any audio or surreal creatures yet.

Technically, v1 implemented the *Oculus SDK* for the *DK1*. Because of the *HMD* and the way, the *SDK* handled rendering, the available resolution was quite low (see amount of black space in Figure 90).

Regarding interactions, users were able to navigate the single available room via the analogue stick of a gamepad. When directly looking at the ceiling light, one could give it an invisible nudge with the push of a button. The light would then physically swing around and dynamically lighten the room wherever it currently aimed. The scratched-out polaroid photographs and an empty cup could also be nudged through the room in the same manner. There were no further interactive objects in v1, and it was not possible to actually solve the puzzle and leave the room.

4.3.3.2 Gooze v2

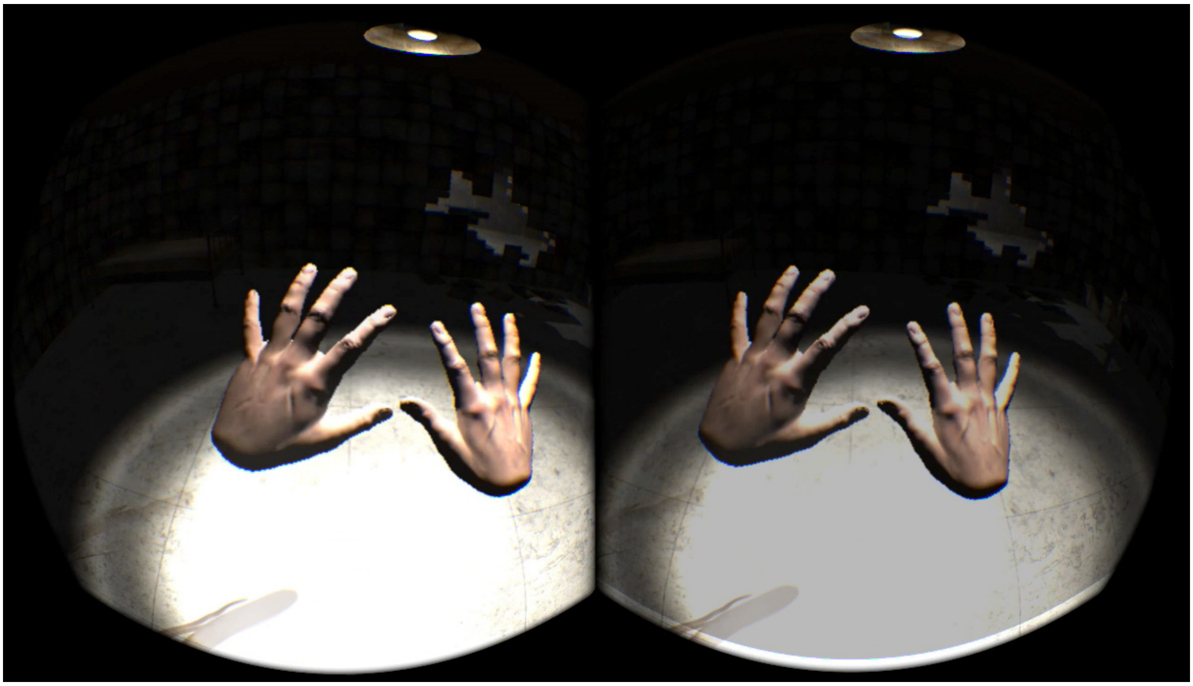


Figure 91: Gooze v2 with updated SDKs of Oculus and Leap Motion for hand and finger tracking

Gooze v2 (see Figure 91) was a huge step forward in terms of the "completeness" of the demo. Of course, this was to advance the corresponding research, but also to submit it to the *Leap Motion 3D Jam* (see page 148). In turn, v2 provided an input interface combining a gamepad with *Controllerless Hand Tracking (CHT)* via the *Leap Motion* controller mounted to the front of the *Oculus DK2.* Although this interface concept arose through utilizing available novel technologies and supported exploring these in more depth, the usability flaws of v2 clearly became apparent during *Showroom* demos. Only technical advances and more thoroughly designed interaction modes within v3 provided truly enjoyable and usable interfaces at the same time.

Nevertheless, the switch from *Oculus DK1* to *DK2* in v2 brought immense improvements, due to offering a higher resolution, a higher refresh rate (75 Hz) and rudimentary desktop aimed positional head tracking. This led to the following changes:

The positional head tracking enabled players to naturally lean their heads in *VR* within certain bounds. This reduced *Simulator Sickness* and at the same time increased *Immersion.*

Short descriptive strings of texts were added in an unobtrusive but readable way, because of the higher resolution. These "thought subtitles" provided subtle hints and thoughts for the user when looking at certain objects (see subtitle in Figure 92), adding a narrative layer to the experience.

Due to the higher resolution in combination with the higher refresh rate and the collected materials from the inspirational expedition to the *Grabowsee Sanatorium* (see from page 143ff.), general adjustments and optimizations of assets and subsystems were made. Among others, these included reworking textures, 3D models and lighting to achieve more high-quality visuals and higher performance, in the majority of situations above 75 FPS. The latter was important, so the part of *Simulator Sickness,* inflicted through technical limitations, could be minimized.

An update of the *Oculus SDK* also generally improved performance and visual quality (a greater part of the screen is used for rendering, see Figure 91). Furthermore, it added the *Synchronous Timewarp* feature (Carmack 2017), which helped to slightly reduce judder by dropped frames.

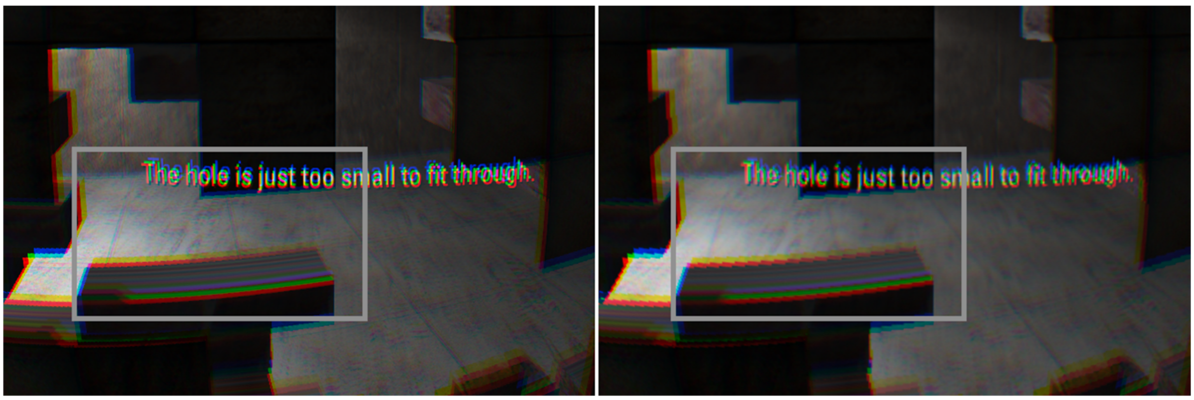


Figure 92: Gooze with render scale factor at 1.0 (max, left) and 0.52 (min, right)

Nevertheless, with the used hardware, it was not possible to eliminate all situations which caused framerates lower than 75 FPS. For that reason, a custom global fallback feature was implemented. It tracked the current framerate and automatically adjusted the render resolution accordingly. In other words, as long as the framerate was below 75 FPS the system would gradually reduce a render scale factor, in turn reducing the actual render resolution (see comparison in Figure 92), until a minimum threshold would be reached, or the framerate would recover above the 75 FPS. If the latter was the case, the system would gradually increase the factor again. So, in performance intensive situations, the system would constantly try to adjust the render resolution. Obviously, this feature was a tradeoff and by itself had a slight performance footprint. Nevertheless, it at least damped the impact of low framerate situations and a conceptually similar feature would later even be included into the official *Oculus SDK.*

Similar to *LizzE* v3 (see from page 110ff.), running the *DK2* at 75 Hz prohibited the application of mirroring its image to another screen on *macOS.* In contrast to *LizzE* v3 though, there was no immediate experimental study planned. Thus, no play sessions needed to be recorded. So, the strategy with *Gooze* v2 was instead to aim for the highest possible quality and the lowest possible *Simulator Sickness,* a *VR* experience could achieve during that time. Obviously, this would complicate presenting the artifact at *Showroom* demos. This could be mitigated though, by verbally guiding play testers during the respective events.

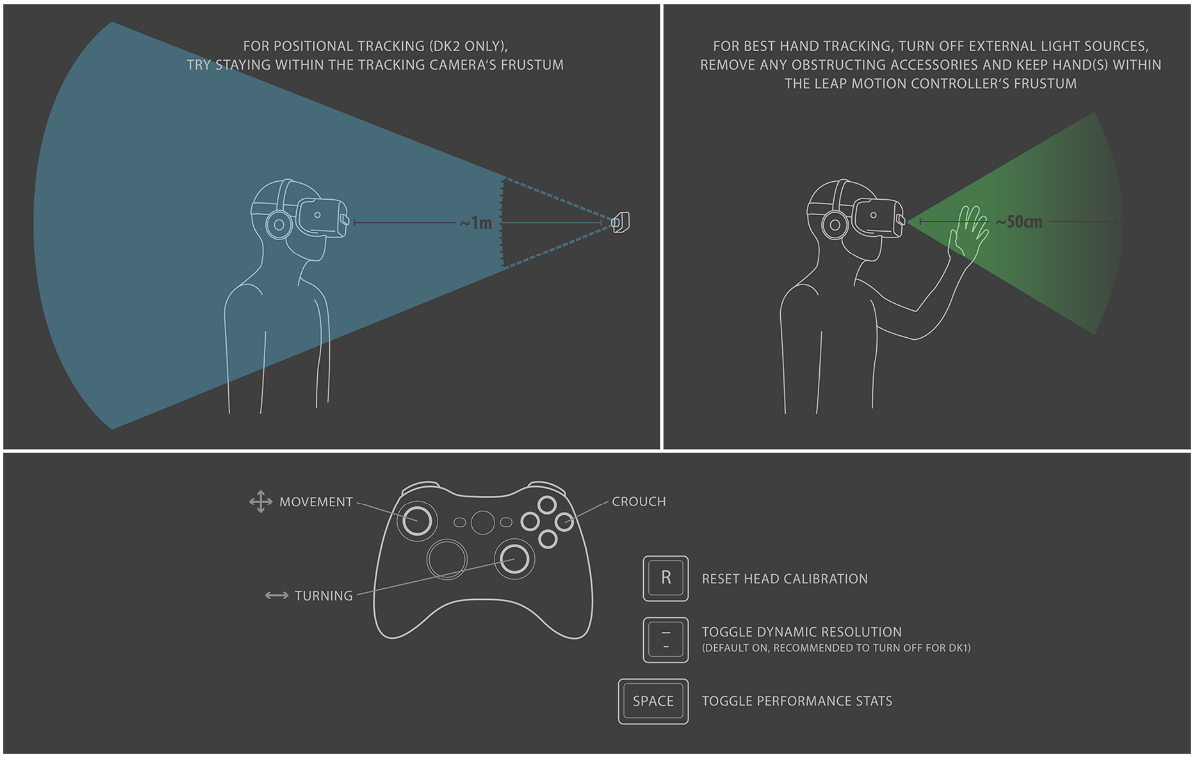


Figure 93: Gooze user guidance on positional tracking, hand tracking and control scheme

Still, v2 also provided proper user guidance within the application, so players would be automatically informed about the technological specifics on the positional head and hand tracking, as well as on the control scheme for the gamepad input (see Figure 93). This was especially important as the game would be independently played by random people during the *Leap Motion 3D Jam* (see page 148), so additional help from the developer side was not possible, like in a real-world situation.

The in v1 previously used mechanic of gazing at an object and pressing a button to perform a push, was completely removed. Figure 93 illustrates the new interface for the player: By using the left analogue stick of the gamepad, one could move through the *VE (Locomotion)* and with the right stick one could gradually rotate. By holding an action button, the virtual character would crouch, so low positioned objects could be reached (e.g. the cup, see Figure 98). This was required, as the positional head tracking of the *DK2* covered only a very limited space and physical crouching would not have been properly tracked.

Regarding *Virtual Object Interaction* within *Gooze* v2, the user could relatively naturally use his or her hands within roughly a ¼ m^3 in front of the body. The physical hands and fingers would be tracked as well as possible and virtual equivalents would behave accordingly. As mentioned before, this was possible by mounting a *Leap Motion* controller to the front of the *HMD* and implementing the *Leap Motion SDK.* Hence, players could interact with virtual objects just by using their hands. This drastically increased *Immersion* and the possibility for *Presence.* An additional custom subsystem made grabbing and carrying objects possible. The system would check the proximity of a hand to an interactive object and the *Grab* and *Pinch* parameter values, provided by *Leap Motion's SDK.* If the parameters would conform to certain thresholds, an object would snap to the respective hand and be posed in a certain predefined way, most fitting to the object. As the hand poses could still be naturally changed within the thresholds, players using this system sometimes created unnatural and crude object to hand poses, which may have resulted in a *Break-in-Presence.* Although these pose combinations were only visual artifacts and did not affect the actual grabbing mechanic, it became clear that a more sophisticated solution would be needed. The idea of using fixed predefined hand and finger poses specific to the grabbed object, eliminating incorrect pose combinations, developed. Although this trade-off solution would mean temporarily limiting absolute control over one's virtual hands, it was implemented in v3 and accepted really well.

Also, work on implementing an equivalent *Virtual Object Interaction* mechanic requiring only a gamepad started during the development of v2, but stayed unfinished until v3, due to its complexity.

Nevertheless, the feature of carrying objects from point A to B did work. Thus, it was finally possible to implement solving the puzzle in *Gooze* v2.

> The solution was to "break off" (grab) a loose bedpost, carry it over to the door with the rusty padlock, "break it apart" (touch it with the bedpost) and open the door (see Figure 98).
> (Wiedemann et al. 2020)

There were several downsides of *Controllerless Hand Tracking* via the *Leap Motion* controller. Some of these were mitigated through *SDK* updates, others would persist even through v3. Most of them were related to the optical *IR* tracking of the *Leap Motion* controller.

E.g. the tracking only worked at all within the relatively limited camera frustum of the device. Hence, when a physical hand would leave the frustum the virtual hand would disappear, causing frustration in users. Even more so, when the hand grabbed an object and thus the object was unintentionally released. This problem would be mitigated only in v3 through a fallback system, which would freeze a grabbing hand at its last position and orientation, when tracking was lost.

Properly inspecting grabbed objects was often impeded by the lack of tracking robustness. Unfortunately, especially a grabbing hand pose (like forming a circle between thumb and the rest of the fingers) was often interpreted as the same pose but turned around by 180 degrees. This behavior was greatly improved through an *SDK* update implemented in v3.

Sometimes false ghost hands were created, clearly out of the user's range. This could be mitigated by restricting the tracking to a certain distance, more sensible for a human being. This approach was later included into *Leap Motion's* official *SDK.*

General issues with the occlusion of hands, external light sources, certain hand poses and misinterpreted objects in the physical surrounding and respective frustration in users could also be observed. Although the fundamental problems with optical tracking could of course not be completely resolved, *Leap Motion* drastically improved their *SDK* over time, regarding these issues. Hence, in v3 the recognized tracking issues largely focused on the limited camera frustum, whereas the other issues were mitigated very much.

Finally, a very atmospheric audio background soundtrack was added to v2, which clearly contributed to the horrifying scenery and intensified the general feeling of the game.

For a video outlining *Gooze* v2 see *Appendix F.3.2* on page 266.

4.3.3.3 Gooze v3 (Experiment Version)

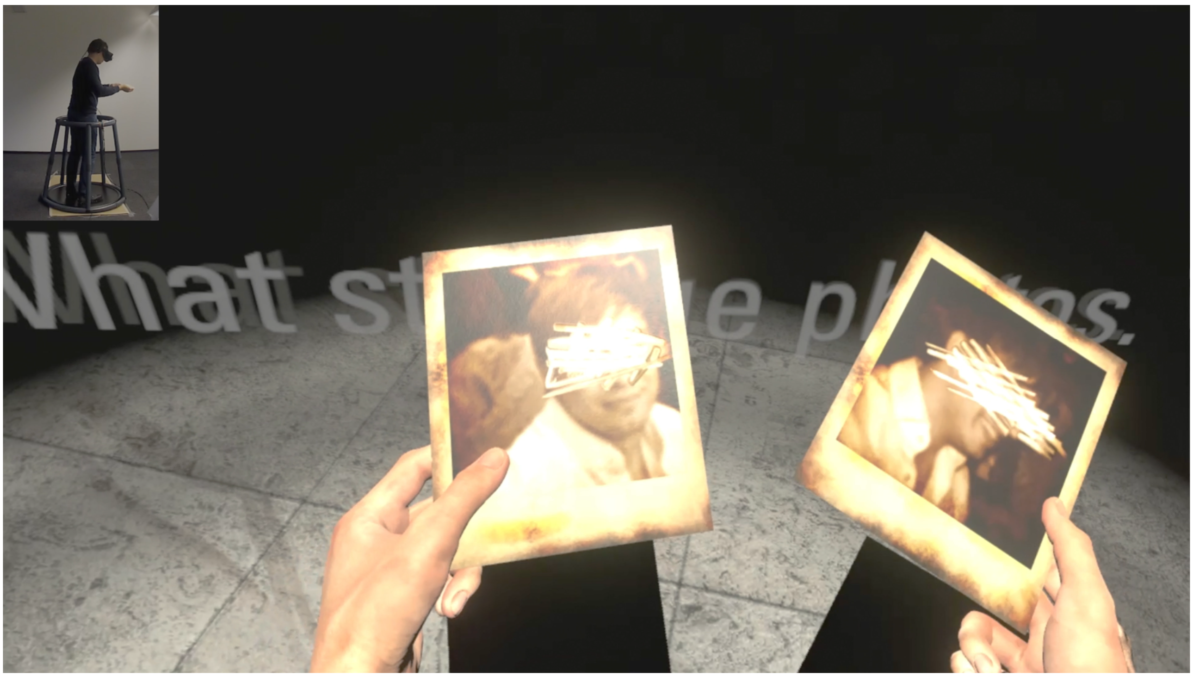


Figure 94: Top left overlay: Using the ROVR treadmill for Locomotion and Controllerless Hand Tracking via Leap Motion controller for Virtual Object Interaction. Gooze v3: Holding and inspecting polaroids (Wiedemann et al. 2020)

Gooze v3 (see Figure 94) was specifically prepared and optimized for the *Lab* experiment on *UX Evaluation of VR Locomotion & Virtual Object Interaction Mechanics* (see from page 150ff.). Due to the considerable amount of passed time between the development phases of *Gooze* v2 and v3 various advantages and disadvantages arose.

Even with proper documentation etc., it is generally harder for a developer to get back into a software project after some months passed, even if it was developed just by that person. In the case of further developing *Gooze* from v2 to v3, over two years passed and basically all previously used software versions, *SDKs* and third-party plugins were outdated. In turn, not only these software packages needed to be updated, but also lots of custom code as *Components, APIs* and whole interaction concepts have changed. Some subsystems either needed to be heavily adjusted or completely redeveloped. E.g. in v2 the light hanging from the ceiling used a third-party plugin to create the physically behaving cable, consisting of various internal joints etc. The joint system in *Unity* completely changed over that time and the plugin was not maintained, making it obsolete. Due to the lack of a proper alternative, a custom solution was developed.

On the other hand, new software versions of course also brought improvements for various aspects of game development. New features could be leveraged in terms of rendering performance (e.g. *Asynchronous Timewarp* and *Spacewarp*, Carmack 2017), rendering quality (e.g. *Physically Based Rendering, PBR),* tracking concepts (e.g. *Roomscale* tracking), tracking robustness (e.g. drastically improved skeletal hand tracking) and whole new interaction possibilities via new input devices were introduced (e.g. *Spatially Tracked Hand Controllers).*

Regarding the used *HMD* and the respective ecosystem, *Gooze* v3 was optimized for the *Oculus Rift CV1* and *Roomscale* tracking via three *Oculus* sensors (see Figure 105). Hence, compared to v2 the resolution, optics and refresh rate (90 Hz) of the *HMD* drastically increased the visual quality again.

The most important aspect of v3 though, was its integration of various input technologies and corresponding mechanics, some of which were only meant for development purposes. Internally a greater selection of interaction modes was available, due to the testing of diverse interaction approaches during development. This was made possible via the flexible custom *Universal Input Manager* (see *Appendix C.3.4* from page 252ff.). Nevertheless, the *Lab* experiment (see from page 150ff.) focused on three of them (see Figure 95), covering a broad range of consumer input devices and interaction strategies and scenarios. Each of the three modes provides mechanics for *Locomotion (LOC)* and *Virtual Object Interaction (VOI),* so the user could move through the *VE* and interact with certain objects (for details on the respective *FTInteractiveObject Component* see *Appendix C.3.1* on page 247ff.).

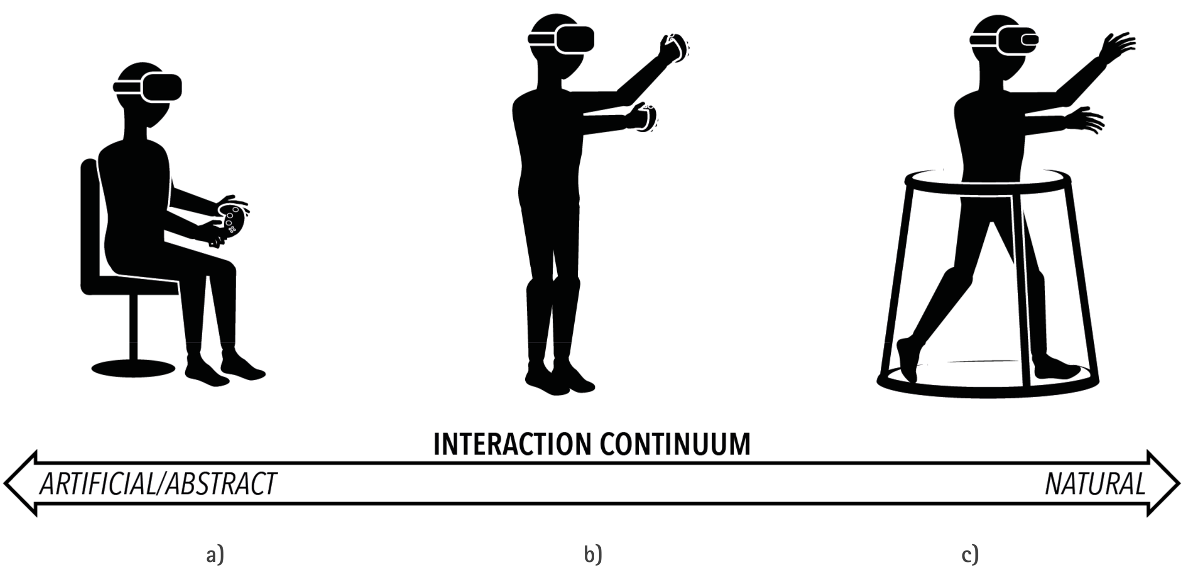


Figure 95 / Figure 106: Interaction modes a) Mode A: LOC and VOI via gamepad, b) Mode B: LOC via physical walking & teleport with Spatially Tracked Hand Controllers and VOI via Spatially Tracked Hand Controllers and c) Mode C: LOC via treadmill and VOI via Controllerless Hand Tracking (Wiedemann et al. 2020)

The in Figure 94 illustrated interaction mode, later referred to as *Mode C* (see Figure 95), uses *Controllerless Hand Tracking* via the *Leap Motion* controller for *VOI* and the *Wizdish ROVR 1 Omnidirectional Treadmill* for *LOC.* So, a user's interaction with the game is entirely based on physical movement.

Compared to v2, skeletal hand tracking was greatly improved by using an updated *Leap Motion SDK,* though some issues with occlusion and the limited tracking frustum persisted, as already mentioned. Individually optimized advanced variants of the object grabbing subsystem from v2 were used in all three interaction modes. The system temporarily also applied a pre-defined hand pose specific to the grabbed object. For more details on this see *Appendix C.3.2 Posing Skeletons and Objects* from page 248ff.

To move through the *VE* a player would need to slide his or her feet back and forth on the *ROVR* treadmill. The very simple microphone-based tracking technology of the device resulted in several downsides: It is only possible to walk forward towards the looking direction and either physical turning movements would cause forward *Locomotion* or higher tracking precision and thus smaller steps would be impossible with this device. For more details on the *Wizdish ROVR Implementation* see *Appendix C.3.6* from page 255ff.

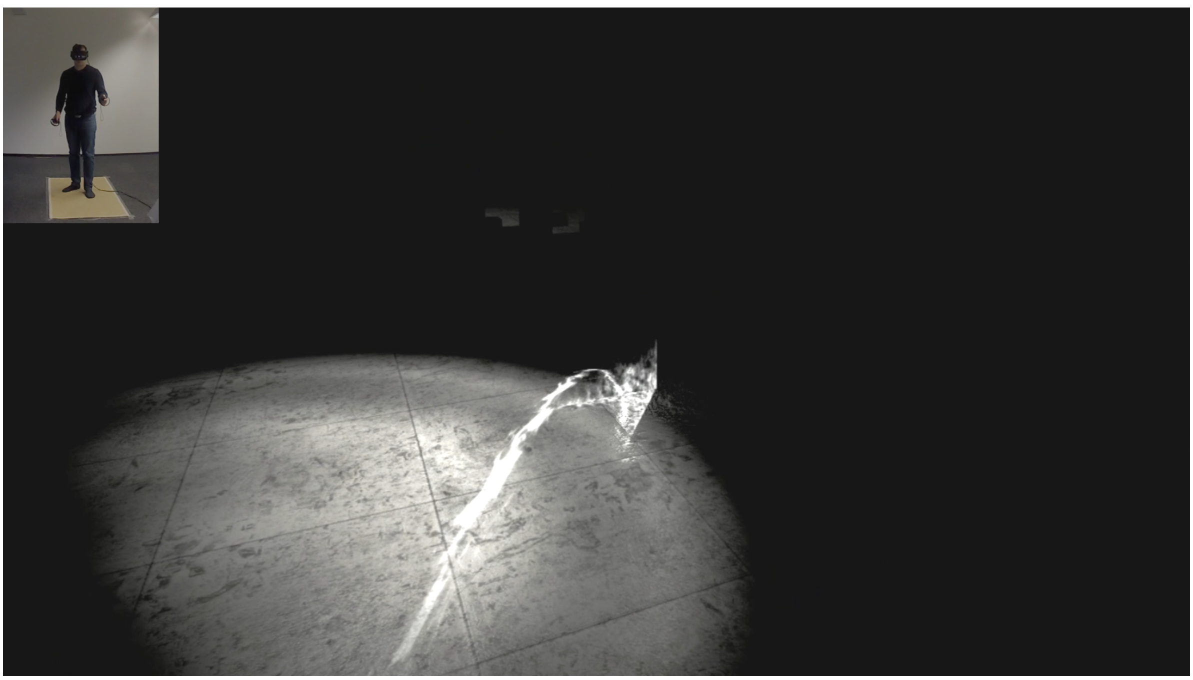


Figure 96: Top left overlay: Using Roomscale walking & teleporting for Locomotion and Spatially Tracked Hand Controllers for Virtual Object Interaction. Gooze v3: Activated teleport parabola with the arrow on the floor showing the direction the user wants to look at, after the teleport (Wiedemann et al. 2020)

The in Figure 96 illustrated interaction mode, later referred to as *Mode B* (see Figure 95), uses *Spatially Tracked Hand Controllers (STHCs,* i.e. *Oculus Touch* controllers) for *VOI* and a combination of *Roomscale* tracked physical walking and teleportation for *LOC.* Thus, a player interacts with the game through a mixture of physical movements and more abstract mechanics like teleportation. The *Roomscale* tracking of the *HMD* and the hand controllers via the three sensors is very robust and precise.

Gooze v3 makes full use of the capabilities of the *Oculus Touch* controllers. By gradually pulling the grab trigger on a *Touch* controller the virtual hand also gradually performs a grab movement. The respective grabbing pose is specific to grabbable objects and depends on their proximity. Independent from this behavior, due to the capacitive sensors of the hand controllers, players can also perform various physical gestures like "thumbs up" and "pointing index finger" and their virtual hands will mimic these. For more details on this see *Appendix C.3.2 Posing Skeletons and Objects* from page 248ff. Compared to *CHT* the *STHCs* can only perform a limited range of different hand poses. Nevertheless, their tracking is very precise and stays reliable in almost all circumstances.

As the virtual space in *Gooze* is larger than the physical tracking space, the user needs to utilize a combination of physical walking and virtual teleportation to move through the *VE.* Once a player reaches the edge of the tracking space and thus possibly physical obstacles, the *Oculus Guardian* system steps in and displays the tracking space boundaries via a blue transparent grid as a safety measure. To still be able to explore the complete *VE*, a user can use the analogue stick on an *STHC* to initiate the teleportation mechanic, which will also temporarily slow down time and apply a visual effect to the game. Following this, a white parabolic stream extends from the virtual hand and can be aimed by this. If the other end of the stream hits the floor at a teleportable position – you cannot teleport through walls or into fixed objects like the table – a white arrow will mark this point. The direction of the arrow can be controlled via the analogue stick and defines the direction the player will look after the teleport. Once the stick is released, the user will extremely quickly dash to this position and rotate accordingly. This movement happens in the blink of an eye, so it does not induce *Simulator Sickness,* while providing a guiding animation, preserving orientation for the player.

Figure 97: Top left overlay: Using the gamepad for Locomotion and Virtual Object Interaction, while sitting on swivel chair. Gooze v3: Holding and directing the ceiling light (Wiedemann et al. 2020)

The in Figure 97 illustrated interaction mode, later referred to as *Mode A* (see Figure 95), uses only a gamepad (i.e. an *Xbox One* controller) for *VOI* and *LOC* and can be used in a seated position. In the *Lab* experiment (see from page 150ff.) participants were placed on a swivel chair, allowing them to additionally physically turn with the chair. Nevertheless, this mode could also provide gameplay in a conventional seated and front-facing scenario. In this mode, the player almost entirely interacts with the game through the abstract use of the gamepad, but it is still possible to physically lean towards something, if needed.

Controlling the virtual hands with the gamepad is rather complex, compared to the previously mentioned more natural interaction mechanics. After a bit of practice though, it is manageable and can even excite players used to conventional gamepad gameplay. In their relaxed state, the virtual hands are positioned at the bottom of the visible area and are moved in relation to the head. By using a combination of shoulder button, analogue stick and trigger each hand can be individually moved and a grab gesture can be gradually performed similar to the other *VOI* mechanics. For more details on the control scheme see section *Mode A: Gamepad* from page 152ff. As an analogue stick only offers a two-dimensional interface, but the hands need to be moved in three dimensions a workaround was required. With the analogue stick the user only controls the hand's movements on the X-Z plane, whereas the height of the hand would be automatically controlled by a custom algorithm, aiming for grabbable objects in reach. For more details on this see *Appendix C.3.5 Controlling Hands via Gamepad: Automatic Height Adjustment* from page 253ff.

Moving through the *VE* via the gamepad conformed to a common control scheme: The left analogue stick would perform slow smooth movement, including strafing. The right stick could be used to rotate in steps of 33 degrees. To avoid causing *Simulator Sickness,* this *Snap Rotation* was used instead of gradual rotation.

This generally overlapping control scheme, using the analogue sticks for *VOI* and *LOC* added a certain complexity, but was chosen to utilize the affordances of the hardware interfaces in a meaningful way.

For more details on the *Interaction Modes & Mechanics* themselves see the respective section from page 151ff. For more details on the diverse results regarding their *UX* see section *Experiment Results* from page 158ff.

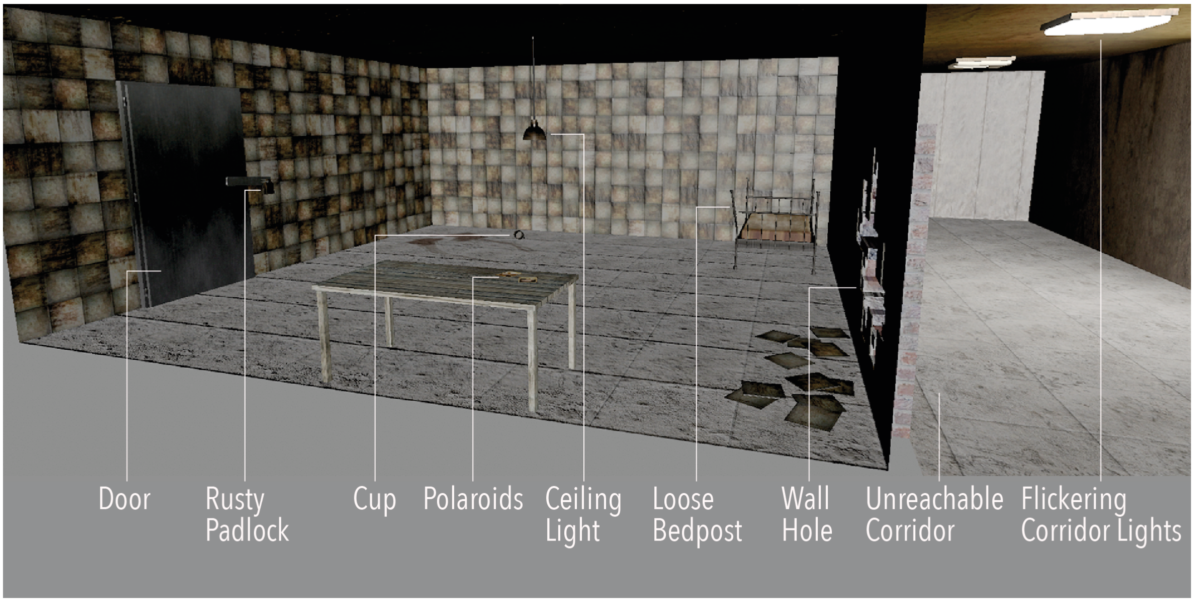


Figure 98: Gooze development screenshot: The level with its various objects (Wiedemann et al. 2020)

Regarding content, *Gooze* v3 included mostly updates for shaders and texture assets due to switching to the *PBR* workflow. The visual quality was improved and by adding several post processing and custom effects the game's general style was polished. Nevertheless, the playable content was not further extended and the v3 demo was still limited to the single level and the single puzzle (see Figure 98) without any initially planned *NPCs.* This was due to time constraints and a focus on integrating specifically well-designed and well-implemented interaction mechanics. The goal to achieve more comparable results through the *Lab* experiment on *UX Evaluation of VR Locomotion & Virtual Object Interaction Mechanics* (see from page 150ff.) further strengthened the decision to not include any horrifying *NPCs* in the demo. The experiment participants may likely have reacted very differently to them, maybe even to the point of aborting a session, which obviously should be avoided.

Finally, also the game's audio system received a major update and a custom system for *Spatialized Dynamic Audio* was implemented. Spatialized and dynamically adjusted audio effects clearly advanced the realism of the game and enhanced *Immersion* and the possibility for *Presence.* For more details on this see *Appendix C.3.3* from page 251ff.

4.3.4 STUDIES

As part of the *CDR* approach, the following section will elaborate on the various studies conducted for or with *Gooze.* The expedition to the *Grabowsee Sanatorium* is depicted, which inspired diverse aspects of the game. The public and informal *Showroom* demos are presented, providing an outline of the events which greatly helped iterating the design of the game. Finally, the *Lab* experiment conducted with the game illustrates the scientific investigation of the *UX* of *VR Locomotion and Virtual Object Interaction Mechanics* (see from page 150ff.).

4.3.4.1 Inspirational Expedition to Derelict Grabowsee Sanatorium

Figure 99: Small selection of inspirational photographs taken at derelict Grabowsee Sanatorium

Already planned while developing *Gooze* v1, in July 2014 I made an inspirational expedition to the derelict *Grabowsee Sanatorium* near *Berlin* (see Figure 99). Originally founded by the red cross as a sanatorium for tuberculosis treatment in 1896, it provided over 400 beds for patients. The whole settlement consists of various buildings, including a church, gasworks, a greenhouse, a stable building, further barracks, residential buildings for personnel and an underground network of connected cellars and more (Jüttemann n.d.). After the *Second World War* the buildings were used as barracks and a military hospital by the *Soviet Union* till 1995. As the usage of the premises steadily decreased over time and as the occupying force did not invest much in maintaining them, they mostly decayed to a degree of dilapidation (Jüttemann n.d.).

During my two-day trip it was not possible to explore all buildings and corners. Nevertheless, the immense network of unlit connected cellars, providing a very special atmosphere, was extremely fascinating and easily the most inspirational place of the venue, when it comes to creating content for the horror genre.

Although the following descriptions of examples try to illustrate certain "scary" situations and my personal respective mental reactions, they undoubtedly fall short of delivering the actual experiential depth under which these situations were lived through.

Though this might seem obvious, the largely general absence of light (except for my flashlight) on its own created an atmosphere, in which that very primal fear of darkness and the unknown could be easily recognized. The almost but just not complete silence further contributed to this creepy feeling, as some very muted and indistinguishable sounds felt incredibly intense, due to missing regular background noise. This feeling was further highlighted, once I left the cellar and stepped out into the overgrown and lively surrounding of the premises on a pleasant day. It felt like an immense pressure was taken off my shoulders and relieve took its place.

A more concrete example was a very long hallway in the cellar maze. It extremely subtly but steadily narrowed in all dimensions, to the point, that I had to start slightly ducking under the overhead pipe installation. Although not at all visually apparent, this tangibly increased the cramped feeling already present throughout the sometimes extremely tight rooms.

Another example was concerned with a very narrow tunnel (around 1.2 x 1.2 m), in which I could only crawl with my backpack already scraping at the ceiling. This might already feel quite intimidating, but the actual clue of the situation was that the tunnel seemed quite long and was slightly curved. This meant you could only see some meters ahead. In turn, you could not see the other end and after some crawling you also lost sight of the entrance. It felt very understandable to lose orientation in such a situation, even when there are but two ways to go. During the whole expedition, this was the only time, when I turned around and did not see the very end of a room or hallway. And even while crawling back the way I came, fully knowing that the entrance should not be far ahead, I was fascinated by having to suppress first light indications of a rising panic.

In another unlit hallway in the cellar maze, I found myself in an almost cliché situation. The batteries of my flashlight died and very suddenly I was enveloped in complete darkness. Although I was thinking of the irony of this situation, seen so many times in horror movies and games, it feels a lot more immediate once it happens to you personally. So, I very quickly tried to replace the batteries and thanked myself for coming prepared.

Finally, through this *Urban Exploration* (Dictionary.com 2017 and Wikipedia 2017b) I was able to create a comprehensive archive of several hundred photographs meant for in-game textures and as an inspirational source for puzzle ideas and creating a believable and astonishing atmosphere in the game.

4.3.4.2 Showroom Demos

During six different *CDR Showroom* presentation events (see timeline in Figure 27), *Gooze* was personally presented to approximately 200 people with different ages, genders and backgrounds including around 90 active play testers, whose informal feedback significantly influenced adjusting and designing various aspects of the game. Additionally, intermediate versions of the game were also downloaded around 2400 times.

4.3.4.2.1 MDX Research Student Summer Conference

Figure 100: MDX Research Student Summer Conference

During the *MDX Research Student Summer Conference* in *London* in June 2014, *Gooze* v1 was presented to approximately 50 researchers and students from various fields. Around 20 of them actively play tested the demo and in spite of its unfinished state, v1 already received a lot of positive and interested attention. Understandably, the novelty of the medium added to the demo's attraction. Nevertheless, feedback was consistently positive and first rough insights on usability and design could be gathered.

4.3.4.2.2 VR Night: Virtual Indie-ality

As already mentioned, during the *VR Night: Virtual Indie-ality* in *London* in June 2014 (see Figure 78), additionally to *LizzE* v2B (see page 113) also *Gooze* v1 was presented. The game was showed to an audience of approximately 100 *VR* and gaming affine people, of which around ten actively play tested *Gooze.* Largely positive feedback was given, which greatly helped to get a broader overview of usability and acceptance of the demo in its current state. E.g. it became clear, that the rudimentary interaction mechanic to give objects a simple push was exciting for players but did not always work as well as expected. Using the head direction for aiming correctly seemed hard for some users. Because of this and advancements in hand tracking, *Gooze* v2 integrated a completely different object interaction mechanic.

4.3.4.2.3 Informal Session with MDX Students

Figure 101: Informal user test sessions with students at MDX

Spontaneously taking place in *London* in October 2014, *Gooze* v2 was informally tested by around ten students from *Middlesex University London* (see Figure 101). Although play testing with v2 could not be directly watched on a second screen, a generally playful and motivated usage of the interaction system could be observed. Some of the users were just fascinated by bouncing around the ceiling light over and over again. Actually grabbing an object was not yet implemented and resulted in slight confusion in some of the players, whereas others took it as a challenge. In turn, solving the puzzle to escape the room was not possible yet either. This was explained to the users and they were told to verbally come up with puzzle solutions until they found the right one. This resulted in interesting answers and supported my assessment of the puzzle providing the right amount of difficulty.

4.3.4.2.4 Super Warehouse Gaming Party

Figure 102: Super Warehouse Gaming Party

Held in *London* in October 2014, the *Super Warehouse Gaming Party* (see Figure 102) provided a platform of gaming affine people. Mostly without any previous *VR* experience, 40 gaming enthusiasts play tested *Gooze* v2 in its current state. Properly grabbing objects and solving the puzzle was not implemented yet, so again users were told to verbally come up with puzzle solutions until they found the right one. Although this way of handling the incompleteness of the game seemed rather dilettante at first, it quickly proved to be an effective way of gathering important feedback and was very well accepted by the players.

A huge interface flaw became apparent, caused by using a gamepad and the *Leap Motion* controller for hand tracking at the same time. Both analogue sticks were needed for *Locomotion* and turning and a button for crouching. So, when users wanted to interact with objects, they needed at least one hand letting go of the gamepad, which prohibited them from performing all other actions properly at the same time. This would get even more problematic once grabbing was implemented and the puzzle could be solved. The issue only eventually got fixed with *Gooze* v3 only providing interaction modes that did not combine gamepad input with hand tracking.

Finally, a simple evaluation of *Simulator Sickness* was conducted. After each session, taking around 5 to 15 minutes, the user was verbally asked to assess current nausea on a scale from 0 to 10. Of course, the circumstances of the evaluation did not lead to scientific results. Nevertheless, this method led to a rough estimation of how well *Gooze* was respectively accepted. Which was surprisingly well when looking at 90% of users placing themselves in the lower third, of which the majority did not feel any nausea at all (65%). The nausea level score's mean and *Standard Deviation* were 0.825 ± 1.466. For more details see the following table:

Simulator Sickness after session (scale from 0 to 10)	Participants
0	65% (26)
1-2	25% (10)
3-4	5% (2)
5	2.5% (1)
6	2.5% (1)
7-10	0% (0)

Table 5: Simulator Sickness after informal Gooze v2 sessions at Super Warehouse Gaming Party

For a video outlining the event see *Appendix F.3.3* on page 267.

4.3.4.2.5 Festive VR Meetup Special!

Figure 103: Interview on Gooze at Inition during Festive VR Meetup Special! (Leap Motion 2015)

The *Festive VR Meetup* took place in December 2014 at *Inition* in *London* and provided a platform to present the further developed *Gooze* v2. A grabbing mechanic was implemented, and the puzzle could be finally solved in the game. This version of the game was play tested by around ten people mostly related to the media industry, but not gaming in general. It was really well accepted by users. Especially its concept, design and atmosphere were praised. Because of *Inition's* connection to *Leap Motion* and *Gooze* taking part in its *3D Jam* competition, a video interview of myself was conducted about the idea finding of *Gooze* and the game's background (see Figure 103). For the interview video see *Appendix F.3.5* on page *268*.

During play, further game and experience braking issues could be observed. E.g. like interactive objects getting inaccessible by falling through the floor or players being infinitely elevated above the level. Regarding the usability issue with using a gamepad and hand tracking at the same time, a poor interim workaround became apparent, which was placing the gamepad on a thigh and controlling it onehandedly. Nevertheless, this clearly needed a fundamentally different approach in the next iteration of *Gooze.*

4.3.4.2.6 Leap Motion 3D Jam powered by IndieCade

Figure 104: Leap Motion 3D Jam powered by IndieCade (Leap Motion 2014)

The *Leap Motion 3D Jam powered by IndieCade*, was a global online competition over six weeks, with over 150 entries and a submission deadline in December 2014. Judging the entries was split into two phases. In the first phase random interested users could download the games and vote for them. *Gooze* was downloaded around 2400 times. With the 20th place, *Gooze* was just voted into the group of semifinalists. After that, staff members of *Leap Motion* were contacting the respective developers and giving them feedback on their applications, so they could further optimize their experiences over a couple of days, until the final judging.

During this time the issues with objects falling through the floor and players being elevated into the air could be fixed. Additionally, a lot of other adjustments concerning usability (e.g. adding graphical user guides at the beginning of the experience), further optimizations and *SDK* updates have been done.

In the second phase of the competition a jury of industry people would then rate the remaining 20 entries, finally pushing *Gooze* up to the 12th place.

4.3.4.3 Lab Experiment: UX Evaluation of VR Locomotion & Virtual Object Interaction Mechanics

Figure 105: Gooze experiment setup

The following *CDR Lab* experiment using *Gooze* v3 was conducted in *Munich* in December 2018 with 89 participants and investigated the *UX* of three different *VR* interaction modes und their underlying diverse *Locomotion* and *Virtual Object Interaction* mechanics.

> When designing and implementing *Virtual Reality (VR)* games and other *VR* applications, typical concerns relate to the important topics of *Locomotion (LOC)* and *Virtual Object Interaction (VOI).* Likewise, those areas are often associated with the broad field of *User Experience (UX)* and very diverse input devices. On the basis of three consumer-oriented hardware setups and their underlying *VOI* and *LOC* mechanics, the following experiment will explore the four *UX* aspects: *Player Enjoyment (PE)*, *Support of Gameplay (SoG)*, *Presence* and *Simulator Sickness (SimSick).* Assessing *Presence* is based on the *igroup Presence Questionnaire (IPQ)*, which outputs the four subscales *General Presence (G)*, *Spatial Presence (SP)*, *Involvement (INV)* and *Experienced Realism (REAL*, igroup 2016). As a *Virtual Environment (VE),* the specifically developed, optimized and polished "real-world" game *Gooze* was used.
> (Wiedemann et al. 2020)

4.3.4.3.1 Interaction Modes & Mechanics

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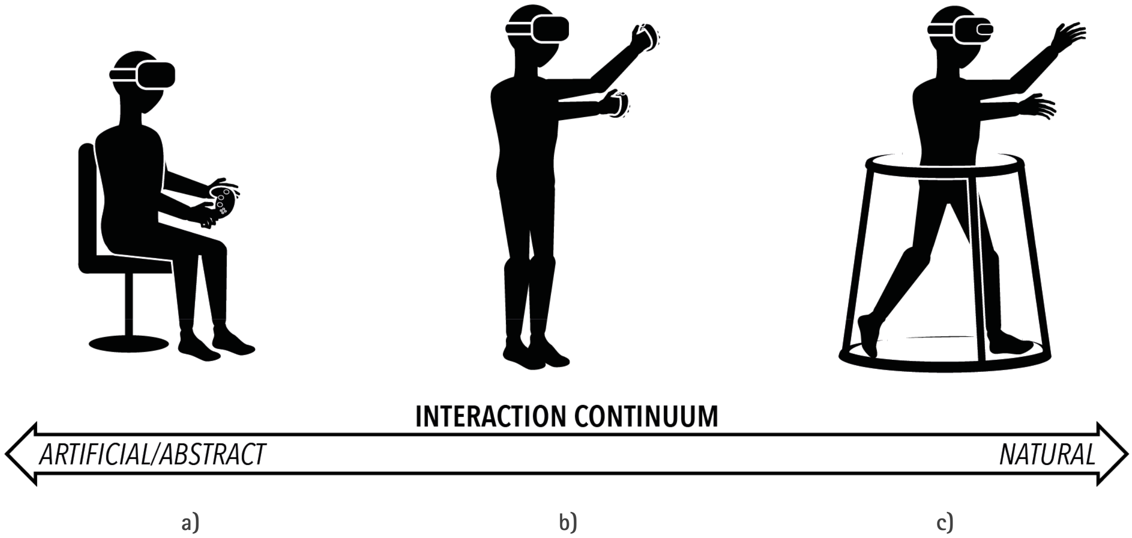
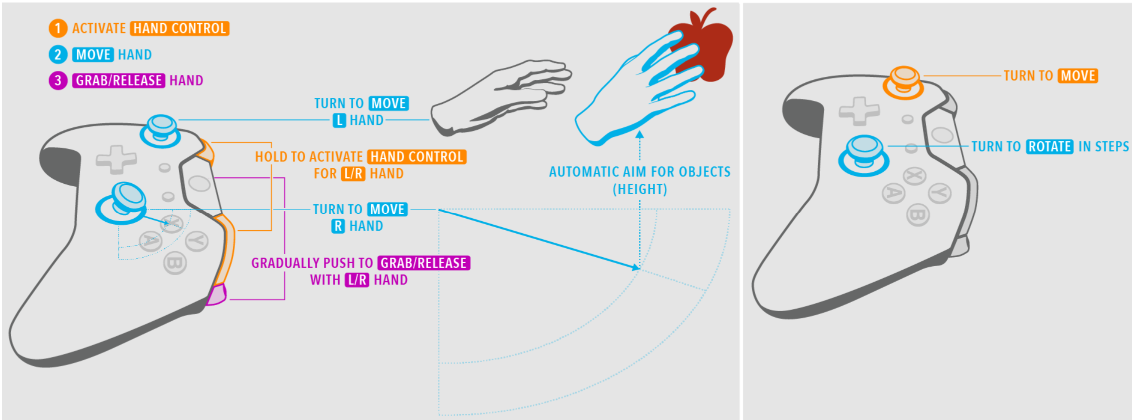


Figure 106 / Figure 95: Interaction modes a) Mode A: LOC and VOI via gamepad, b) Mode B: LOC via physical walking & teleport with STHCs and VOI via STHCs and c) Mode C: LOC via treadmill and VOI via CHT

The three assessed interaction modes have been deliberately selected from nine theoretically possible combinations of the implemented *VOI* and *LOC* mechanics. The selection was based on previous experience through pre-studies. Likewise, design and implementation were informed by previous development iterations (Wiedemann et al. 2017b). Each interaction mode makes use of different input hardware to cover a broad range of possible consumer setups with diverse requirements, e.g. like investment costs and available physical play space. The combinations of mechanics make the most of the affordances offered by the hardware interfaces in a meaningful way. E.g. it is more sensible to map the character movement onto an analogue stick on the gamepad, instead of the action buttons. Likewise, the combinations of input devices are not awkward or obstructive to use in parallel and instead provide a reasonable usability. E.g. using the gamepad together with the treadmill would hinder the player to comfortably grab the treadmill's handlebar for balance. Additionally, the mode selection provides seated and standing experiences, as these are typical *VR* gaming scenarios. Finally, the selected interaction modes map to three rather discreet points on the *Interaction Continuum* between artificial/abstract and more natural human computer interactions (see Figure 106). E.g. to grab with a virtual hand in *Mode A,* one needs to pull a gamepad trigger, whereas in *Mode C* one just naturally performs the gesture with a physical hand. Or to virtually move forward in *Mode A,* one steers a gamepad's analogue stick, whereas in *Mode C* one just slides the physical feet back and forth.

It needs to be emphasized, that the results of this study are intrinsic to the selected interaction modes and their specific design, implementation and configuration. Nevertheless, assumptions can be extracted and transferred to similar setups and even non-gaming *VR* scenarios, which require the user to virtually move and interact with virtual objects.
(Wiedemann et al. 2020)

4.3.4.3.1.1 Mode A: Gamepad



a) b)

Figure 107: Mode A control schemes for participants a) for VOI and b) for LOC

Mode A uses the most artificial/abstract interaction mechanics in this study. To provide a very common gaming scenario, the player is seated, in this case on a regular swivel chair. This provides freedom to physically look around, rotate and e.g. lean forward and sideways. On the other hand, this locks the player to a fixed position, which in turn does not require a large physical play space (see Figure 106a). In this mode, the participant uses a common gamepad to control *VOI* and *LOC.*

To control the movement of the left virtual hand on the X-Z axes, the user needs to hold the left bumper and steer the left analogue stick. This behavior is mirrored for the right sub-controls, respectively (see Figure 107a). A non-trivial aiming system will automatically interpolate the Y position of the hand, according to surrounding interactable objects [see *Appendix C.3.5 Controlling Hands via Gamepad: Automatic Height Adjustment* from page 253ff.]. The user can neither actively control the rotation of the hands nor perform any finger specific gestures. To grab an interactable object, the respective trigger needs to be pressed (see Figure 107a). This will gradually transition the regular hand pose to a fist, when there are no grabbable objects in range, or to a pre-defined corresponding grabbing pose. This grabbing pose automatic and the related snapping of a grabble object into the hand in an equally pre-defined "optimal" pose [see *Appendix C.3.2 Posing Skeletons and Objects* from page 248ff.] helps users to identify distinct object grabs while providing a clear visual and software-physical experience. This approach was implemented into all three modes in individually optimized variations (see Figure 94 and Figure 97). If a hand collides with an object, grabs it or a grabbed object collides with another object *Mode A* further provides the user with haptic feedback via various types of gamepad vibrations.

When not pressing the left shoulder bumper, the player is able to virtually move through the *VE* via steering the left analogue stick (see Figure 107b). When the right shoulder bumper is not pressed, the user can rotate his view along the Y axis in distinct 33-degree steps using the right analogue stick (see Figure 107b). This *"Snap Rotation"* was chosen over continuous rotation, to avoid *SimSick.* Additionally, the participant was able to physically rotate with the swivel chair in a continuous manner.

(Wiedemann et al. 2020)

4.3.4.3.1.2 Mode B: Spatially Tracked Hand Controllers (STHCs)

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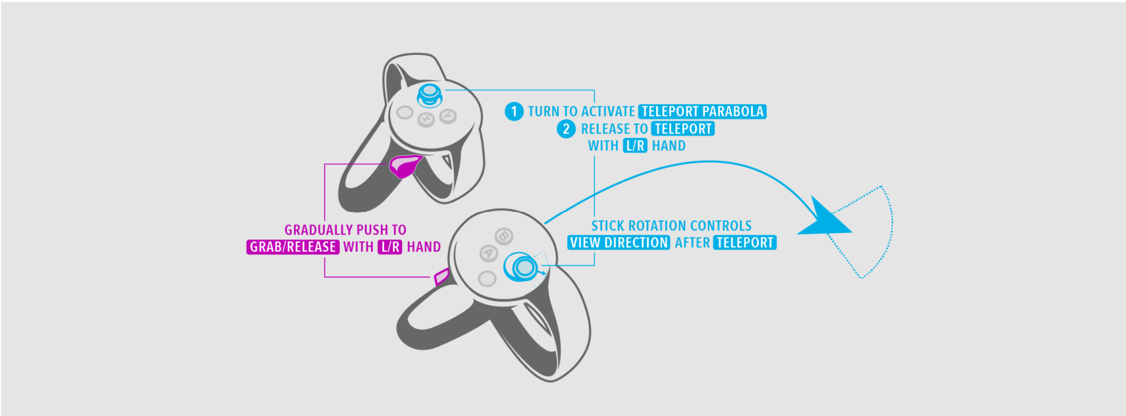

Figure 108: Mode B control scheme for participants

Mode B uses a combination of abstract and rather natural mechanics. In this mode, the player is standing and can naturally move within a ~3 x 3 meters play area (see Figure 106b). In turn, a rather large physical play space is required, as well as an alternative abstract method for *Locomotion* (i.e. teleportation). This is due to the fact, that the *VE* in *Gooze* is larger, then the physical play area. The participant is given two *STHCs*, to control the *VOI* and the teleport *LOC* mechanics.

The positions and orientations of the virtual hands are automatically linked to those of the *STHCs* and thus the user's hands. Via capacitive sensors in the sub-controls of the *STHCs*, physical gestures like thumbs up, pointing index fingers or "firing the handgun" are mimicked rather naturally. Similarly to *Mode A*, to make a virtual fist or grab a virtual object, the player can gradually press the respective grab trigger (see Figure 108). *Mode B* also provides the user with haptic feedback via vibrations of the *STHCs*. Only in contrast to *Mode A*, the haptic feedback is correctly split between the corresponding hands.

The participant's head position and orientation will be mimicked quasi immediately. Hence, to virtually move, the player can naturally move in the physical play area. Although, when getting too close to the edge, a blue virtual grid temporally fades in, visualizing the area's boundaries as a safety measure. In turn, due to the disparity between the virtual and the physical space, an additional teleportation mechanic was implemented, inspired by the one in *DOOM VFR* (Bethesda 2019). Once the user steers one of the analogue sticks on the *STHCs*, a visual parabola fades in, connected to the corresponding hand. Its direction and length are controlled by naturally posing the respective hand. The point where it hits the floor is marked by an arrow (see Figure 96), representing the exit position and direction the user wants to look at after the teleportation. The teleport is executed once the user lets go of the analogue stick. The arrow's direction can be controlled by directing the analogue stick (see Figure 108). The teleportable area is restricted by the walls of the room and the static objects like the bed and table (see Figure 98).

(Wiedemann et al. 2020)

4.3.4.3.1.3 Mode C: Controllerless Hand Tracking (CHT) & Omnidirectional Treadmill

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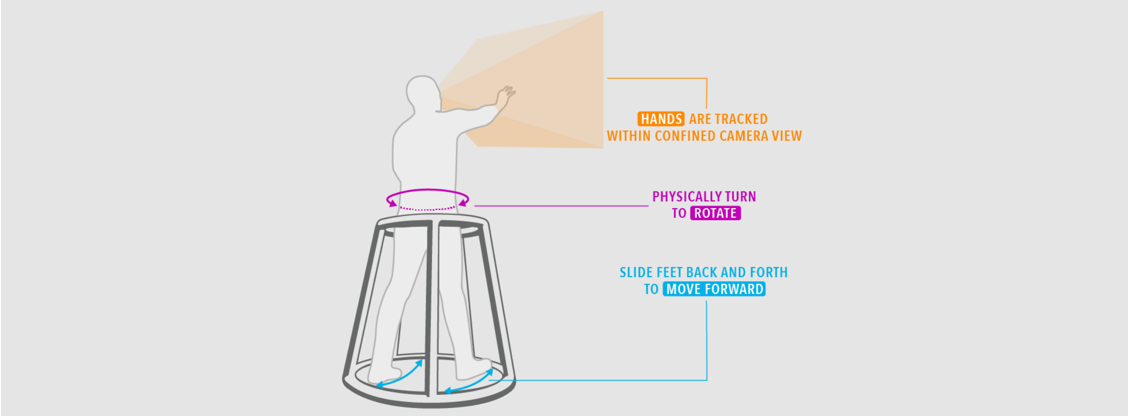

Figure 109: Mode C control scheme for participants

Mode C uses the most natural combination of interaction mechanics assessed in this study. The player is standing in a stationary treadmill. This provides freedom to physically look around, rotate and lean in various directions. On the other hand, it does not require a large physical play space (see Figure 106c). No hand controllers are involved and both the *VOI* and *LOC* mechanics are controlled via the participant's physical movements only.

This mode uses an *Infrared* sensor, mounted to the front of the *HMD* (see Figure 106c), which tries to track skeletal representations of the user's hands down to the bending of each finger joint. So, to grab a virtual object, the user just needs to physically move a hand and grab in mid-air. Similar to the other modes, once the grab or pinch threshold is passed, a close enough grabbable object will snap into the virtual hand in a pre-defined pose and the virtual hand pose will transition to the corresponding grab pose. To avoid unintendedly releasing an object by moving the hand out of the sensor frustum (see Figure 109), a fallback system freezes the grabbing virtual hand to the last tracked position and orientation. This mode does not provide the user with any haptic feedback.

In this study, the assessed treadmill, requires the player to slide his or her feet back and forth to virtually move forward towards the looking direction. The device works as a microphone and provides only a single output parameter, the noise volume of the sliding feet. Hence, it does not support moving backwards or sideways, but still facilitates a close to natural physical movement to virtually move forward. A generically calibrated volume-to-speed curve was implemented, to compensate the none-linear relation between the volume of the sliding feet and their actual movement speed. It further applied a minimum volume threshold to avoid unintended forward motion, when turning around and thus creating noise. [For more details see *Appendix C.3.6 Wizdish ROVR Implementation* from page 255ff.]

(Wiedemann et al. 2020)

4.3.4.3.2 Experiment Methodology

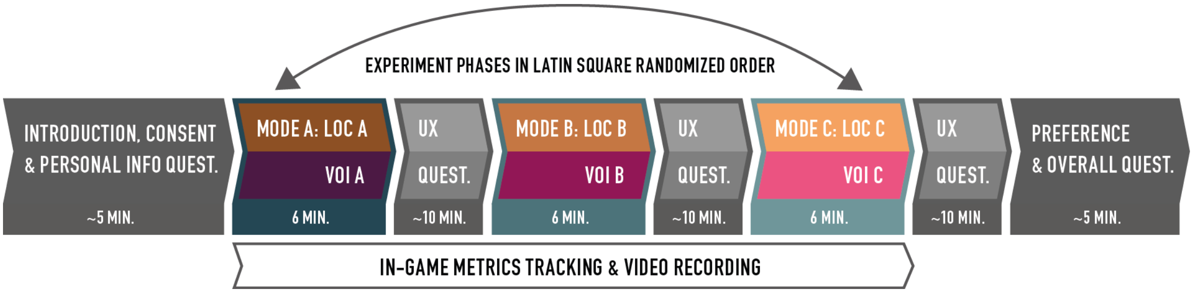

Figure 110: Experiment phases and procedure

> The following will describe the adjusted and refined design of the previously outlined experiment (Wiedemann et al. 2017b). Its aim was to investigate several *UX* aspects of different interface mechanics in a "real-world" scenario with corresponding challenges in gaming and *Human Computer Interaction.* Three interaction modes (also referred to as *Combined Modes* or modes) were primarily compared, each including one specific mechanic for *VOI* and one for *LOC.* However, [I was] also interested to see if users could distinguish how the *VOI* and *LOC* mechanics individually contributed to the different *UX* parameters. The experiment task required the participants to move through the *VE* and interact with virtual objects at the same time. Accordingly, they completed separate, but almost identical *VOI* and *LOC* questionnaires after each mode [see Figure 112]. The *VOI* and *LOC* scores were then averaged to produce a single set of scores per condition.
>
> In the within-subjects design, using quantitative and qualitative evaluation methods, each participant went through the following procedure (see Figure 110): After being informed about health and safety, the participant consented to the experiment procedure and the appropriate and ethical use of the collected data. Following this, the subject filled out a questionnaire on personal information, e.g. age, gender, handedness and subjective experience with *VR* and digital games.
>
> (Wiedemann et al. 2020)

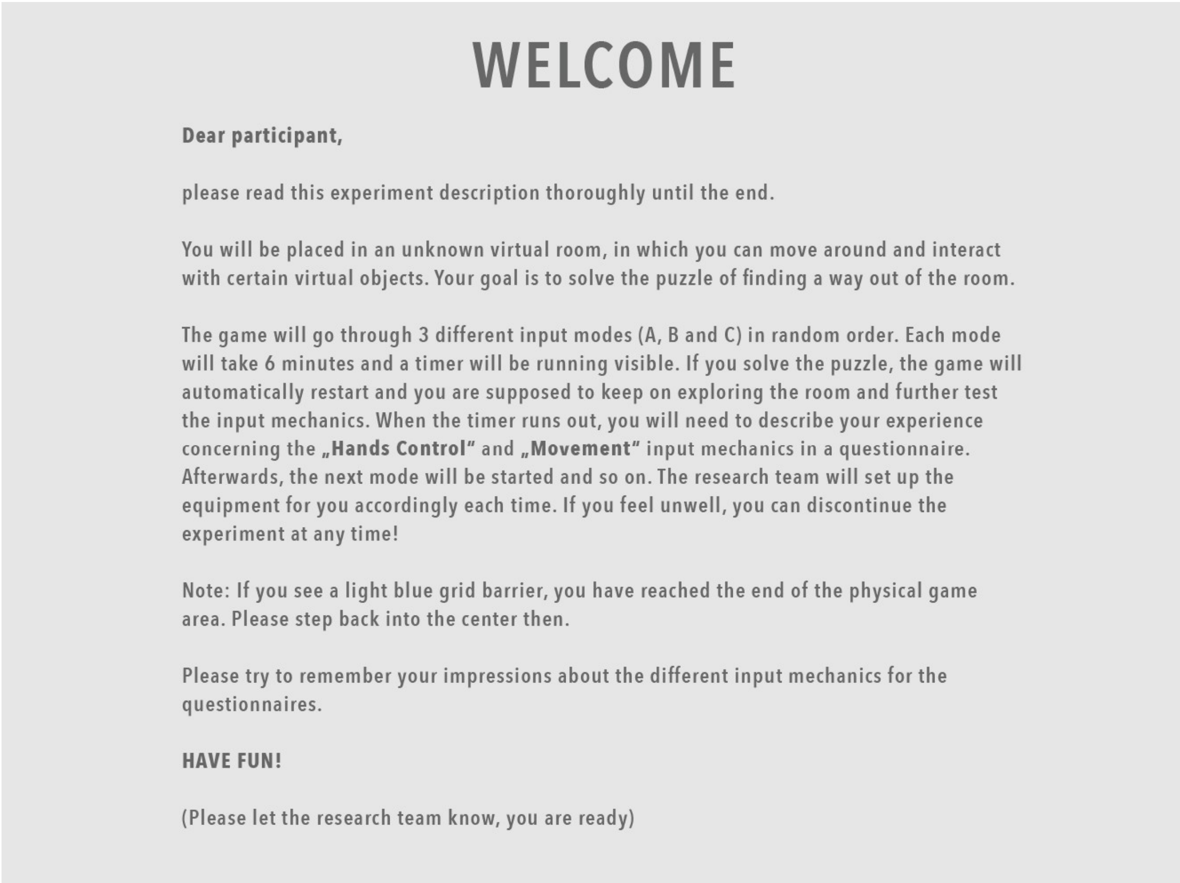

Figure 111: Gooze experiment application's first screen

> The participant then played the game *Gooze* (see Figure 94), using three different interaction modes (i.e. *Mode A*, *B* and *C*, see Figure 110) and evaluated them one after the other. The individual mode order was pseudo randomized based on Latin square sequences and each mode would last for six minutes, with a visible countdown for the player. The subject was given the task, to solve the puzzle of escaping the virtual room [see Figure 111]. The solution was to "break off" (grab) a loose bedpost, carry it over to the door with the rusty padlock, "break it apart" (touch it with the bedpost) and open the door (see Figure 98). So, the user needed to move through the virtual room and interact with certain objects by controlling virtual hands (e.g. inspect, grab, direct, carry and use). After solving the puzzle, the level would reload and the player would be instructed to keep on moving, interacting and generally playing around until the timer runs out. The available level was the same one for each mode.
> (Wiedemann et al. 2020)

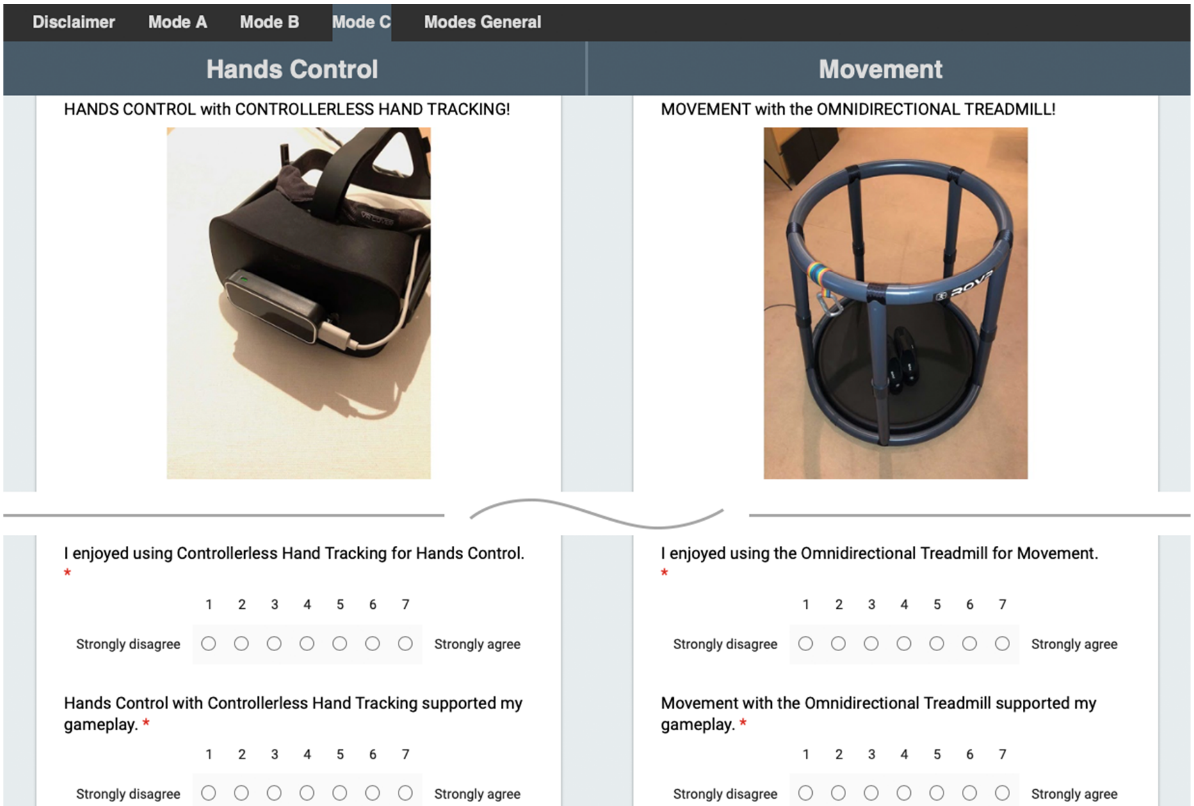

Figure 112: Truncated screenshot of double questionnaire (here for Mode C)

> After a mode ended, the participant could rest, while parallelly filling out the side-by-side *VOI/LOC* double questionnaire on the previous experience [see Figure 112]. [Instead of "Virtual Object Interaction" and "Locomotion", a simplified wording of "Hands Control" and "Movement" was used respectively for the participants.] Each individual questionnaire included four sections: *Player Enjoyment* and *Support of Gameplay* (two 7-point Likert scales), *Presence* based on the validated *IPQ* (14 7-point Likert scale items, igroup 2016), two optional qualitative free text questions for specific individual feedback and a *Simulator Sickness* scale (from 0 to 10). After evaluating all three modes, one last general questionnaire had to be filled out, [asking about the participant's *Preference* regarding the *VOI* mechanics, the *LOC* mechanics and the *Combined Modes,* and also including] one final optional free text field for any sort of feedback (see Figure 110). Additionally to the questionnaire data, all play test sessions were video recorded, to analyze verbal remarks or retrace specific behavior.
> (Wiedemann et al. 2020)

Furthermore, several in-game parameters on puzzle solving, virtually moving and interacting with objects were automatically tracked by the application for later analysis (see *Appendix D.1 XML Excel Export of In-Game Parameters* from page 257ff.).

The hardware setup consisted of a *Windows PC* with a 4.2 GHz *Intel Core i7-7700K CPU*, an *AMD Radeon RX480* graphics card and 16 GB of *RAM.* This machine ran the experiment game *Gooze* at a steady 90 Hz in *Stereoscopic 3D* and thus did not negatively influence *SimSick*, e.g. by causing stutter or lags.

> [The] *Oculus Rift CV1* was used as a *Head Mounted Display (HMD)* with three sensors for *Roomscale* tracking (~3 x 3 meters) and two *Oculus Touch* controllers as *Spatially Tracked Hand Controllers (STHCs*, Oculus 2016c). A standard wireless *Xbox One* controller (Microsoft 2019a) was used as a gamepad. To provide *Controllerless Hand Tracking (CHT),* a *Leap Motion* controller (Leap Motion 2019) was mounted to the front of the *HMD.* Finally, a *Wizdish ROVR 1* (Wizdish 2017) was used as an *Omnidirectional Treadmill.*
> (Wiedemann et al. 2020)

For a video outlining the experiment procedure, the three interaction modes and a selection of edited recordings of participant sessions see *Appendix F.3.4* on page 267.

4.3.4.3.3 Experiment Results

> The experiment was conducted with 89 participants (total n = 89), who did not receive any compensation. Because of nausea, one participant (P32, participant ID) had to discontinue playing through *Mode A,* but fully completed the other two modes afterwards. The subjects consisted of 61 males and 28 females and their ages ranged from 20 to 78 years and averaged at 35 years. According to the statement "I am an experienced digital game player", 42 were rather inexperienced (< 4 on 7-point Likert scale) and 47 rather experienced (>= 4) subjects, with a mean of 3.888. 37 participants noted, they were playing digital games between "less than once a year" and "once every some months", whereas 52 noted they would play digital games between "once a month" and "every day". According to the statement "I have experience with *Virtual Reality",* 63 were rather *VR* inexperienced (< 4) and 26 rather experienced (>= 4) subjects, with a mean of 2.640. The analysis of the qualitative data was conducted similar to the *"Thematic Analysis"* approach (Braun and Clarke 2006), though the process was condensed into the following three phases: Read the data to become familiar with it, split the comments into thematically separated phrases or words, accumulate these phrases or words in thematic clusters and structure them hierarchically on the fly. To facilitate this process, [I] developed the free online qualitative analysis tool *"Text Clusters Generator"* (Wiedemann 2019) and used it in this study [see *Appendix D.2 Text Clusters Generator* from page 258ff]. Regarding the scores of *UX* aspects, [I] visually inspected associated *VOI* and *LOC* parameter histograms and found them to be approximately similar. So, to compare parameters for the three modes, illustrating the combined operating of *VOI* and *LOC* mechanics, the *VOI* and *LOC* scores were averaged to produce a single set of scores per condition, i.e. the *"Combined Mode"* values.
> (Wiedemann et al. 2020)

4.3.4.3.3.1 Player Enjoyment & Support of Gameplay

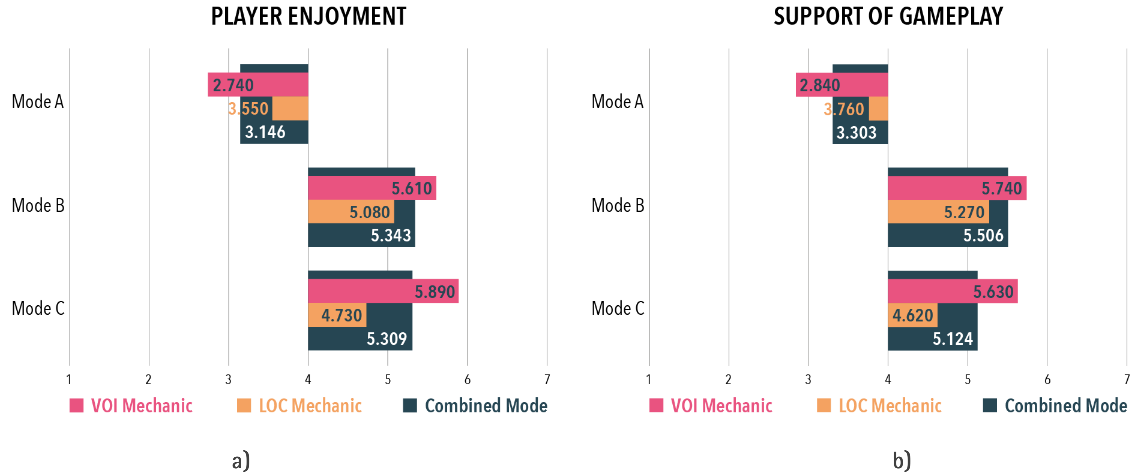

Figure 113: Ratings of a) Player Enjoyment and b) Support of Gameplay

By conducting six non-parametric *Friedman* tests (level of confidence $p < 0.05$, Laerd Statistics 2015a and e), [I] determined significant differences between the associated *PE* and the associated *SoG* scores across the *VOI* mechanics, the *LOC* mechanics and the *Combined Modes.* All p-values are < 0.0005. Post hoc analysis revealed statistically significant differences for the pairwise comparisons apart from scores between *B* and *C,* except for the *SoG* scores for *LOC* mechanics, which instead did not show a significant difference between *LOC A* and *LOC C.*

It is clear, that the *VOI* mechanics in general have the biggest impact on *PE* and *SoG* (see Figure 113a and b). Also, most participants did not get along very well with *Mode A* and in particular *VOI* via the gamepad. Around half of the participants regarded the overall controls of *Mode A* as "difficult" or even "obstructive" and negatively highlighted the overlapping input scheme of the *VOI* and *LOC* controls. This is likely due to the fact, that many participants had never used a gamepad before. In contrast, a couple of experienced players specifically advocated the sophisticated gamepad controls over the hands and interactions: "I like how I had to manually control the grabbing and moving, unlike most of the games that combine the entire process into a single button" (P62). Several players complained about the *Snap Rotation* feature to be "irritating" or "disorienting". Finally, the need for additional practice was mentioned multiple times, which is not surprising, regarding the 6-minute time limit.

Mode B's Combined Mode values either score on par *(PE)* or better *(SoG)* than *Mode C.* Around half of the participants described *VOI* via *STHCs* in positive terms like "easy", "enjoyable" and "intuitive". Moreover, several players illustrated their experience in similar words to: "The *[STHCs]* allowed me to interact with the virtual world in a very natural way" (P73). Although *Mode B* had the highest scores for *LOC* in *PE* and *SoG,* some participants' comments also showed a certain degree of reservation towards both physical walking and teleportation. Even though many described physical walking as being "intuitive", "realistic" and "freeing", others also addressed their concerns about being scared "to trip over the cable" (P48) and especially about the blue safety grid: "The blue grid often bothered me and made me change my plans." (P83). Nevertheless, there seems to be no practical alternative to a virtual safety system, when using a *Roomscale* setup. Although the concept of walking and teleporting seems to require some practice, most users described teleportation positively as being "easy", "fun", "convenient" and "fast": "Teleportation helped me get where I want to be very fast" (P19), which is supported by the high *PE* and *SoG* scores. Nevertheless, some players also regarded it as "unrealistic", "less immersive" and sometimes "disorienting". The latter is likely due to the inexperience of some participants with the usage of analogue sticks. Inspecting the session recordings, it became clear, that some players did not fully understand the teleportation's rotation control. Thus, some participants teleported, while applying an unintentional and disorienting rotation and then physically turned around.

In *Mode C, VOI* via *CHT* was overall regarded positively by a majority of participants, which is supported by its *PE* scores. Users described the mechanic as "easy", "intuitive", "natural" and "immersive". Furthermore, users highlighted the "detailed skeletal hand tracking" and how it "encourages interactions": "I liked how precise the finger movements were shown" (P54) and "It encourages you to interact with [the] environment on [a] new [and] deeper level." (P78). However, the *SoG* scores, which are slightly lower than the ones of *VOI* via *STHCs*, are likely due to the inherent limitations of the *Infrared* tracking: "in-game hands did not always match the real hands" (P80) and "I dropped some objects unintentionally because I twisted my [virtual] hand." (P42). Likewise, due to the limited tracking space, grabbing and directing the ceiling light was an issue for many participants. When a user wanted to look at the illuminated area, the grabbing hand would leave the tracking frustum and the hand freezing fallback system did not always perform in an optimal way. Another issue is connected to the handlebar of the treadmill, which restricted users from comfortably bending down to pick an object up. Although it was possible for most participants a minority with shorter extremities was completely obstructed by this: "I wasn't able to pick up items from the floor" (P77). Finally, some users also complained about the lack of any haptic feedback, when grabbing and interacting in mid-air: "grabbing something with no resistance (e.g. feeling something in your hand) feels unnatural." (P41). In comparison to *Mode B, LOC* via the treadmill clearly did not score well regarding *PE* and *SoG.* Almost a third of the participants commented the treadmill in a positive manner, using terms like "fun", "intuitive" and even "natural": "It's very close to feel like walking" (P04). Nevertheless, the majority of users described issues inherent to the device and its implementation. The concept of sliding your feet in the device was described as "slippery", "insecure" and even "dangerous": "it introduces a certain danger of slipping that you need to stay aware of" (P73). This may possibly be compensated with more practice. The sliding motion itself, coupled with holding onto the handlebar for support, on the other hand was regarded as "unrealistic" and "less immersive" by some participants: "Funny but not very realistic" (P20). The device's capabilities of only supporting forward motion seemed to be a prominent and even "obstructing" issue with some participants, especially when they unintendedly overran a targeted position: "you [had] to turn 180 degrees, go back, then turn around again and approach the object very slowly." (P42) and "the inability to move backwards strongly influenced my perception." (P06). Around a quarter of the participants complained about the "lack of precision": "Hard to make smaller steps and to navigate to a specific spot in the room." (P47). Related to this is the problem of "turning around was often interpreted as walking forward." (P75). These issues are due to the very simple microphone tracking of the device. To avoid *SimSick* a minimum volume threshold was implemented to prevent users from being unintendedly pushed forward, while only turning. In turn, this prohibits the tracking of fine-grained movements. Additionally, participants physically moved in very individual ways. Hence, the applied generic calibration of the mechanic did not optimally fit all users. (Wiedemann et al. 2020)

4.3.4.3.3.2 Presence

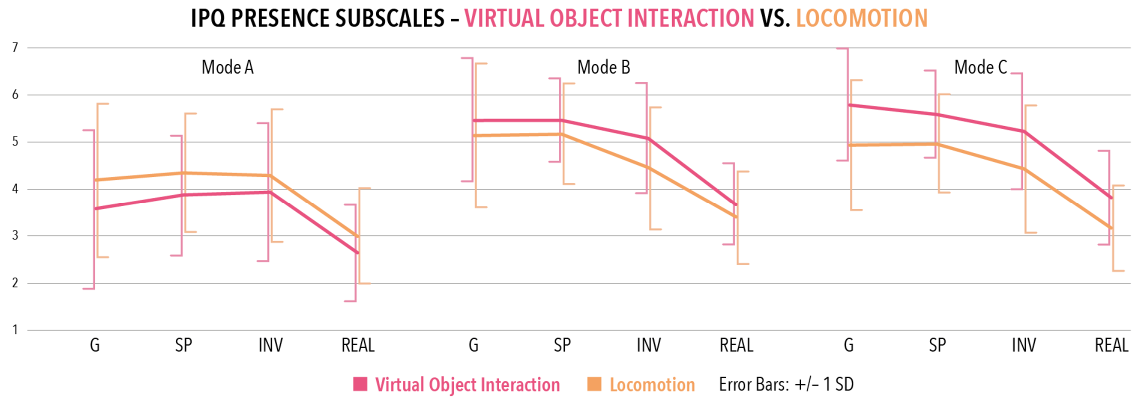

Figure 114: Graphs for IPQ Presence subscales of VOI vs. LOC mechanics

By conducting 12 non-parametric *Wilcoxon Signed Rank* tests (level of confidence p < 0.05, Laerd Statistics 2015a and f), [I] determined significant differences between all associated *VOI* and *LOC* scores of the four *IPQ Presence* subscales (igroup 2016), across all three modes. Most p-values are < 0.0005, with *"Mode B: VOI G - LOC G"* having the highest value of p = 0.013, but also being the only p-value > 0.01. Visually inspecting the graph profiles in Figure 114 (based on Table 6), uncovers them to be very similarly shaped (similar bending without any intersections) and to provide an almost equal distance from *VOI* to *LOC* subscales, per mode. Hence, the data seems to suggest, that *VOI* and *LOC* affected *Presence* in separate ways and that participants could differentiate between the respective mechanics.

	VOI				*LOC*			
Mode	*G*	*SP*	*INV*	*REAL*	*G*	*SP*	*INV*	*REAL*
A	3,570±1,691	3,865±1,271	3,927±1,478	2,646±1,033	4,190±1,630	4,344±1,263	4,303±1,414	3,008±1,015
B	5,480±1,315	5,476±0,889	5,096±1,176	3,683±0,870	5,130±1,531	5,189±1,074	4,463±1,301	3,396±0,995
C	5,810±1,186	5,600±0,928	5,239±1,244	3,817±0,993	4,930±1,380	4,980±1,057	4,433±1,364	3,163±0,909

Table 6: Mean ± SD of IPQ Presence subscales for VOI and LOC mechanics

By conducting 12 non-parametric *Friedman* tests (level of confidence p < 0.05, Laerd Statistics 2015a and e), [I] determined significant differences between the associated scores of the four *IPQ Presence* subscales (igroup 2016), across the *VOI* mechanics, the *LOC* mechanics and the *Combined Modes*, except for *"LOC INV"* (p = 0.305). All other significant p-values are < 0.0005, except for *"LOC REAL"* (p = 0.028). Post hoc analysis revealed statistically significant differences for corresponding pairwise comparisons apart from the scores between *B* and *C* and *"LOC REAL" A* and *C*.

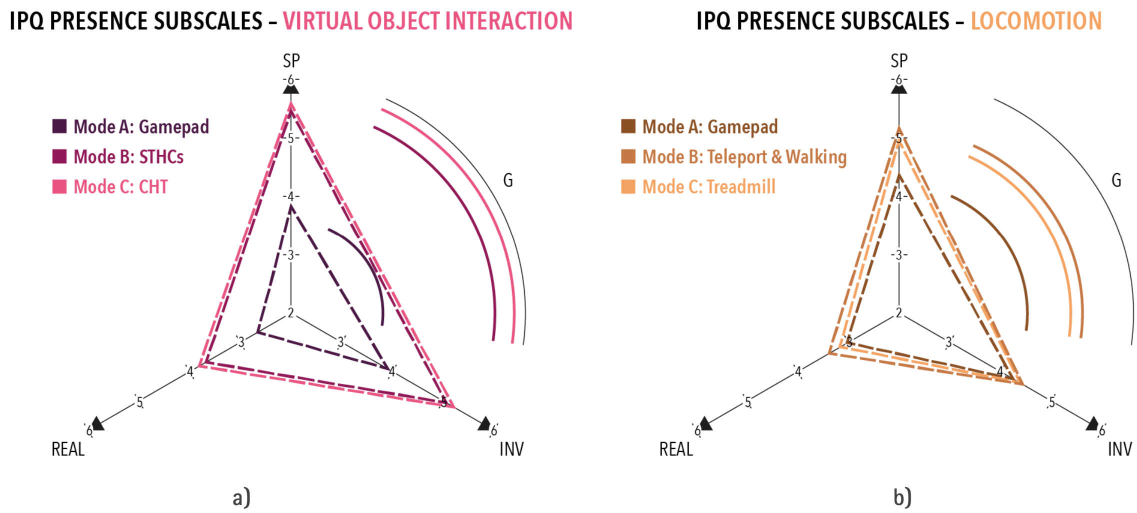

Figure 115: Ratings of IPQ subscales for a) VOI and b) LOC mechanics

Examining the *VOI, LOC* and *Combined Mode Presence* values (see Figure 115a, b and Figure 116), only the sub-parameters *"G", "SP", "INV"* show fluctuating values, below and above the neutral score of 4. *VOI* clearly shows a greater impact on *Presence* than *LOC*, when inspecting the corresponding diagrams (see Figure 115a and b). Regarding the *Presence* structures of *VOI* mechanics, the gamepad is clearly outperformed by the *STHCs* and *CHT*, with the latter providing the deepest *Presence* feeling. This is likely due to the naturalness of *CHT: "[CHT]* did significantly contribute to enhance the entire *Virtual Reality* journey." (P07). In terms of *LOC*, there are still differences, but not as distinct ones. Although it combined a very abstract with a very natural mechanic, *Mode B's* teleport and walking *LOC* mechanic seemed to provide the strongest *Presence* feeling: "it blends nicely the *Immersion* of walking around" (P70) and "I sometimes forgot that I could just use my real physical movements to move around after I had been teleporting a lot." (P64).

Examining the *Combined Mode Presence* diagrams (see Figure 116), *Mode B* and *C* both provide a structure, almost identical in shape and strength. Hence, they seem to provide an equally strong and positive *Presence* feeling. In contrast, *Mode A* clearly scores worse, likely due to the complexity of the controls and the short time limit to get accustomed to them: "I was more concentrated on managing the Gamepad than I was on the game itself." (P88).

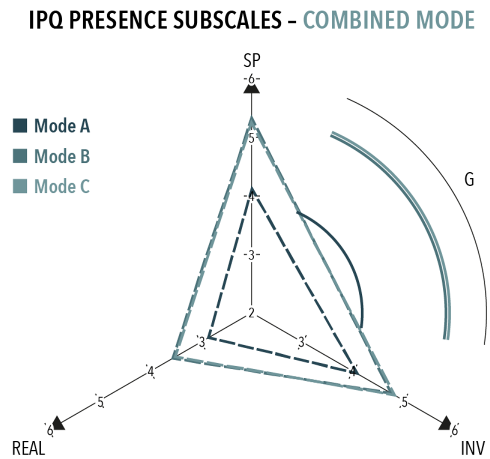

Figure 116: Ratings of IPQ subscales for the Combined Modes

(Wiedemann et al. 2020)

4.3.4.3.3.3 Simulator Sickness

“

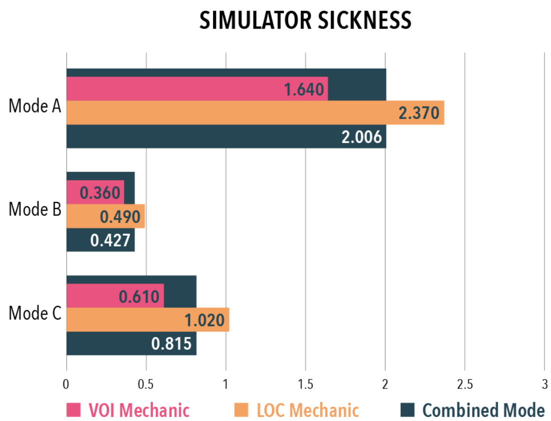

Figure 117: Ratings of Simulator Sickness

By conducting three non-parametric *Friedman* tests (level of confidence $p < 0.05$, Laerd Statistics 2015a and e), [I] determined significant differences between the associated *SimSick* scores across the *VOI* mechanics, the *LOC* mechanics and the *Combined Modes.* All p-values are < 0.0005. Post hoc analysis revealed statistically significant differences for corresponding pairwise comparisons apart from the scores between *B* and *C.*

LOC clearly shows a greater and more negative impact on *SimSick* than *VOI*, when inspecting the corresponding diagrams (see Figure 117). Nevertheless, the effect of *VOI* on *SimSick* should not be ignored. Overall though, due to implementing *LOC* mechanics, specifically avoiding *SimSick*, very low levels could be reached.

Although *Mode A* clearly shows the worst *SimSick* scores, it is interesting how *LOC* via gamepad was improved in this regard, comparing it with prior iterations (Wiedemann et al. 2017b). This is likely due to the reduced speed and the combination of *Snap Rotation* with swivel chair rotation. The relatively high score for *VOI* via gamepad may be caused by naive users needing to concentrate a lot on operating the mechanic: "I had to think a lot about what button to release/press." (P70).

In contrast, *Mode B* clearly shows the lowest *SimSick*, for both *VOI* and *LOC*. This seems due to the sub-mechanics not inducing any vection: "I can see the necessity of teleports due to motion sickness issues for new users." (P51).

Mode C closely follows *B*, regarding *SimSick*. A certain disparity between foot motion and virtual movement and thus vection could not be entirely avoided. Nevertheless, physically moving the feet, greatly helped in reducing *SimSick*, compared to *LOC* via gamepad. However, this was likely not the case, when players tried to move into a different direction than forward: "Not being able to move backwards was disturbing." (P21). Minor *SimSick* through *VOI* via *CHT* may have been caused by incorrect tracking and attempting to reach correct tracking again.
(Wiedemann et al. 2020)

4.3.4.3.3.4 In-Game Parameters

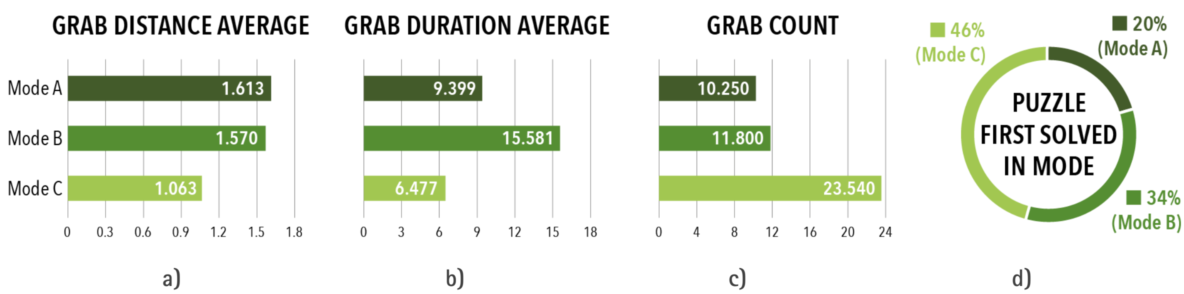

Figure 118: Scores of in-game parameters for a) Grab Distance Average, b) Grab Duration Average, c) Grab Count and d) Puzzle First Solved in Mode

Mode	n	Observed Grab Hand Side distribution		Expected Grab Hand Side distribution		Min. Exp. Freq.	p
		Left	Right	Left	Right		
A	81	41	40	7	74	7	< 0,0005
B	82	10	72	7	75	7	0,230
C	87	8	79	6	81	6	0,398

Table 7: Most often used Grab Hand Side vs. handedness

By conducting three non-parametric *Friedman* tests (level of confidence $p < 0.05$, Laerd Statistics 2015a and e), I determined significant differences between the *VOI* mechanics for the in-game parameters *Grab Distance Average*, *Grab Duration Average* and *Grab Count*. All p-values are < 0.0005. Post hoc analysis revealed statistically significant differences for corresponding pairwise comparisons apart from the scores between *A* and *B*.

By conducting three non-parametric *Chi-Square Goodness of Fit* tests (level of confidence $p < 0.05$, Laerd Statistics 2015a and b), I determined a significant difference between the hand side (left or right) most often used for grabbing and the participants' actual handedness for *Mode A* ($p < 0.0005$), but not for *Mode B* and *C*. For more details see Table 7.

By conducting another non-parametric *Chi-Square Goodness of Fit* test ($n = 74$, minimum expected frequency = 24.7 and level of confidence $p < 0.05$, Laerd Statistics 2015a and b), I determined significant differences between the number of participants, who initially solved the puzzle in a respective mode ($p = 0.026$).

Examining the tracked in-game parameters, other *UX* results can be put in relation with them.

Comparing *Mode A* and *B's* rather similar values for the parameters *Grab Distance Average, Grab Duration Average* and *Grab Count* with those of *Mode C*, it is clear that grabbed objects were carried for shorter distances and durations via the corresponding *CHT* mechanic. Additionally, *CHT* led to around the doubled amount of object grabs, compared to the *VOI* mechanics of *Mode A* and *B* (see Figure 118a, b and c). Both is likely due to a combination of two opposing aspects. On the one side, tracking issues led to unintentional object releases, so certain objects needed to be grabbed again. On the other side, *CHT* per se encouraged interactions with virtual objects.

Looking at the *Grab Hand Side* values of participants and their handedness per mode, using the gamepad in *Mode A* for *VOI* led to an indifference in players of choosing the normally preferred hand side (left or right) to grab objects. In contrast, the *VOI* mechanics of *Mode B* and *C* confirmed the normally preferred hand side of the participant (see Table 7). This is due to the artificial nature of the gamepad, whereas *STHCs* and *CHT* are rather natural interfaces.

Although possible learning effects for individual participants cannot be entirely excluded, the pseudo randomized mode order for each of the participants likely mitigated an overall influence. In turn, examining the *Puzzle First Solved in Mode* values, it is interesting to see that almost half of the players solved the puzzle first in *Mode C* (see Figure 118d). This is likely due to the intuitiveness and naturalness of the respective interfaces, which did not require much practice or concentration and thus made it easier for players to instead concentrate on the task of solving the puzzle.

4.3.4.3.3.5 Preferences

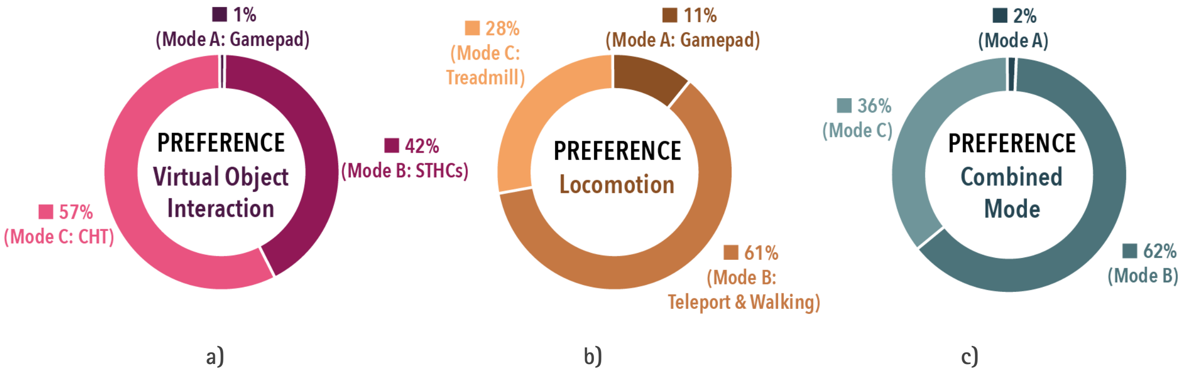

Figure 119: Participant Preferences for a) VOI mechanics, b) LOC mechanics and c) Combined Modes

By conducting three non-parametric *Chi-Square Goodness of Fit* tests (minimum expected frequency = 29.7 and level of confidence $p < 0.05$, Laerd Statistics 2015a and b), I determined significant differences between the participants' *Preferences* for the *VOI* mechanics, the *LOC* mechanics and the *Combined Modes.* All p-values are < 0.0005.

Examining the participants' simple *Preferences* regarding *VOI, LOC* and *Combined Modes* (see Figure 119a, b and c) in relation to the previous results, it becomes apparent how players in the end prioritize the corresponding advantages and disadvantages of the interfaces.

Although *Mode A* did not score well in terms of *UX* for the majority of users, a small minority of players actually prefers this mode over the others. This is likely due to the gaming experience of the corresponding participants and in respect to the gamepad, *Mode A's* combination of an innovative *VOI* mechanic and a rather common *LOC* mechanic, even though some practice is needed. Finally, some players just preferred a seated experience.

As a *Combined Mode, Mode B* clearly scored best, with almost two thirds of participants. Similarly, its *LOC* mechanic, using teleportation and walking, scored very well amongst players, confirming the other *UX* results. It is interesting though, that although using *STHCs* for *VOI* seemed to work more reliably and was generally enjoyed, less players preferred it over *CHT.*

On the other hand, *CHT* in *Mode C* was preferred by a majority of users. This was likely due to the high-fidelity hand representations and the strong *Presence* feeling, even though there were many complaints about the tracking's limitations. In contrast, *LOC* via the assessed treadmill was only preferred by less than a third of the participants. Finally, as a *Combined Mode, Mode C* was preferred by slightly over a third of the players, confirming the other *UX* results.

4.3.4.3.4 Experiment Limitations

The experimental procedure included filling out a questionnaire after each interaction mode, including Likert scale as well as free text questions. This resulted in several shifts of media for the participants (from *VR* to questionnaire and back etc.), including corresponding *Breaks-in-Presence.* The latter may likely have been experienced stronger by users due to the shifts of media compared to "in-VR questionnaires" (Schwind et al. 2019 and Putze et al. 2020), possibly resulting in slight overall uncontrolled biases regarding *Presence* (Putze et al. 2020). On the other hand, these shifts of media were inevitable, as the hardware setups needed to be changed between the modes by the researcher. Furthermore, this procedure provided participants with a phase of recovery (e.g. regarding *Simulator Sickness),* while also keeping the memory of the latest experience fresh and accurate for the relatively complex double questionnaire. Finally, order effects could be mitigated like this and self-reporting participant evaluations could be more clearly referenced to the most currently used mechanics.

4.3.4.3.5 Experiment Conclusion

> This [study] illustrated how to implement a highly optimized *VR* game or non-gaming application with sophisticated interaction requirements, while offering compatibility to a broad range of consumer-oriented hardware setups. The respective study assessing these *VR* setups and their underlying *VOI* and *LOC* mechanics provided corresponding individual advantages and disadvantages related to *UX* and general requirements.
>
> *Mode A* marks the low-end setup in this study, not requiring a large playing area and as a seated experience it provides a certain attraction for some users. However, it was outperformed in all assessed *UX* aspects. This is likely due to the limited inherent interface possibilities of the gamepad, which resulted in a complex input scheme requiring more adaptation time from users.
>
> *Mode B* comes with medium costs but requires a rather large playing area for *Roomscale* tracking. It scored either on par or better than *Mode C,* regarding *PE* and *SoG* and was generally well accepted as rather intuitive and well-fitting for *VR.* Additionally, it induced a strong *Presence* feeling, while minimizing *SimSick.*
>
> *Mode C* marks the high-end setup in this study, also not requiring a large playing area and seemingly especially suitable for running applications. It performed either on par or slightly worse than *Mode B* regarding *UX.* The naturalness of *CHT* induced a very high *Presence* feeling. Nevertheless, both the hand and feet motion tracking devices revealed their limitations. Thus, *VOI* was not as robust and *LOC* not as precise or versatile, as the corresponding mechanics in *Mode B.*
>
> Future research could take multiple directions. E.g. follow up experiments could investigate the *VOI* and *LOC* mechanics separately. Furthermore, optimizations and extensions could be applied to the mechanics: e.g. using more sophisticated grab methods, adding a calibration procedure to create individual *ROVR* profiles for user motion and body dimensions, adding a turning prediction to allow more fine-grained movements, using a more sophisticated treadmill altogether and further optimizing the fallback system handling grabbing hands leaving the sensor frustum.
>
> (Wiedemann et al. 2020)

4.3.5 DISTINCTIONS

4.3.5.1 Leap Motion 3D Jam powered by IndieCade – 12th Place Semifinalist Award

The game was awarded with the 12th place as a semifinalist in this online competition with over 150 entries (see *Appendix E.3* on page 261), including a cash reward.

4.3.5.2 SciFi-It'2020 – Best Paper of Conference Award

The corresponding paper to the before-described experiment on *UX Evaluation of VR Locomotion & Virtual Object Interaction Mechanics* (see from page 150ff.) was awarded with the *Best Paper of Conference* award for the international *SciFi-It'2020* conference in *Ghent, Belgium* (see *Appendix E.4* on page 262).

4.3.6 REFLECTIVE DISCOURSE

As part of the *CDR* approach, the following section will reflect more thoroughly on some of the aspects of the artifact's development and its corresponding studies.

Gooze is a very successful artifact, best fitting the mantra of creating a game from the ground up specifically for *VR.* It provides an attractive gameplay, intriguing visuals, a captivating storyline and a mechanically comfortable player experience. At the same time, although its content is very limited, it is easily the most complex artifact from the portfolio with a 60% larger code base compared to the other two games. This amount of code was required for several reasons: The game should be comfortably playable with a diverse range of input devices. Custom editor tools should simplify development and further extending the game content. Finally, various effect subsystems should provide an immersive experience regarding visuals, audio and haptics, ultimately leading to a high-quality experience. This is also supported by the positive player feedback gathered through the various *Showroom* demos and the *Lab* experiment.

Gooze also worked as a testing platform for various mechanics in *VR,* with a focus on *Locomotion* and *Virtual Object Interaction*, although other aspects were explored as well. The game's development benefited the parallel developments of the other two artifacts, as general insights on comfortable *VR* could partly be transferred (e.g. constantly high framerates, a reduced smooth *Locomotion* pace and the reduction of overlaying *GUI* elements). Also, the general implementation of the *Oculus SDK* and its various features and options could be explored and improved. During the development of the game, some issues regarding the pre-consumer-release versions of the hardware and software needed to be fixed. I implemented solutions like dynamic resolution scaling to reduce the negative effects of framerate drops and added a brightness adjustment layer for one eye, as the *DK2* for some reason did show a disparity between both eyes. These issues have been resolved in later hardware and software versions and even some strategies, like dynamic resolution scaling, have been included into the official *SDKs.*

The development of *Gooze* clearly showed the need to more thoroughly research diverse approaches on *VR Locomotion* and *Virtual Object Interaction.* Hence, the *Lab* experiment on *UX Evaluation of VR Locomotion & Virtual Object Interaction Mechanics* (see from page 150ff.) was conceived. It was also easily the most complex experiment, requiring the most preparations, conducted with the largest participant panel, capturing the largest amount of data by far, in this research. In turn, this even led to developing a special tool to simplify the clustering and evaluation of qualitative comments (see *Appendix D.2 Text Clusters Generator* from page 258ff.) and ultimately a very differentiated evaluation of the mechanics.

The user's *Rollenwahrnehmung* in *Gooze* is affected in multiple ways. How to utilize the interaction mechanics is made very clear, so the user can achieve his or her goals as well as possible. On the other hand, in terms of content and storyline, the player is purposefully left in uncertainty regarding his or her role in the plot. Only minor hints, disguised as thoughts of the player character, provide a bit of guidance on how to progress in the game. The game tries to create a strong connection between the user and the player character, e.g. by using thought subtitles instead of pre-recorded voice samples. This is to increase *Immersion* and eventually, to envelop the player more tightly in the horrifying experience, which is further strengthened by making use of the *1st Person Perspective.*

In turn, the user's visual *Perspective* is unbreakably linked to the one of the player character and mimics one of a regular human being. On the other hand, the game does not directly provide a *Perspective* on the storyline in the metaphorical sense. Instead, it tries to leave room for the player's own thoughts and interpretations of the situation, pulling him or her deeper into the experience. Additionally, the clue at the end of the story supposedly creates a shift in *Perspective*, as with uncovering this idea of overcoming multiple personalities, a completely different impression of the whole previous part of the game is presented.

The game handles *Space* in various forms. The possibility of using a rather large *Roomscale* play area or instead just the footprint of a single chair, creates a dynamically scalable physical *Space* for gaming. In contrast, the virtual *Space* is fixed, but it tries to create spatial situations which affect the player's feelings. E.g. looking through the hole in the wall may satisfy the user's curiosity but may also induce a sense of vulnerability in this horrifying environment. Although this may also be true for other *VR* applications, *Gooze* of course generally transforms the *Space* around the player into a scenery, which is fundamentally different, mysterious and emotionally charged. Finally, the different *Locomotion* mechanics also affect the perception of the physical and virtual *Space.* Some of them require physical movement, which more closely links the physical to the virtual *Space* and others make use of abstract procedures like teleportation, clearly separating the connection between the physical and the virtual *Space.*

4.3.7 CONTRIBUTION TO OVERALL STUDY

The artifact *Gooze,* its various iterations and the *Showroom* and *Lab* investigations provide several contributions to the overall study.

A general know-how for implementing *1st Person VR* experiences was established, also benefitting the development process of the other two artifacts *Nicely Dicely* and *LizzE.* Especially the important topics of performance optimizations, *VR Locomotion, Virtual Object Interaction* and implementing well-designed interfaces for different input hardware, could be explored.

The *Showroom* demos resulted in several informal, but nevertheless important and easy to gather understandings on general aspects of the artifact and essential user guidance within modern *VR* applications. Furthermore, especially the obstacles concerned with *VR Locomotion* and *Virtual Object Interaction* could be observed, inspiring ideas for later solutions. The *Lab* experiment, with refined versions of previous interaction mechanics and additional ones, created a better understanding of these topics via a deeper investigation. This led to a differentiated analysis of the tested mechanics, including a breakdown of their up and downsides.

Regarding the investigation of the three guiding key areas, *Gooze* provides its individual take on these. The *Rollenwahrnehmung* is clearly affected in a multifaceted way. It is made very clear how to utilize the interaction mechanics so the user's goals can be achieved. In contrast, it also involves the player being left in uncertainty, regarding his or her role in the plot, while trying to create a deep connection to the player character and ultimately the whole experience, which is further strengthened by using the *1st Person Perspective.* Hence, the visual *Perspective* of user and player character are identical and mimics a human being. On the other hand, a *Perspective* on the storyline is not directly provided, highlighting the player's own thoughts and interpretations. Only eventually, the clue at the end of the game's storyline creates a shift in *Perspective. Space* is affected in several ways, too. It is possible to play the game in small and large physical areas. Whereas the game transforms the physical *Space* into a mysterious virtual scenery, including diverse spatial situations, trying to provoke emotions in the player. Due to their fundamental differences, the *Locomotion* mechanics further affect the user's perception of the physical and virtual *Space.*

Finally, the artifact *Gooze* and its documented iterations act as an individual precedent for design, development and research and thus add significant elements to the overall precedent, i.e. the portfolio of artifacts.

4.4 CRITICAL REFLECTION SUMMARY

The following section will link together the previous three research projects and summarize their critical reflections.

As previously mentioned, the process of the overall study was not a linear one. The development of the three artifacts sometimes overlapped, whereas during other times, there was a concentrated focus on just one of them. Although it was not obvious how the different projects may be connected together, there was always a steady exchange of knowledge and insights between the artifacts. This interlocking exchange happened on different levels, including development, design and research and was amplified through the freely evolving and non-linear nature of the whole process. Although each of the three artifacts and their respective research projects show individual specifics, the connection between them is also clearly reflected in the very similar structure of the previously presented three exegeses.

The development processes of all three artifacts could be structured in iterations, illustrating the *Constructive Iterative Cycle* (see section *Individual Configuration of CDR* from page 64ff.). So, one or multiple ideas would be designed and developed to a prototype, which would be tested by users during *Showroom* demos or *Lab* experiments. Following, the established outputs and the artifacts themselves would be evaluated, leading to the completion and possibly the restart of the *Constructive Iterative Cycle.*

The previous chapter documented the various iterations of the three artifacts, highlighting certain design aspects, features and issues of diverse kinds. Related custom software development solutions are further described in the *Appendix C Software Developments for Artifacts* from page 243ff. Due to the limited space of this thesis, it is not an exhaustive documentation of the artifacts and their iterations, but a selection of their most prominent aspects.

Nicely Dicely received the most iterations and is surely the most complete one amongst the three games. It is not a *VR* game per se, but it investigated the related and important aspects of *3D Stereoscopy* and *Immersion.* With its *Local Multiplayer* game concept, it adds an important *Social Game Type* and diversifies the portfolio with it.

The base version of *LizzE – And the Light of Dreams* was developed before the overall study began. Because of that, it was a great starting point to explore various technologies, ultimately leading to *3D Stereoscopy* and *VR* ports of the game, both supporting the developments of the other two artifacts. Furthermore, its *3rd Person Perspective* added a more exotic twist to designing *VR* games and thus led to the development and investigation of several camera behavior modes.

Gooze was conceived as a *1st Person VR* game right from the start, benefitting from the developments of the other two artifacts. It always tried to deliver the best *UX* with the current cutting-edge technologies and received the longest development time. Although its playable content is limited, it is the most complex one of the three artifacts, due to its successful implementation of a very diverse range of input devices and corresponding interaction mechanics. This also led to a differentiated and elaborate investigation of the respective *VR Locomotion* and *Virtual Object Interaction* mechanics.

Still, as the artifacts are highly interactive and dynamic applications, experiencing them at firsthand definitely further extends the previously documented knowledge and provides a more complete understanding of them.

The previous chapter furthermore elaborated on the studies conducted with a diverse audience of users.

For each artifact various *Showroom* demos could be documented, ranging from thematically related public *Meetup* events, over online competitions, to research conferences and more. Although these events included only informal play testing sessions, the respective insights gathered in a straightforward way, were vital to improving the design and development of the artifacts.

There was also one *Lab* experiment conducted with each artifact, investigating a specific topic in a more scientific manner.

Nicely Dicely's experiment was concerned with how *3D Stereoscopy* would affect *Immersion* in *Local Multiplayer* situations. Its results suggest that *3D Stereoscopy* indeed does increase *Player Immersion* even in a possibly distracting environment, which may include chatting and friendly banter amongst players.

The experiment conducted with *LizzE* investigated five different *3rd Person* camera behavior modes in *VR.* In the context of a level design, freely explorable in all directions, the *Buffered Pulling* mode seemed to provide the most comfortable and usable *UX* amongst the tested camera behaviors.

The third and last experiment, was conducted with the *1st Person VR* game *Gooze.* It was concerned with evaluating the *UX* of three *Locomotion* and three *Virtual Object Interaction* mechanics in *VR,* as well as their combined interaction modes. The mechanics were based on utilizing a diverse range of consumer input devices and covered several playing scenarios, including seated and *Roomscale* experiences. The experiment resulted in a differentiated evaluation of the mechanics and an individual breakdown of up and downsides for each of them.

The previous chapter additionally documented various distinctions in the fields of design, game design and research, which could be achieved with the artifacts and their research projects.

Furthermore, the chapter presented a reflective discourse for each artifact's development and its corresponding studies. Despite the non-linear research process obscuring this a bit, the overall study was clearly interconnected. Hence, deeper reflection and critical discourse could arrange the different research pieces along a central theme guided by the three key areas: *Rollenwahrnehmung, Perspective* and *Space.*

This process eventually also led to the overarching research question **"In which ways may *VR* game interfaces affect *Rollenwahrnehmung, Perspective* and *Space* for the player?".** The very diverse artifacts, game concepts and studies led to a manifold answer to this question.

Finally, the previous chapter also provides individual summaries of what each artifact contributes to knowledge and the overall study.

5 CONCLUSION

The following chapter will summarize the achievements of this research, including its contributions to knowledge. It will further illustrate possible areas for future research and provide an overall conclusion.

5.1 CONTRIBUTIONS TO KNOWLEDGE

At the beginning of this thesis several aims and research questions were defined for the overall study. The subsequent elaboration will reference them and provide specific responses.

5.1.1 THREE DIGITAL GAME ARTIFACTS

As the overall study belongs to the field of practice-based research, its foundation lies within its practical output. For that reason, a portfolio of three unique digital games was designed, developed and evaluated over several iterations. For a more complete understanding of these dynamic and highly interactive artifacts, they should be experienced at firsthand. Still, the previous chapter provided a detailed documentation of the games and their respective iterations and studies.

Nicely Dicely stands out through its *Local Multiplayer* gameplay in one screen and its *3D Stereoscopy Mode.* Although not being a *VR* game per se, it explored related and important aspects of the medium. Furthermore, it is the most complete game in the portfolio and provides the most polished gameplay.

LizzE – And the Light of Dreams is distinguished by its *3rd Person Perspective.* Utilized as an investigative platform, it explored adding *3D Stereoscopy* and *VR* to an existing game. This resulted in identifying respective challenges (e.g. handling *GUIs* in *3D Stereoscopy)* and innovating and testing first solution approaches.

Gooze was conceived as a *1st Person VR* game right from the start. It is highlighted by its compatibility with a diverse range of input devices and its corresponding *VR Locomotion* and *Virtual Object Interaction* mechanics. It is the most complex one amongst the three artifacts and provides a very differentiated evaluation of its mechanics. Although its content is limited, it presents the most sophisticated *VR* experience in the portfolio.

In combination with this thesis, the portfolio of artifacts serves in whole as a complex precedent for academia and provides inspiration and guidance for the design and development of a diverse range of digital games with a focus on *VR.*

Additionally, each artifact on its own serves as an individual precedent, contributing to knowledge in research and practice in the areas of *HCI, VR* research, games research, interaction design, game design, game development and *VR* development.

5.1.2 GUIDELINES FOR SPECIFIC ASPECTS OF VIRTUAL REALITY GAMES

There is a plethora of details regarding the design and development of digital games and *VR* applications, which can be extracted from the previous documentations of artifacts and *Appendix C Software Developments for*

Artifacts from page 243ff. The following will outline the most prominent general topics and summarize the knowledge gathered through the three *Lab* experiments on very specific aspects.

In general, when trying to develop believable and captivating *VR* games, it is important to aim for an extensive *Immersion* and ultimately *Presence* of the player. To achieve this, the overall *UX* needs to be fine-tuned in all its facets and should be tested with actual users, most likely resulting in multiple iterations. Good game design, providing appropriate *Flow* for the player is of course a general requirement. More specific to *VR* games, further topics gain additional importance. In this "new" medium, well-designed user guidance is essential for players to quickly understand possibly novel interaction paradigms, corresponding interface mechanics and the technical limitations of the hardware. Maybe the most important topic, when developing any kind of *VR* application, is minimizing the possibilities for *Simulator Sickness.* From the perspective of an end product developer, to achieve this, the two most essential topics are rather constantly reaching the framerate of the aimed for *HMD* and providing well-designed and evaluated interfaces for the player. E.g. *GUIs* in *3D Stereoscopy* can be problematic and should either be integrated and handled with care or entirely circumvented by using alternative design paradigms.

Further interfaces and related aspects were examined during the *Lab* experiments, leading to very detailed knowledge (see corresponding *Experiment Results* sections from page 94ff., 121ff. and 158ff.). The following guidelines could be extrapolated from them.

In which ways can *3D Stereoscopy* affect *Immersion* for the player of a *Local Multiplayer* game:
The *Immersion* of the player can be increased by applying *3D Stereoscopy* to a game, even in a *Local Multiplayer* environment, including chatting and friendly banter between players. The *Lab* experiment conducted with *Nicely Dicely* produced the respective statistically significant results.

In which ways can *3D Stereoscopy* affect gameplay for the player of a *Local Multiplayer* game:
The same experiment also led to the conclusion that adding *3D Stereoscopy* to a game not only results in an increased perceived realness and graphical attractiveness of the *VE,* but furthermore in a subjectively better gameplay, caused by an improved depth perception.

In which ways can *3rd Person VR* games work for a broad audience:
The *Lab* experiment with *LizzE* made clear, that *3rd Person VR* can only work for a broad audience, if causes for *Simulator Sickness* are reduced to a minimum, while still maintaining an attractive gameplay and that an appropriate camera behavior is essential in achieving this. Although the experiment's quantitative results did not always show statistical significance (significance level at $p < 0.05$), regarding them in combination with the qualitative comments led to the following recommendation: With a level design, freely explorable in all

directions, from the tested camera behavior modes, fine-tuned versions of *Buffered Pulling* (default) and *Blink Circling* (optional) should be offered. This gives the users the option to play via physical movement or stationery, e.g. in a seated position.

In which ways can *VR Locomotion* mechanics affect the *User Experience* of a player:
The *Lab* experiment with *Gooze* provided a very detailed evaluation of the tested interaction mechanics for this and the next research question. Its results were based on a combination of qualitative and quantitative data, with the large majority of the latter providing statistical significance.

If there is no space available for a *Roomscale* setup or the user aims for a seated experience or a traditional input mechanic, *Locomotion* with the gamepad is a viable solution. However, this mechanic was outperformed in all assessed *UX* aspects and may clearly cause *Simulator Sickness* issues for sensitive users.

Using physical walking and teleportation in a *Roomscale* setup was generally well accepted. Furthermore, it provided a strong *Presence* feeling, while minimizing *Simulator Sickness.* Still, the teleportation mechanic required a bit of practice.

Although the treadmill offered physical *VR Locomotion* on a rather small footprint, the tested device did not support precise or versatile control over the virtual movements. Nevertheless, it decently scored with the assessed *UX* aspects, clearly outperforming the gamepad, but generally staying behind walking and teleporting.

In which ways can *VR Virtual Object Interaction* mechanics affect the *User Experience* of a player:
Virtual Object Interaction via the gamepad was limited by the device's inherent interface capabilities, which resulted in a complex input scheme requiring more adaptation time from players. Due to its complexity, the mechanic did not score well across the *UX* assessment in comparison to the other ones. Nevertheless, gamepad experienced participants praised the clever implementation and a small number of them even preferred this mechanic over others.

Using *Spatially Tracked Hand Controllers* for *Virtual Object Interaction* was a well-accepted solution in *VR.* Although it requires the corresponding physical space for the movements, it generally provided a solid tracking and a rather intuitive and versatile *UX.*

Regarding the induction of *Presence* though, the natural *Controllerless Hand Tracking* received better scores and pulled the user even further into the experience. Still, its tracking revealed several limitations and could not reach the robustness of the *Spatially Tracked Hand Controllers.*

This set of guidelines and knowledge for *VR* game design and development, extrapolated from the artifacts and their studies, supports a variety of game types and addresses a multitude of important *VR* aspects, contributing to the areas of *HCI, VR* research, games research, interaction design, game design, game development and *VR* development.

5.1.3 ROLLENWAHRNEHMUNG, PERSPECTIVE & SPACE

The discussion in the *Context* section and the reflective discourse of the three artifacts has successfully established the term *Rollenwahrnehmung.* Due to its foundation in the German language, it instantly fits into the already established German-based psychological terminology. Furthermore, *Rollenwahrnehmung* provides a unique meaning composited of the terms "role", "perception" and "fulfillment" and thus describes a very specific psychological aspect. The usage of the term in this thesis has shown its contribution to the areas of philosophy, psychology and game design.

Over the course of this research the following main guiding research question arose:

- **In which ways may *VR* game interfaces affect *Rollenwahrnehmung, Perspective* and *Space* for the player?**

The following will provide summarized replies to the contributory sub-questions, based on different aspects extrapolated from the creation and evaluation of the three artifacts.

In which ways may *VR* game interfaces affect *Rollenwahrnehmung* for the player:

In *Nicely Dicely* the *Rollenwahrnehmung* is purposefully kept loose and easy, to support the party game concept of the game. Whereas the *VRification* of *LizzE* clearly affected the user's *Rollenwahrnehmung* through the *Entity Split*, meaning he or she does not directly identify anymore with the player character, but instead feels as a separate and independent entity. In *Gooze* the user is clearly informed about how to utilize the interaction mechanics to achieve his or her goals. Still, the *Rollenwahrnehmung* involves the player being left in uncertainty, regarding his or her role in the plot, while trying to create a deep connection to the player character and ultimately the whole experience.

In which ways may *VR* game interfaces affect *Perspective* for the player:

Further supporting the party game concept, *Nicely Dicely* uses a single *Perspective* shared by all players, making it more accessible. This visual *Perspective* is altered when switching between *Non-3D Monoscopic* and *3D Stereoscopic Vision.* The *Entity Split* in *LizzE* not only caused a change in visual *Perspective*, but also one in the metaphorical sense, which raises new communication and interaction possibilities between player, player character, *NPCs* and the game world. The game's diverse camera behavior modes further approach the visual *Perspective* in *3rd Person VR* in different ways. In the *1st Person* game *Gooze* the visual *Perspective* of user and player character are identical and mimics a human being. On the other hand, a *Perspective* on the storyline is not directly provided, highlighting the player's own thoughts and interpretations. Only eventually, the clue at the end of the game's storyline creates a shift in *Perspective.*

In which ways may *VR* game interfaces affect *Space* for the player:

The *Local Multiplayer* aspect in *Nicely Dicely* transforms the *Space* around the game and its players to a shared and communicative gaming *Space*, getting further connected by visually merging the physical with the virtual

Space through *3D Stereoscopy.* Although not being unique to *LizzE,* its *VRification* is concerned with the transformation of *Space,* as the look through a small window into a *VE* shifts to an encompassing virtual experience for the user. In *Gooze, Space* is affected by being able to play in small and large physical areas. The game also transforms the physical *Space* into a mysterious virtual scenery, including diverse spatial situations, trying to provoke emotions in the player. Due to their fundamental differences, *Gooze's Locomotion* mechanics further affect the user's perception of the physical and virtual *Space.*

These reflected rationales, on how presented *VR* game interfaces affect *Rollenwahrnehmung, Perspective* and *Space* for the user, contribute to design, *VR* and games research, as well as inspires game design.

5.1.4 EXTENDING CONSTRUCTIVE DESIGN RESEARCH

CDR was successfully applied as an overarching methodology for this research. Its flexible, iterative and reflective approach very much suited the creative and constructive nature of the overall study.

Although, other works related to games (e.g. Garner et al. 2014 and Kajastila et al. 2016) or *VR* (e.g. Usoh et al. 1999 and Stoakley et al. 1995) can be considered *Constructive Design Research,* they rarely clearly name or reference this methodological underlying.

In contrast, the portfolio of games and this thesis represent an explicitly referenced and effective utilization of *CDR* in the area of designing and developing digital games, *VR* artifacts and corresponding interfaces, contributing to the respective communities in research and practice.

Additionally, the rationales behind the various *Showroom* and *Lab* examinations, as well as their specific evaluation methods, extend the toolset of *CDR* and may be of interest to designers and researchers alike. This includes introducing e.g. game festivals, game jams, gaming parties, game development meetups, game pitches and academic conferences as *Showroom* demo events, during which informal user feedback can be gathered. Furthermore, the three *Lab* experiments illustrated effectively utilizing subjective evaluation methods like the *IPQ,* as well as custom questionnaire elements to assess *UX* aspects like e.g. *Player Enjoyment, Support of Gameplay* and *Simulator Sickness.* Also, the objective in-game parameter tracking during *Lab* experiments led to relevant results. Finally, presenting these subjective and objective, as well as qualitative and quantitative results in a combinatory manner concluded in specific, but more holistic evaluations of matters.

5.1.5 HYBRID JOURNALING TECHNIQUE USING VERSIONING REPOSITORIES

In which ways can versioning repositories, used in software developments, contribute to journaling aimed for reflection:

Two essential aspects of this research were concerned with developing software and using reflection for later evaluation. In modern software development it is common practice to use versioning repositories to track changes and make them easily reversable. In the case of developing the three games, I was regularly committing changes using *git* repositories, including more and more detailed commit messages. The value lying in these messages became clear, wanting to retrace certain developments, timeframes and relationships between systems.

In parallel I irregularly also maintained a hand-written research journal for more general and overarching aspects of this research. So, during the overall study, I decided on embracing this situation and actively fostering the *Hybrid Journaling Technique*, by adding more details and thoughts to the commit messages, very much supporting the later reflective process.

This technique may be particularly useful to the communities of design research, software development of all sorts and *HCI.*

5.2 AREAS FOR FUTURE RESEARCH

Based on this work there are numerous possibilities for future research, some of which are related to the overall study in a more general sense, whereas others are more specific to a certain artifact or a corresponding study.

As this research is based on three design precedents, it is of course possible to create further games, focusing on different gameplay and other kinds of interactions, to widen the variety of the portfolio and thus cover additional areas of interest.

Although *Simulator Sickness* always played an important role during the assessment of an artifact, a more detailed evaluation of the topic could be useful. Based on the existing portfolio of artifacts, conducting between-subjects studies with more elaborate examination tools could lead to a better understanding of *Simulator Sickness* in *VR* games and its causes.

Regarding the methodology of this research, it would be interesting to explore the *Hybrid Journaling Technique* for reflection in more detail, possibly also in software development projects of other industries.

As the applied *Constructive Iterative Cycle* forms a loop, the existing artifacts could theoretically be further adjusted, fine-tuned and evaluated over an infinite number of iterations. The following will outline some related suggestions.

As v2 of *Nicely Dicely* was evaluated during the game's *Lab* experiment, it would already be possible to repeat the study with v3.2, including the spatialized cooldown *HUDs* and the optimized gameplay. Such an experiment could further benefit of a larger sample size and a specifically prepared "non-laboratory-like" playing environment. Hence, it could test this iteration of the game for a higher *Preference* of *3D Stereoscopy* and an increased effect on *Immersion*.

Regarding the *Lab* experiment with *LizzE,* the two recommended camera behavior modes *Blink Circling* and *Buffered Pulling* could be further optimized to counter their weak points. The *Blink Circling* approach could benefit from well-designed graphical indicators for the "north" direction and when the next blink will be performed, improving the orientation of users. These *UI* solutions could be applied in an onboarding process and made optional for the user. Other fixed angle configurations (e.g. steps every 90°) and blink countdown times could also be explored. The *Buffered Pulling* approach could also be improved by adding a directive indicator for the player character, once it leaves the viewport. It would furthermore be interesting to explore automatically circumnavigating the user's position, so the player character could not be steered right below him or her. Of course, further camera behavior approaches could be explored, too. These could include ones, which let the player manually control the camera or which are utilizing scripted level dependent camera angles.

The *VOI* and *LOC* mechanics tested in the *Lab* experiment with *Gooze* could also be further optimized and adjusted. Grabbing objects would likely benefit from the more sophisticated grab methods described in the section *Virtual Object Interaction* (from page 34ff.). The suboptimal fallback system, freezing grabbing hands when they leave the sensor frustum, could be improved. A calibration procedure, creating individual user motion and body dimension profiles could be added to improve the usability of the *ROVR* treadmill. Furthermore, a turning prediction algorithm could allow more fine-grained movements. Finally, a more sophisticated treadmill could be used altogether.

5.3 OVERALL CONCLUSION

This *PhD* thesis forms the exegesis to the portfolio of three *VR* related gaming artifacts, i.e. *Nicely Dicely, LizzE – And the Light of Dreams* and *Gooze.*

In the beginning, it introduced the general area of this practice-based research, outlined the *PhD* design research process and provided definitions for the three guiding key areas *Rollenwahrnehmung, Perspective* and *Space.* Subsequently, it defined to the overall study specific research questions, listed its aims and contributions to knowledge and outlined its boundaries.

The following chapter elaborated on the three-part state-of-the-art *Context,* in which this research took place. The *Literature* review discussed works concerned with practice-related research, the three guiding key areas, subjective aspects of immersive experiences and specific interface related aspects. The *Technology* review introduced the hardware technologies directly involved in the overall study (i.e. *PC VR HMDs,* control peripherals and a *Stereoscopic 3D Projection* system) and illustrated why they were chosen. The *Games & Experiences* review discussed various relevant *VR* applications and how they related to the three artifacts of the overall study.

The subsequent *Methodology* chapter was concerned with discussing the overall approach of this research. It elaborated on *Design Research* and specifically *Constructive Design Research* as the overarching methodology, exercised critique on it and presented its applied individual configuration. Additionally, the *Hybrid Journaling Technique* using versioning repositories for reflection was described.

The chapter *Critical Reflection: Artifacts & Studies* documented the various iterations of the three games *Nicely Dicely, LizzE – And the Light of Dreams* and *Gooze* and elaborated on their respective *Showroom* and *Lab* studies. Furthermore, a reflective discourse was provided for each artifact and their contributions to the overall study were outlined.

Following, this *Conclusion* chapter provided a summary of the overall study's various contributions to knowledge and an outlook for possible areas of future research.

Finally, in the succeeding section all *References* will be listed and the *Appendices* will provide an exhaustive glossary and relevant supplementary information and materials.

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APPENDICES

A. GLOSSARY & ACRONYMS

In this thesis, certain terms are used, which might be interpreted in various ways by numerous disciplines. Because of that the following glossary will define these terms for the purpose of the overall study and list their acronyms.

A.1 1^{ST} PERSON PERSPECTIVE

In digital simulations *1^{st} Person Perspective* or *View* describes the point of view of an experience. In *1^{st} Person* the virtual camera/s are positioned where the head of the player character is positioned, so it feels like you are looking through its eyes into the *VE* (see page 211).

A.2 3^{RD} PERSON PERSPECTIVE

Unlike *1^{st} Person Perspective*, in *3^{rd} Person Perspective* the user can actually see the player character from the outside. The virtual camera/s hover in a certain distance behind or over it (Sabbagh 2015).

A.3 AAA – TRIPLE A

AAA stands for the highest level of production quality of a medium. For this thesis, *AAA* relates to very high-quality produced games.

A.4 AHRC – ARTS AND HUMANITIES RESEARCH COUNCIL

The *Arts and Humanities Research Council (AHRC)* is an organization which funds research across various disciplines, based in the *UK*.

A.5 AI – ARTIFICIAL INTELLIGENCE

Artificial Intelligence (AI) covers the whole range of computer-based intelligence from very complex dynamic neural networks to very simple hardcoded algorithms (de Byl 2012).

A.6 AMOLED – ACTIVE-MATRIX ORGANIC LIGHT-EMITTING DIODE

AMOLED is a specific version of the *OLED* display technology (see page 206).

A.7 ANOVA – ANALYSIS OF VARIANCE

An *ANOVA* is a tool to analyze differences between and among group means in an experiment sample, based on a statistical model (Laerd Statistics 2015c).

A.8 API – APPLICATION PROGRAMMING INTERFACE

An *Application Programming Interface (API)* identifies the accessible interface of a code base or software package, which can be utilized by a developer to create custom programming code connected to that package.

A.9 AR – AUGMENTED REALITY

Augmented Reality (AR) refers to a combination of the real world augmented with virtual objects (Jerald 2016). This can be achieved by using a semi-transparent display that shows overlaid virtual objects for example in special glasses or by using the camera image of a smart device and overlaying the displayed video stream with virtual objects on the device's screen. The overlaid virtual objects stay mapped to the real world through various tracking algorithms and like that seem to be part of it.

A.10 ARTIFACT

If not expressed differently, for this document, an *Artifact* is the result or an intermediate product, established through a creational process (Carroll and Kellogg 1989 and Koskinen et al. 2011). In the case of the overall study, it likely consists of a digital computer application that offers a way of visualizing information and graphics to one or more observers and might furthermore provide an interface for one or multiple users to interact with.

A.11 BREAK-IN-PRESENCE

When the illusion of being present in the *VE* (see page 211) collapses for some reason, this is called a *"Break-in-Presence"* (Slater and Steed 2000 and Jerald 2016). See *Presence* on page 207.

A.12 CCP

CCP is the game studio behind *Eve Valkyrie* (see from page 48ff.), based in *Iceland.*

A.13 CDR – CONSTRUCTIVE DESIGN RESEARCH

Constructive Design Research (CDR) is a methodology that focuses on the constructive and creational aspect of design research (Koskinen et al. 2011). This overarching methodology will be explained in more detail in the *Constructive Design Research* section (see page 17ff.) and its application in the overall study will be elaborated on in the *Methodology* section (see page 57ff.).

A.14 CHARACTER

For this thesis *Character* refers to a digital character entity (e.g. a person), which might either be a *Non-Player Character (NPC,* see page 206) controlled by the application's *AI* or a *Player Character* controlled by a user (de Byl 2012).

A.15 CHI PLAY

CHI PLAY is an international academic *HCI* conference with a specific focus on games and play (see page 88).

A.16 CHT – CONTROLLERLESS HAND TRACKING

Controllerless Hand Tracking (CHT) describes a technique to track the user's hands and their skeletons, without the need for holding any hand controllers (see from page 39ff.).

A.17 COMPONENT – UNITY

If no other meaning is apparent from the context, a *Component* in most cases refers to a *Unity Component.* The extensible *Unity Game Engine* uses a system of *Components* applied to *GameObjects*, to provide them with certain features. Custom *Scripts* can often apply their programming code by attaching them as *Components.*

A.18 CONSTELLATION TRACKING – OCULUS

The *Constellation Tracking* method (Wikipedia 2016a), was initially used for *Positional Tracking* (see page 207) by *Oculus.* One or multiple separate *IR* cameras keep track of the constellation of *IR LEDs* under the surface of the *HMD*, blinking in a certain pattern.

A.19 CPU – CENTRAL PROCESSING UNIT

The *Central Processing Unit (CPU)* is the main chip in a computer, handling the majority of the processing. See also *GPU* on page 201.

A.20 CV1 – OCULUS RIFT CONSUMER VERSION 1

The *Oculus Rift Consumer Version 1 (CV1)* was the company's first consumer *VR HMD* (see from page 37ff.).

A.21 DK1 – OCULUS RIFT DEVELOPMENT KIT 1

The *Oculus Rift Development Kit 1 (DK1)* was the company's first *VR HMD*, meant for developers, not consumers (see from page 37ff.).

A.22 DK2 – OCULUS RIFT DEVELOPMENT KIT 2

The *Oculus Rift Development Kit 2 (DK2)* was the company's second *VR HMD*, meant for developers, not consumers (see from page 37ff.).

A.23 DPS – DESIGN PRACTICE STREAM

The "*Design practice stream (DPS)* tools" are a software suite to comfortably handle recordings of software design meetings (Nakakoji et al. 2012, see from page 17ff.).

A.24 EEG – ELECTROENCEPHALOGRAM

An *Electroencephalogram (EEG)* is a method for recording and monitoring electrical brain activity (Wikipedia 2020a).

A.25 EXPERIENCE

Unlike *User Experience* (see page 211), an *Experience* in this case refers to some sort of variably interactive human computer artifact (Dewey 1980 and Koskinen et al. 2011). This might be a fully interactive digital game but could also refer to a less interactive and non-gaming context application between user and computer.

A.26 FIELD

The *Field* (Koskinen et al. 2011) describes a loose grouping of projects and the corresponding *CDR* toolset (see section *The Constructive Design Research Approach* from page 59ff.). See also *Lab* (on page 204) and *Showroom* (on page 209).

A.27 FIVE – FRAMEWORK FOR IMMERSIVE VIRTUAL ENVIRONMENTS

The *Framework for Immersive Virtual Environments (FIVE)* highlights several conditions, which can lead to *Immersion* (Slater and Wilbur 1997). For more details see section *Immersion* from page 22ff.

A.28 FLOW

"In an ideal situation where skills and challenges are high and in balance, an optimal state of flow occurs." (Csikszentmihalyi 1991). This *Flow* state can be seen as part of *UX* (see page 210) and describes the optimal state for the user, in which the user's skills are perfectly balanced with the current challenges, so neither frustration nor boredom establishes within the user. For more details see section *Flow* from page 26ff.

A.29 FOV – FIELD OF VIEW

The *Field of View (FOV)* describes the visible angle from a single point of view and a single point in time (Jerald 2016).

A.30 FPS – FIRST PERSON SHOOTER

A *First Person Shooter (FPS)* is a game of a common genre (Lugrin et al. 2013). In it, the user plays in *1st Person Perspective* (see page 197), most commonly with a gun protruding in from the lower viewport edge. As the name suggests, shooting makes up a big part of the gameplay.

A.31 FPS – FRAMES PER SECOND

FPS can also refer to *Frames per Second*, which is a unit to define how many frames (images) can be rendered and sent to e.g. a screen per second, the frame rate. It is a synonym for the frequency of displayed frames per second, which can also be declared in *Hertz (Hz)*. The difference to *First Person Shooter* will be clear from the context.

A.32 G – GENERAL PRESENCE

General Presence (G) is a subjective subscale of the *IPQ* (see page 203, igroup 2016).

A.33 GAME

If not noted otherwise, *Game* refers to a digital game with some form of human computer interface, that lets a single user or multiple ones interact with the game software application (Huizinga 1992 and Salen et al. 2003).

A.34 GAMEPAD

A *Gamepad* is a handheld controller device for the user, most commonly with buttons, triggers and analogue sticks etc. (see page 39).

A.35 GPU – GRAPHICS PROCESSING UNIT

The *Graphics Processing Unit (GPU)* is the chip in a computer specialized on processing graphics related calculations. See also *CPU* on page 199.

A.36 GUI – GRAPHICAL USER INTERFACE

The *Graphical User Interface (GUI* also *UI)* is a more obvious variant of the software interface, as it mostly refers to information made clearly visible to the user (Oulasvirta and Abowd 2016). This might for example be a non-interactive visualization of a compass on a map, but also the menu with its buttons and other interactive graphical elements.

A.37 GUID – GLOBALLY UNIQUE IDENTIFIER

A *Globally Unique Identifier (GUID)* is a specifically styled *ID,* which due to its length and pseudo randomized creation process basically guarantees uniqueness.

A.38 HACK AND SLAY

A *Hack and Slay* is a game of a common genre. In it, the user plays mostly in *3rd Person Perspective* (see page 197). As the name suggests, hacking and slaying e.g. monsters makes up a big part of the gameplay.

A.39 HCI – HUMAN COMPUTER INTERACTION

Human Computer Interaction (HCI) is a research field concerned with studying interfaces and interface designs between humans and computers.

A.40 HDK – HACKER DEVELOPMENT KIT

The *Hacker Development Kit (HDK)* is an open source hardware and software platform for *VR HMDs* and peripherals, hosted by *OSVR* (see page 225).

A.41 HDMI – HIGH-DEFINITION MULTIMEDIA INTERFACE

HDMI is a cable and transmission standard for transmitting digital video, audio and networking.

A.42 HMD – HEAD MOUNTED DISPLAY

Head Mounted Display (HMD) refers to a combination of display, optics and sensor technologies all combined in wearable goggles to create extended realities (Jerald 2016). In terms of *AR/MR* these can be semi see through or completely enclosing in terms of *VR.* If not noted otherwise, *HMD* refers to a *Virtual Reality Head Mounted Display* in this thesis.

A.43 HTC

HTC is a consumer electronics manufacturer, based in *Taiwan.*

A.44 HUD – HEAD-UP-DISPLAY

In the case of this thesis a *Head-up-Display (HUD)* means a semi-transparent *GUI* element (see page 201), which is commonly overlaid on top of the main viewport. A *HUD* in most cases displays additional meta information for the user, e.g. like available ammunition or health.

A.45 IDE – INTEGRATED DEVELOPMENT ENVIRONMENT

An *Integrated Development Environment (IDE)* is a comprehensive software for developers, with several integrated tools like code editor, debugger, build automation and more, depending on the exact *IDE* (Wikipedia 2019a).

A.46 IDEO

IDEO is an international design and design consulting company.

A.47 IMMERSION

Immersion can be seen as part of *UX* (see page 210) and describes the concentration or submerging of a user in for example a process, story, application or some other form of experience or activity (Oxford Dictionaries 2017a). In contrast to the *VR* specific form of *Immersion* (Slater and Wilbur 1997 and Jerald 2016), this mental aspect in general is not restricted to *VR.* See section *Immersion* for more details (page 22ff.).

A.48 IMU – INERTIAL MEASUREMENT UNIT

An *Inertial Measurement Unit (IMU)* is an electronic component (can be just one small form factor chip). Via a combination of accelerometers and gyroscopes, it measures forces and angular rate on its body and, when additionally equipped with magnetometers, the magnetic field surrounding it. Without any secondary correctional system, *IMUs* on their own mostly suffer from drifting caused by accumulated errors (Wikipedia 2016d).

A.49 INSIDE-OUT TRACKING

Inside-Out Tracking uses cameras attached to a device and advanced image processing to calculate *Positional Tracking* (see page 207) and possibly surfaces and physical object boundaries. For the *Oculus Rift S* and *Quest HMDs* the *Oculus Insight* method is used.

A.50 INTERFACE

An *Interface* refers to either a computer hardware technology that lets a user interact with an application, by sending and/or receiving input output *(I/O)* information to and/or from the user. For example, a game controller lets the user send button inputs to the application, from which it might also receive instructions to vibrate at certain situations. Or *Interface* may also refer to part of a software that handles *I/O* information inside the main application, which might or might not happen apparently to the user (Koskinen et al. 2011 and Oulasvirta and Abowd 2016). For example, the way a *Player Character* might be steered by the user, but also the rendered viewport of an application in a whole might be referred to as an *Interface*. This will be apparent from the context.

A.51 INV – INVOLVEMENT

Involvement (INV) is a subjective subscale of the *IPQ* (see page 203, igroup 2016).

A.52 IPD – INTER-PUPILLARY DISTANCE

The *Inter-Pupillary Distance (IPD)* mostly describes the physical distance between the pupils of a person, but it can also describe the closely related distance of two cameras, which are used to capture a *stereoscopic* image.

A.53 IPQ – IGROUP PRESENCE QUESTIONNAIRE

The *igroup Presence Questionnaire (IPQ,* igroup 2016) is a tool to subjectively evaluate the *Presence* feeling (see section *Presence* on page 207).

A.54 IQR – INTER-QUARTILE RANGE

The *Inter-Quartile Range (IQR)* is a term related to descriptive statistics. More specifically it "is a measure of variability, based on dividing a data set into quartiles" and it results from subtracting the first quartile from the third (Wikipedia 2019d). The *IQR* is often used to create box plots with whiskers and to define thresholds for mild and extreme outliers in a data set.

A.55 IR – INFRARED

Infrared (IR) describes a long wavelength part of the light spectrum, which is non-visible to the human eye, but can be captured by digital cameras.

A.56 ISO – INTERNATIONAL ORGANIZATION FOR STANDARDIZATION

The *International Organization for Standardization (ISO)* "is an independent, non-governmental international organization with a membership of 165 national standards bodies.", which "brings together experts to share knowledge and develop voluntary, consensus-based, market relevant International Standards that support innovation and provide solutions to global challenges." (ISO n.d.).

A.57 KURTOSIS

Kurtosis is used in statistics as a numerical measure to describe the convexity/concavity of a distribution of values, often to decide how close the latter is to a normal distribution (Laerd Statistics 2015g). Regarding normality, the *Kurtosis* value is analyzed in combination with a *Skewness* value (see page 209).

A.58 LAB

The *Lab* (Koskinen et al. 2011) describes a loose grouping of projects and the corresponding *CDR* toolset (see section *The Constructive Design Research Approach* from page 59ff.). See also *Field* (on page 200) and *Showroom* (on page 209).

A.59 LCD – LIQUID-CRYSTAL DISPLAY

LCD is a specific display technology for flat panels.

A.60 LED – LIGHT-EMITTING DIODE

An *LED* is a specific light emitting component, used in electronics.

A.61 LIGHTHOUSE TRACKING – STEAM VR

The *Lighthouse* or *Steam VR Tracking* technique is based on two base stations emitting structured light via lasers and simple photo sensors on objects to be positionally tracked (Wikipedia 2016c), like e.g. an *HMD.* It is used by the *HTC Vive* and *Valve Index* systems, but also by further *VR* products. See also *Positional Tracking* on page 207.

A.62 LOC – LOCOMOTION

Locomotion (LOC) in this document refers to the positional movement of a digital character or object in an application (Warren et al. 2001 and Jerald 2016). For more details see section *Lab Experiment: UX Evaluation of VR Locomotion & Virtual Object Interaction Mechanics* from page 150ff.

A.63 LOD – LEVEL OF DETAIL

A *Level of Detail (LOD)* system handles the automatic switching of e.g. textures and geometry according to the distance of the 3D objects to the camera. This is a performance optimization technique, so high quality assets are presented when the respective objects are close to the camera, whereas lower and lower versions of those assets are presented the further away they are from the camera.

A.64 M – JOYSTICK WITH A MONITOR

The *Joystick with a Monitor (M)* condition was part of a study on *Locomotion* techniques by Zanbaka et al. (see from page 31ff.). See also *RW* (on page 208), *VW3* (on page 212) and *VW6* (on page 212).

A.65 MDX – MIDDLESEX UNIVERSITY LONDON

The *Middlesex University London (MDX)* is based in the *UK.* It is the academic institute where this research was supervised.

A.66 MECHANIC

If not stated differently, *Mechanics* do not refer to any physical industrial machinery or parts of that. Instead a *Mechanic* refers to the metaphorical equivalent, which is to say a process or routine possibly involving several virtual parts and interface interactions, which combined in the right order form one procedure. E.g. collecting coins in *Nintendo's Super Mario Bros.* to guide the user on a specific route through a level or performing pinch and zoom gestures on a smartphone to zoom in or out of imagery are *Mechanics*.

A.67 MIT – MASSACHUSETTS INSTITUTE OF TECHNOLOGY

The *Massachusetts Institute of Technology (MIT)* is based in the *USA.* Its *Media Lab* is well-known for its design-oriented technology and media research.

A.68 MONOSCOPY

A *Monoscopic* image is based on one physical or virtual camera and ultimately results in a rather flat perception of the captured scene. See also section *Stereoscopy* on page 210.

A.69 MOTION TRACKING

Motion Tracking refers to the process of digitally acquiring accurate movement information of physical objects or persons via different sensor technologies. Subtypes are *Positional Tracking* and *Rotational Tracking* that do not only capture movements and rotations relative to some unknown initial state, but absolute values relative to physical space. See also Constellation Tracking – Oculus (on page 199), *Inside-Out Tracking* (on page 203) and *Lighthouse Tracking – Steam VR* (on page 204).

A.70 MPHIL – MASTER OF PHILOSOPHY

The *Master of Philosophy (MPhil)* is an academic degree. In the *UK, MPhil-PhD* research programs are widespread, during which it is possible to finish early with an *MPhil* or to transfer to *PhD* research after a certain time. See also *PhD* on page 207.

A.71 MR – MIXED REALITY

Mixed Reality (MR) is very similar to *AR* (see section *AR – Augmented Reality* on page 197) and refers to a combination of the real world mixed with virtual objects (Jerald 2016).

A.72 MS – MICROSOFT

Microsoft (MS) is an international software and electronics company.

A.73 MULTIPLAYER

See section *Social Game Type* on page 209.

A.74 NPC – NON-PLAYER CHARACTER

See section *Character* on page 198.

A.75 OASIS – ONTOLOGICALLY ANTHROPOCENTRIC SENSORY IMMERSIVE SIM.

The *Ontologically Anthropocentric Sensory Immersive Simulation (OASIS)* is some sort of fictional *VR Internet* from the story *Ready Player One* (Cline 2011), in which people can virtually do everything in a connected way.

A.76 OLED – ORGANIC LIGHT-EMITTING DIODE

OLED is a specific display technology, among other features, with flexible bending capabilities.

A.77 ONSP – OCULUS NATIVE SPATIALIZER PLUGIN

The *Oculus Native Spatializer Plugin (ONSP)* is a development software plugin concerned with simulating near-realistic sounding spatialized audio.

A.78 OSVR – OPEN SOURCE VIRTUAL REALITY

OSVR is an open source *VR* hardware and software platform.

A.79 OS X – MACOS

OS X or *macOS* is the operating system of *Apple* computers.

A.80 PBR – PHYSICALLY BASED RENDERING

Physically Based Rendering (PBR) or *Physically Based Shading (PBS)* is a certain kind of rendering and shading technique, which conforms to various physically based rules. This paradigm shift in handling rendering/shading and corresponding assets in turn creates very “realistic” looking materials.

A.81 PC – PERSONAL COMPUTER

A *PC* is a locally and individually used computer.

A.82 PCIE – PERIPHERAL COMPONENT INTERCONNECT EXPRESS

PCIe is a bus standard for possibly extending the hardware of a *PC.*

A.83 PE – PLAYER ENJOYMENT

Player Enjoyment (PE) was used as a subjective scale in combination with *Support of Gameplay (SoG*, see page 210) in several experiments of the overall study and is part of *UX.* In combination, both scales were used to evaluate if an interface would be enjoyable for the player on the one hand and if it would actually support the gameplay on the other hand.

A.84 PERSPECTIVE

In the case of this thesis, *Perspective* refers to one of the three investigated key areas of this research. See section *Perspective* from page 21ff.

A.85 PHD – DOCTOR OF PHILOSOPHY

The *Doctor of Philosophy (PhD)* is one of the highest academic degrees, awarded by universities in most countries after a course of study and research (Wikipedia 2020b). In the *UK*, *MPhil-PhD* research programs are widespread, during which it is possible to finish early with an *MPhil* or to transfer to *PhD* research after a certain time. See also *MPhil* on page 205.

A.86 PIFF – PRESENCE INVOLVEMENT FLOW FRAMEWORK

The *Presence Involvement Flow Framework (PIFF)* is a complex subjective game *UX* evaluation tool by Takatalo (2011).

A.87 PLAYER CHARACTER

See section *Character* on page 198.

A.88 POSITIONAL TRACKING

See section *Motion Tracking* on page 205.

A.89 PRESENCE

The feeling of *Presence* can be seen as part of *UX* (see page 210) and describes the "The feeling of being in a realistic place" (Lombard and Ditton 1997). This is arguably only possible through some form of *VR,* in which the user reacts to its *VE* (see page 211) out of instincts and previously learned behaviors. He or she feels like being really there in the *VE* instead of thinking of or realizing where he or she might be in physical reality (International Society for Presence Research 2000 and Jerald 2016). See section *Presence* for more details (page 24ff.).

A.90 PS – PLAYSTATION

The *PlayStation (PS)* is a gaming console from *Sony.*

A.91 PSVR – PLAYSTATION VIRTUAL REALITY

PSVR is a *VR* extension kit for the *PlayStation* gaming console.

A.92 RAM – RANDOM-ACCESS MEMORY

RAM is the non-persistent working memory of a computer.

A.93 REAL – EXPERIENCED REALISM

Experienced Realism (REAL) is a subjective subscale of the *IPQ* (see page 203, igroup 2016).

A.94 ROLLENWAHRNEHMUNG

In the case of this thesis, *Rollenwahrnehmung* refers to one of the three investigated key areas of this research. See section *Rollenwahrnehmung* from page 19ff.

A.95 ROOMSCALE TRACKING

Roomscale Tracking refers to a standing *VR* experience, in which the system's *Positional Tracking* makes it possible for the user to move and turn freely in a certain confined space (around the size of "a room") instead of a more directed and possibly seated experience (TechTarget 2016).

A.96 ROTATIONAL TRACKING

See section *Motion Tracking* on page 205.

A.97 RSS – RICH SITE SUMMARY

Rich Site Summary or *Really Simple Syndication (RSS)* is an *XML* format (see page 211) mostly used as a web feed, to index web articles and notify subscribers of updates to websites (Wikipedia 2020c).

A.98 RW – REAL WALKING

The *Real Walking (RW)* condition was part of a study on *Locomotion* techniques by Zanbaka et al. (see from page 31ff.). See also *M* (on page 205), *VW3* (on page 212) and *VW6* (on page 212).

A.99 SBS – SIDE BY SIDE

Side-by-Side (SBS) is one of several video formats, which are used to deliver *3D Stereoscopic* imagery. In *SBS3D,* the left and right frames needed for *3D Stereoscopy* are each squeezed to half of their width and placed in a single frame, most commonly with a final standard aspect ratio of 16:9 or 16:10. If viewed with a *3D* compatible setup, these left and right images are separated, stretched to their full width and then merged again to a *3D*

Stereoscopic View, e.g. by rapidly alternating between left and right eye and using synchronized *Shutter Glasses.* The downside of this format is the loss of half of the resolution.

A.100 SD – STANDARD DEVIATION

Standard Deviation (SD) indicates the variation of a set of values and is used as a measure in statistics (Wikipedia 2020d).

A.101 SDK – SOFTWARE DEVELOPMENT KIT

A *Software Development Kit (SDK)* commonly consists of a set of software development tools and libraries of a specific software package, so developers can more easily build upon an existing technology (Wikipedia 2019c).

A.102 SE – STANDARD ERROR

Standard Error (SE) is a measure in statistics (Wikipedia 2020e) and closely related to *SD* (see page 209).

A.103 SHOWROOM

The *Showroom* (Koskinen et al. 2011) describes a loose grouping of projects and the corresponding *CDR* toolset (see section *The Constructive Design Research Approach* from page 59ff.). See also *Field* (on page 200) and *Lab* (on page 204).

A.104 SIMSICK – SIMULATOR SICKNESS

Simulator Sickness (SimSick) is closely related to motion sickness or seasickness. This form of nausea and in extreme cases also vertigo can be experienced by users when using *XR* (see page 211). It establishes sometimes with some users when the experienced simulation differs too much in certain aspects with what their bodies expect in physical reality (Pausch et al. 1992 and Jerald 2016). For more details see section *Simulator Sickness* from page 27ff.

A.105 SINGLEPLAYER

See section *Social Game Type* on page 209.

A.106 SKEWNESS

Skewness is used in statistics as a numerical measure to describe the inclination of a distribution of values, often to decide how close the latter is to a normal distribution (Laerd Statistics 2015g). Regarding normality, the *Skewness* value is analyzed in combination with a *Kurtosis* value (see page 204).

A.107 SOCIAL GAME TYPE

Though some games offer both types, at a time a game can traditionally only be played either in *Singleplayer* or *Multiplayer* mode. As the terms suggest the *Singleplayer Social Game Type* lets the user only play with him or herself or against some form of *AI* in the computer program. In *Multiplayer* mode on the other hand multiple players can cooperatively play together, against each other or both.

A.108 SOG – SUPPORT OF GAMEPLAY

Support of Gameplay (SoG) was used as a subjective scale in combination with *Player Enjoyment (PE,* see page 206) in several experiments of the overall study and is part of *UX.* In combination, both scales were used to evaluate if an interface would be enjoyable for the player on the one hand and if it would actually support the gameplay on the other hand.

A.109 SP – SPATIAL PRESENCE

Spatial Presence (SP) is a subjective subscale of the *IPQ* (see page 203, igroup 2016).

A.110 SPACE

In the case of this thesis, *Space* refers to one of the three investigated key areas of this research. See section *Space* from page 22ff.

A.111 STEREOSCOPY

Unlike *Monoscopy* (see page 205), *Stereoscopic* imagery is based on the images of two either physical or virtual cameras. Through different hardware technologies these two images can be send to the two eyes of a human to simulate some form of depth perception (Jerald 2016). For more details, see section *Stereoscopic 3D* on page 42.

A.112 STHC – SPATIALLY TRACKED HAND CONTROLLER

Spatially Tracked Hand Controllers (STHCs) are handheld controller devices to track the user's hands (see page 40).

A.113 TREADMILL – OMNIDIRECTIONAL TREADMILL

An *Omnidirectional Treadmill,* or *Treadmill* in short, is a device to track a user's physical walking movements in a stationary way (see page 41). *Omnidirectional* refers to the user being able to walk towards any direction.

A.114 TSV – TAB SEPARATED VALUES

TSV is a text-based file format, which separates string or number values by tabs and line endings. It can be directly imported into *MS Excel* as a table structured data set.

A.115 TV – TELEVISION

A *TV* is a device for receiving, displaying and emitting video and audio signals.

A.116 UI – USER INTERFACE

See *GUI* on page 201.

A.117 USB – UNIVERSAL SERIAL BUS

USB is a widespread connection standard for data and power transmission.

A.118 UX – USER EXPERIENCE

User Experience (UX) describes the overall experience a user might have with an artifact (Bernhaupt 2010 and Koskinen et al. 2011). This includes all possible sensory aspects of a user, psychological effects provided through the artifact, the influential surrounding context and how all of this affects the user's perception of certain aspects of the artifact or the artifact as a whole. For more details see section *User Experience (UX)* on page 5.

A.119 VE – VIRTUAL ENVIRONMENT

A *Virtual Environment (VE)* refers to some sort of space based on simulated objects and scenery (Jerald 2016).

A.120 VIRTUAL CAMERA

When one wants to accurately capture the physical world to imagery, one uses a camera. When one wants to draw an image of a *VE* (see page 211) a *Virtual Camera* is used that captures the scenes geometry, textures, lighting and other visual effects and sends this data to the renderer (de Byl 2012). Based on this, the renderer than creates a pixel image and for example displays it to a screen. If not stated otherwise *Camera* refers to *Virtual Camera* in this thesis.

A.121 VOI – VIRTUAL OBJECT INTERACTION

Virtual Object Interaction (VOI) describes the aspect of a user interacting with virtual objects, e.g. like aiming a virtual hand towards a virtual apple, grabbing, holding and releasing it. For more details see section *Lab Experiment: UX Evaluation of VR Locomotion & Virtual Object Interaction Mechanics* from page 150ff.

A.122 VR – VIRTUAL REALITY

Virtual Reality (VR) describes a solely virtual simulation, in which a possibly interacting user feels completely enclosed, with little or no reference to the physical reality (Sherman and Craig 2003 and Jerald 2016). In the most common case this involves the use of a *VR HMD* (see page 201) to track the user's position, movement and orientation in quasi real-time, which adjusts the virtual simulation accordingly. Thus, the user may think he or she is present (see section *Presence* on page 207) in that *VE* (see page 211). For more details see section *Virtual Reality (VR)* on page 5.

A.123 VRIFICATION

VRification describes the process of either porting an existing experience to *VR* and optimizing it accordingly or realizing a new concept in *VR* (see from page 127ff.).

A.124 VW3 – VIRTUAL WALKING USING THREE-DEGREES-OF-FREEDOM TRACKING

The *Virtual Walking using Three-Degrees-of-Freedom Tracking (VW3)* condition was part of a study on *Locomotion* techniques by Zanbaka et al. (see from page 31ff.). See also *M* (on page 205), *RW* (on page 208) and *VW6* (on page 212).

A.125 VW6 – VIRTUAL WALKING USING SIX-DEGREES-OF-FREEDOM TRACKING

The *Virtual Walking using Six-Degrees-of-Freedom Tracking (VW6)* condition was part of a study on *Locomotion* techniques by Zanbaka et al. (see from page 31ff.). See also *M* (on page 205), *RW* (on page 208) and *VW3* (on page 212).

A.126 WMR – WINDOWS MIXED REALITY

Windows Mixed Reality (WMR) is an *MR* (see page 205) platform integrated into the *Windows* operating system.

A.127 XML – EXTENSIBLE MARKUP LANGUAGE

XML is a set of rules to create or reuse an individually configurable markup language, which is human and machine readable. E.g. one can create a text-based *MS Excel* file by using the corresponding *XML* conform markup.

A.128 XR – EXTENDED REALITY

Extended Reality (XR) is the overall term for *AR, MR, VR* (see pages 197, 205, 211) and anything in-between.

B. TECHNOLOGY CONTEXT (EXTENDED)

Today, there is a variety of different *VR* hardware available to consumers and professionals. This development and the revival of the medium was initiated when Palmer Luckey introduced a garage-made duct tape version of a very early *HMD* prototype (Wilde 2012). With the help of game programming legend John Carmack and other industry heavyweights like Gabe Newell and Cliff Bleszinski, a later iteration became the *Oculus Rift* headset. Its first *Development Kit (DK1)* was a huge crowd funding success on *Kickstarter* (Wilde 2012). This renewed interest in *VR* was underlined by *Facebook's* multi-billion $ acquisition of *Oculus* and its industry leading research unit is supported by Michael Abrash as the *Oculus Chief Scientist* (Oculus 2014). Their determination to bring games and other media to the next level and create the next big computing platform is clearly tangible (Zuckerberg 2014), hence the *"Virtual Reality* arms race" began (EDGE 2014).

At the time of this writing, this first hype phase has now passed, and a sort of normality settled over the industry. Furthermore, a variety of hard problems are persisting (e.g. resolution, optics and dynamic foveated rendering etc.), requiring years of further research to get solved. Nevertheless, although the growing consumer market is still relatively small, this time *VR* is here to stay, as the medium's advantages are very clear, once you tried a modern *VR* setup at firsthand.

Providing a more detailed technological context for the overall study, the following will elaborate on a non-exhaustive list of prominent related technologies and consumer-oriented devices, extending the limited *Technology* section from page 37ff.

Regarding setting up the *VR* hardware and software, the ease of installation varies a lot and will not be discussed here in detail. Still, all developer kits and some release hardware need various time-consuming steps to set up in terms of connecting cables, adjusting and calibrating the position of peripherals and configuring the computers operating system accordingly. The needed time to set up varies, but should not be underestimated, though manufacturers have learned from previous products and immensely optimized their onboarding procedures for the user (e.g. see *Oculus Quest* on page 230).

B.1 AUGMENTED/MIXED REALITY

Due to sharing many sensors and tracking techniques, *VR* and *AR/MR* technologies are closely intertwined (Planck 2017). Hence, the latter need to be mentioned, though use-cases and applications might aim for different directions.

Figure 120: View through a Microsoft Hololense on a representation of what an HTC Vive user created (Gottlieb 2017)

Supporting this symbiotic relationship between *VR* and *AR/MR*, there are interesting attempts in linking both technology platforms together. In one of them, a “shared understanding of space” (Gottlieb 2017) was developed, by using a *Microsoft Hololense* (see Figure 122) and an *HTC Vive* (see Figure 126). In this demo “people can collaborate within the same space, across virtual and holographic environments” (see Figure 120). Agreeing with Gottlieb, this mixed *Extended Reality* (*XR)* space very much seems especially suited for collaboration in the creative industries (Gottlieb 2017).

B.1.1 Augmented Reality via Mobile Device

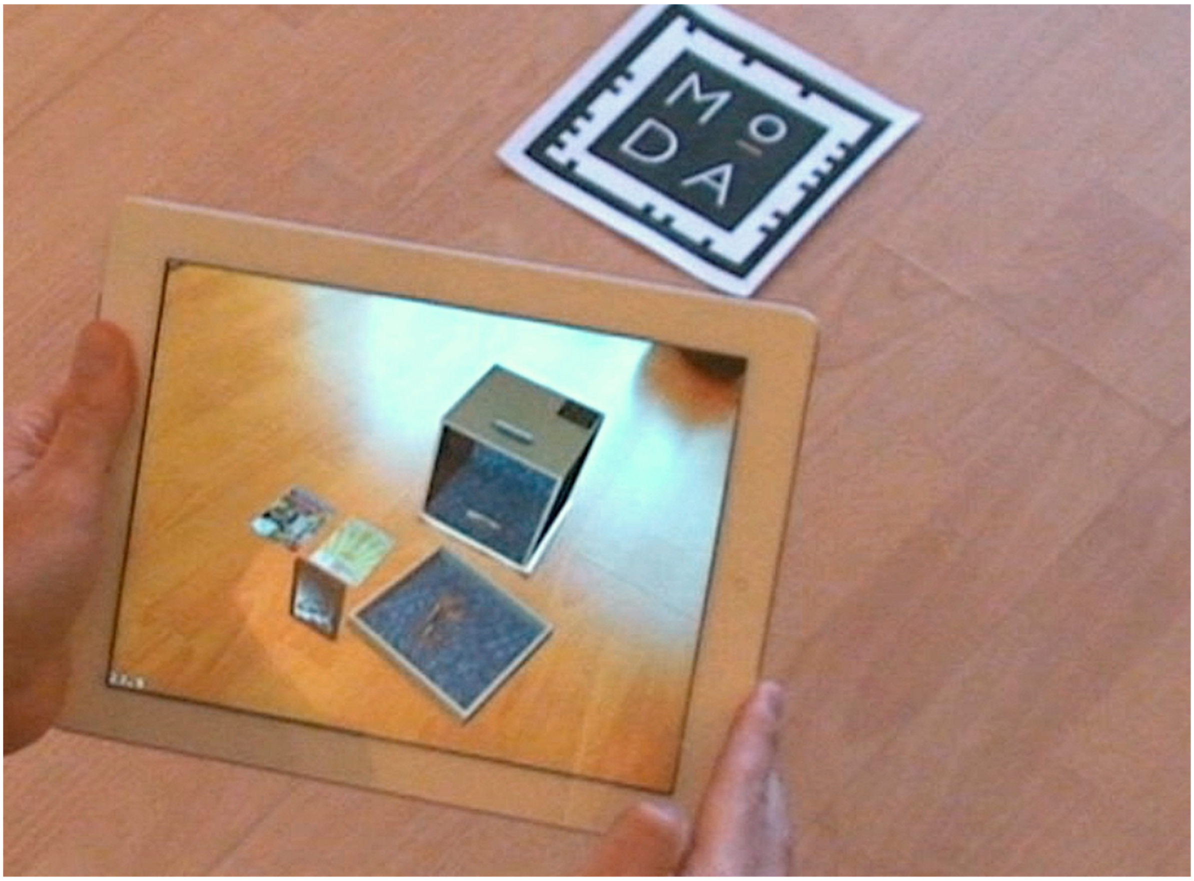

Figure 121: iPad with AR app tracking a marker and rendering a toppled box and some objects on top (Wiedemann 2012)

AR can be achieved in various degrees with different approaches. The most common one is to use a smart device, that comes with a camera, a screen and enough performance to calculate tracking and rendering of 2D and 3D objects at the same time. In the simplest form of *AR*, the smart device uses its camera and other available sensors to perform the tracking of an optical marker. More sophisticated *AR* tracking techniques do not need a specific marker anymore, but instead track a multitude of visual features and can further detect and understand surfaces. Even the detection and understanding of certain objects is already possible in specific scenarios. Once tracking is acquired, possibly interactive graphical elements, like 3D models but also 2D *GUI* elements, can be positioned on top of the video footage, positioned and rotated as if they were in that physical space (see Figure 121).

B.1.2 Augmented/Mixed Reality HMDs

Figure 122: Microsoft Hololens 2 (Microsoft 2019b)

Figure 123: Magic Leap One (Magic Leap 2019)

Microsoft's Hololens (see Figure 122) and the *Magic Leap One* headset (see Figure 123) work in a different way to create *MR.* Both glasses use some sort of semitransparent display system that lets users see the physical world overlaid with digitally rendered objects. The headsets use various sophisticated sensors in fusion to perform not only positional and rotational tracking of the device itself but also some sort of 3D scanning to create a more or less simple three-dimensional representation of the physical surrounding. Like this, overlaid digital objects can be correctly placed into the physical scenery. Built-in sensors are furthermore used for recognizing hand or finger gestures to be able to interact with these digital objects or a separate hand controller is used for interaction. Both the *Hololens* and the *Magic Leap One* are mobile devices, where the former stores its complete hardware in the headset and the latter instead uses a tethered break-out box, which can be clipped to the trousers. These headsets create various opportunities for content, e.g. like fighting invading robots coming through the roof and walls around you or walking around the concept design of some product and more.

B.1.3 Low-Fi AR/MR via Leap Motion Video Pass-Through

Figure 124: Leap Motion controller and its mount to an HMD (Leap Motion 2016a)

Originally conceived as a standalone hand and finger tracking device, the *Leap Motion* controller also showed its relevance in *VR* and *AR/MR*. The device and its capabilities were explained on page 39. Regarding *AR/MR*, mounted to an *HMD* (see Figure 124), its grey scale *IR* video stream can be passed through to the application. Though the low definition image quality may not be on par with *AR/MR* specialized hardware, it is still an interesting way to "upgrade" a *VR HMD* to handle certain *AR/MR* applications.

More modern devices like the *Oculus Quest* (see page 230) use similar techniques to provide safety measures for users, when they reach the border of the physical play area.

B.2 TETHERED VR HEAD MOUNTED DISPLAYS

For the overall study only tethered *VR HMDs* were used. This was the case, as early development kits were wired devices and tethered *HMDs* generally provided higher-end features. Additionally, the developed *VR* games could utilize the full computational power of a dedicated *PC*. Thus, the applications did not need to be specifically optimized for the performance capabilities of a mobile device.

The following will outline several prominent tethered *VR HMDs*, which either need a *PC* or a gaming console to render the application.

B.2.1 Oculus Rift Development Kit 1 – DK1

The *Oculus Rift DK1* (see Figure 4) was released in 2013 (Wikipedia 2016a). Beside the expensive headsets mostly used in academia, due to its low price and its high *FOV* it became the starting point for a broader developer base creating *VR* experiences. The *DK1* was also used for the first *VR* explorations of this research.

The *HMD* uses two elastic head straps to compensate the weight of the hardware in the front. Its single *LCD* panel is split between both eyes, resulting in a resolution of 640 x 800 pixels per eye (1280 x 800 pixels total, Wikipedia 2016a) running at 60 Hz. Each eye's image is digitally barrel distorted (Kuhl et al. 2009), including deliberate chromatic aberration at the seams. The distortion and chromatic aberration are countered by a pincushion distortion applied through the lenses (Kuhl et al. 2009). Through this, a *FOV* of around 110 degrees is achieved. Furthermore, a user can mechanically adjust the distance between the eyes and the lenses. Head rotation tracking without drift and low latency (1000 Hz refresh rate) is achieved by using a combination of 3-axis gyroscopes, accelerometers and magnetometers (Wikipedia 2016a).

The two main downsides of the *DK1* are its missing positional tracking and its relatively low resolution, resulting in a clearly visible screen door effect (Wikipedia 2016b) and bad text readability.

B.2.2 Oculus Rift Development Kit 2 – DK2

Having learned from the *DK1* the *Oculus Rift DK2* (see Figure 5) became an even bigger success amongst developers, when it was released in 2014 (Wikipedia 2016a).

The *DK2* drastically improved on its predecessor, providing an *OLED* display panel running at a maximum of 75 Hz and offering low latency and low persistency, minimizing unwanted motion blur. The display also offers doubled 960 × 1080 pixels per eye (1920 x 1080 pixels total, Wikipedia 2016a), reducing the screen door effect and making text more readable.

The second improvement comes with positional tracking via the *Constellation* method (Wikipedia 2016a). A separate *IR* camera (see Figure 5) keeps track of the constellation of *IR LEDs* under the surface of the *HMD,* blinking in a certain pattern. If within the camera's frustum the *HMD's* relative position to the camera can be extrapolated. In turn, users are also able to bend down, lean forward or backward or stretch upwards and their movements get naturally translated in *VR,* creating new gameplay possibilities, while at the same time reducing *Simulator Sickness.*

The downsides of the *DK2* were its still relatively low resolution, the relatively slow refresh rate of 75 Hz, the very limited area for the front facing only positional tracking and the complete loss of tracking when looking away from the camera.

During the development and user testing of some of the artifacts of the overall study the *DK2* was used most of the time. This was the case, as it was the most common *HMD* at the time and because I already had experience with the corresponding *Oculus SDK,* which additionally offered the best implementation in *Unity.*

B.2.3 Oculus Rift Consumer Version 1 – CV1

After its two *Development Kits* and further intermediary prototypes *Oculus* finally released its *Consumer Version 1* in 2016 (see Figure 6, Oculus 2016b).

The *HMD's* built in display is a special *PenTile OLED* panel (OLED-info 2017) running at 90 Hz with a resolution of 1080 x 1200 pixels per eye (2160 x 1200 pixels total, Wikipedia 2016a). The high resolution in combination with the specially produced *Fresnel* lenses (Edmund Optics 2016) almost completely removes any visible screen door effect. The *FOV* stayed at approximately 110 degrees. One downside to the *Fresnel* lens design are possible visual artifacts called *"God Rays"* (Doc-Ok.org 2016), which may occur during high contrast imagery.

The front, containing the display, has been partly wrapped in textile, reducing the weight of the device (470 g, Wikipedia 2016a) and providing an outlet for possible perspiration. At the bottom, the *CV1* provides a slider to quickly adjust the distance of the lenses to the user's *IPD.* A flexible and durable three-strand strap structure is used for the head fastening. Additionally, the straps include invisible *IR LEDs* on the backside so positional tracking can continue, even if the user's head is turned away from the tracking sensor. The headset further provides high quality built in on-ear headphones, whose fit can easily be adjusted to the user's needs (see Figure 6), completely removing any hassle with external headphones and additional cables.

To achieve *Roomscale* tracking *Oculus* recommends three *IR* sensors, possibly covering a tracking space of approximately 2.5 x 2.5 m (Carbotte 2016).

B.2.4 Oculus Rift S

Figure 125: Oculus Rift S (Oculus 2019a)

The successor of the *CV1*, the *Oculus Rift S* was released in 2019 and co-developed with *Lenovo* (see Figure 125, Wikipedia 2019e).

The *HMD* uses a single low-persistence fast-switch *LCD* panel with 1280 × 1440 pixels per eye (2560 × 1440 pixels total), running at 80 Hz. The denser and more high-resolution display reduces the screen-door effect even further compared to the *CV1.* Additionally, the lens design was further optimized, almost completely removing *God Ray* artifacts and providing a slightly larger *FOV* of around 115 degrees. Instead of external sensors the *Rift S* uses *Oculus' Insight* tracking system (Wikipedia 2019e). For this inside-out tracking system to work, the *HMD* is equipped with five cameras quasi instantly tracking the user's movements within the room. The same system also tracks the second-generation *Oculus Touch* controllers (see Figure 125) and provides a passthrough mode, so the user can possibly see the physical environment, without taking off the headset. In general, the *Oculus Insight* tracking system is a sensible tradeoff solution, as it provides still good enough tracking, while at the same time drastically reducing the setup time and the *USB* requirements of the whole *VR* system.

The *Rift S* uses a comfortable halo headband design with integrated speakers, directing the audio to the user's ears, which helps with putting the headset on, but also lets external sounds through.

Nevertheless, the *HMD's* single display comes with a downside. Because of it, the physical *IPD* adjustment slider was removed and replaced with a software adjustment.

B.2.5 HTC Vive

Figure 126: HTC Vive HMD and hand controllers (HTC 2016a)

Figure 127: HTC Vive Lighthouse tracking base stations (HTC 2016a)

Initially in a similar price range as the *CV1*, the *HTC Vive* (see Figure 126) was released in 2016 (Wikipedia 2016c). The raw specs are similar to those of the *CV1* as well. Running at 90 Hz, the *Vive* offers a resolution of 1080 x 1200 pixels per eye split between two display panels (2160 x 1200 pixels total, Wikipedia 2016c). It offers a built-in front facing camera to stream video directly into applications (Wikipedia 2016c) and provides a similar 110 degrees *FOV* (HTC 2016b) also through specially designed *Fresnel* lenses. The *HMD* is not equipped with built-in speakers or headphones. The *Vive* furthermore comes with two hand controllers (see Figure 126), referred to as the *"Vive Wands"*, which will be explained in more detail later on (see page 231ff.).

The *Vive* offers *Roomscale* tracking via their *Lighthouse* system (a.k.a *SteamVR)*, which is also often used by other *HMD* manufacturers like *Pimax* etc. Two *Lighthouse* base stations (see Figure 127) are needed to provide a tracking space of approximately 4.5 x 4.5 m (Carbotte 2016). In its second generation the system can cover an even larger space and may be used in parallel with multiple *Lighthouse* setups. The tracking system is generally very robust, precise and easy to install, as the base stations are wirelessly synched, only requiring a power connection, but no *USB* connection. The tracking technique is based on the base stations emitting structured light via lasers and simple photo sensors on objects to be tracked (Wikipedia 2016c), like the *HMD* itself (see indentations on the *HMD* in Figure 126).

The downsides of the Vive are its missing audio solution and seemingly stronger *God Rays* in high contrast imagery, a heavier cable and an overall inferior product design in relation to the *Oculus HMDs* starting from the *CV1*. Nevertheless, the *HMD* with its wide *FOV*, robust tracking and the included hand controllers delivered a high-end *VR UX*, which was further improved with a later released *Vive Pro* model (see Figure 128).

Figure 128: HTC Vive Pro with wireless adapter (HTC 2019a)

An often-addressed issue, especially with tethered *Roomscale VR* is that users can trip over or get entangled in the cable (Infante 2015). *HTC* offers a solution to this with its relatively expensive optional wireless adapter (see Figure 128). Mounted to the top of the *HMD,* the adapter includes a battery, providing up to 2.5 hours of usage and a wireless transceiver. It sends tracking information and receives the rendered imagery via a dedicated wireless connection, for which a separate *PCIe* card needs to be installed in the *PC* (HTC 2019a).

B.2.6 HTC Vive Pro Eye

Figure 129: HTC Vive Pro Eye (HTC 2019b)

In 2019, *HTC* released a further version of the *Vive Pro* with eye tracking, the *HTC Vive Pro Eye* (see Figure 129, Hollister 2019). As the *HMD* is relatively expensive, *HTC* aims with this device more at professionals and enterprises. Although this research is more focused on consumer hardware, the *Vive Pro Eye* should be mentioned exemplary for its eye tracking capabilities and being at least close to consumer prices. So, it is likely for the technology to trickle down to consumer *HMDs* in the near future.

There are several very interesting topics, for which eye tracking und thus knowing where the user looks at can be beneficial (Hollister 2019). Regarding computing performance, so called *Foveated Rendering* could focus high resolution rendering on the parts of the virtual scenery, which are actually looked at and thus spare performance by rendering the rest only in reduced quality (Abrash 2016). The same technique could also be used to simulate various focus distances and thus dynamic *Depth of Field.* Furthermore, a virtual avatar could simulate the looking direction of the user (Hollister 2019), either enhancing *Social Presence* when connected with other human beings, or improving *NPC* capabilities, by implementing additional ways they could react to the user's gaze.

B.2.7 PlayStation VR

Figure 130: PlayStation VR, PlayStation Camera and PlayStation Move hand controller (PlayStation 2016a)

PlayStation VR (PSVR) is an accessory to the widespread *PlayStation 4 (PS4)* and *PlayStation 4 Pro (PS4Pro)* gaming consoles from *Sony.* In its simplest configuration, it consists of the *PSVR HMD* (see Figure 130), a *PS4,* a *PlayStation Camera* for tracking (see Figure 130) and a breakout box which *Sony* called *Processing Unit* belonging to the *PSVR* system. The *Processing Unit* handles some of the processing and the splitting of the *HDMI* video signal between the *HMD* and a *TV* (PlayStation 2016b).

The *HMD* provides a *FOV* of approximately 100 degrees with an *OLED* display panel running at either 90 or 120 Hz with a resolution of 960 x 1080 pixels per eye (1920 x 1080 pixels total, PlayStation 2016c). The cable connecting the *HMD* with the *Processing Unit* offers a stereo headphone jack, to either connect the included in-ear headphones or third-party ones for 3D audio. The headset uses a single halo headband to fasten it to the user's head (PlayStation 2016b).

Users can interact with applications either via a wireless *DualShock 4* controller (see Figure 141) or the *PlayStation Move* controllers (see Figure 130), which will be explained in more detail later on (see page 231 and 231ff.). Both devices' positions and the *HMD* are tracked via the *PlayStation Camera*, which only supports front facing tracking. Regarding tracking quality, the *PSVR* system is performing sub-par regarding robustness and accuracy, compared to the systems of *Oculus* and *SteamVR* (Lang 2016a).

B.2.8 Windows Mixed Reality

Figure 131: Windows MR HMD: Samsung Odyssey+ (Samsung 2019)

Instead of releasing a *VR HMD* and compatible hand controllers themselves, *Microsoft* provided blueprint designs and an outline of specs for third-party manufacturers like *Samsung*, *Dell*, *Lenovo* etc. The corresponding *Windows Mixed Reality (WMR)* platform indeed offers a variety of different *HMDs* with only slight differences. Especially its inside-out tracking technique is built on *Microsoft's* previous experience with the *Hololens* headset.

As an example, for this whole category of *VR* setups, the *Samsung Odyssey+* will be outlined in the following (see Figure 131). It is equipped with two *AMOLED* displays offering 1440 x 1600 pixels per eye (2880 x 1600 pixels total, Samsung 2019), running at 90 Hz. With its *Fresnel* lenses, the *HMD* provides an *FOV* of approximately 110 degrees. *Samsung* further added built-in on-ear headphones and a physical *IPD* adjustment. To track the *HMD's* and the controllers' positions, it uses two built-in cameras (see Figure 131).

The tracking is ok, but not as robust as the systems with external sensors like *Constellation* or *Lighthouse.* Also compared to *Oculus' Insight* system used in the *Rift S* and *Quest*, the *WMR* tracking seems to be sub-par. Furthermore, the *WMR* hand controllers feel relatively cheap and do not provide the versatility of e.g. the *Oculus Touch* controllers.

Nevertheless, *WMR* can be a relatively cheap introduction to *VR*, offering easy to set up inside-out tracking and a good feature set for its current price, provided *Microsoft* does not discontinue its support in the near future.

B.2.9 OSVR Hardware Development Kit

Figure 132: OSVR Hacker Development Kit 2 (OSVR 2016a)

OSVR is a combined industry movement "to create a universal *Open Source VR* ecosystem for technologies across different brands and companies" (OSVR 2016b). Through their series of *Hacker Development Kits (HDKs)* and their community based *Open Source SDK*, *OSVR* tries to create an open *VR* platform for hard and software. They seem to be aiming for compatibility to the shared minimal feature set of the high-end systems like those of *Oculus* and *SteamVR*.

The raw specs of the *HDK2* seem very similar to those of the *CV1* and *Vive*. Furthermore, the tracking technique is very similar to *Oculus' Constellation* system, but lacked robustness compared to the *DK2* for example. Finally, the product design clearly cannot compete with that of high-end *HMDs*, but *OSVR* nevertheless offers hard and software developers an inexpensive platform to participate in creating custom *VR* technologies.

B.2.10 Pimax

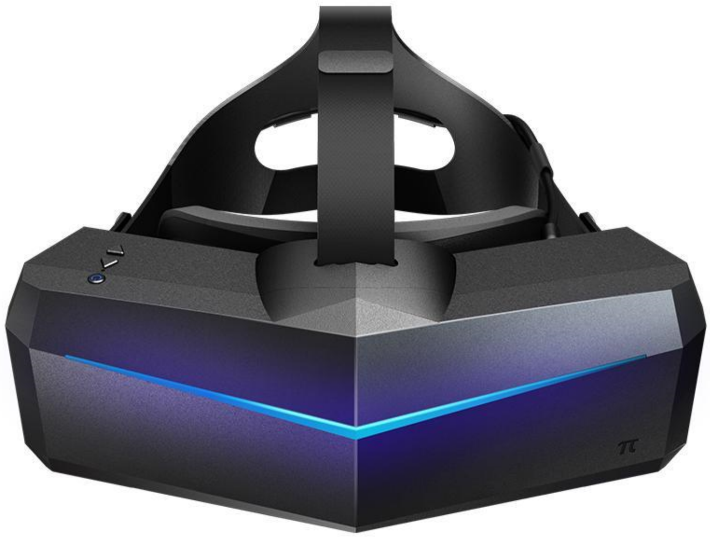

Figure 133: Pimax 5K+ (Pimax 2019)

The *HMDs* from *Pimax* are interesting, because they offer a very high resolution and *FOV*, for a consumer-affordable price. E.g. the *Pimax 5K+* (see Figure 133), released in 2019 (Wikipedia 2019f), uses two custom low persistence *LCD* panels offering 2560 x 1440 pixels per eye (5120 x 1440 pixels total), running at 120 Hz (Pimax 2019). In combination with *Fresnel* lenses the *HMD* reaches an *FOV* of approximately 200 degrees. It further offers a physical *IPD* adjustment. Regarding tracking, the *Pimax* headsets are compatible to the *Lighthouse* system (Pimax 2019).

Although the *FOV* and resolution are quite high relative to other current high-end consumer *HMDs*, *Pimax* headsets come with severe downsides. To some degree the headsets are "cheating", as the high resolution is often reached through some form of internal upscaling, e.g. in the *Pimax 8K*. The displayed image further uses a gradual stretching at the sides of the peripheral vision, so the wide *FOV* does not really present more information. Still, the high resolution reduces the screen door effect, but also requires more computing performance and thus a faster *PC*.

B.3 MOBILE VR HEAD MOUNTED DISPLAYS

Though mobile *HMDs* were not included in any artifact of the overall study, this category still needs to be mentioned as the mobility and especially the wireless nature of a headset can provide various advantages, but also clearly requires great attention in certain areas. Practically all studies in this research, concerned with tethered *VR*, exposed the safety risks of stumbling over the cable and the diminished quality of *Presence* and *UX*, due to being reminded of the physical surrounding by the pulling cable or getting entangled in it over time. Additionally, a mobile *HMD* can offer a broader range of gameplay concepts and general applications, than one, which is fixed to an immovable *PC*. On the other hand, mobile headsets need to handle the same issues as all other mobile devices. These topics typically include, reduced computing performance, battery capacity, weight, physical dimensions and heat management. As a content developer it is critical to optimize an application for the reduced performance of a mobile device.

The basic principle of the first wave of *Mobile VR* can be seen in a plethora of *HMDs:* A smart device is slid into the front of the *HMD.* Its display will be used as the display of the headset, looked at through lenses. The smart device further takes care of processing the data from its own sensors to achieve rotational tracking and of rendering the *VR* application. In its simplest version, the *HMD* itself can be completely passive and "dumb". There are various downsides to this design, e.g. concerned with display refresh rates, suboptimal latency, lacking positional tracking and performance and battery issues.

The second wave of *Mobile VR* headsets further embraces the idea of dedicated *VR HMDs* and thus is comprised of all-in-one devices. The *Oculus* headsets *Go* and especially the *Quest* (see from page 230ff.) present very promising solutions.

The following will outline several mobile *HMDs* of the first wave and with the *Oculus Quest* the currently highest quality consumer headset of the second wave.

B.3.1 Google Cardboard

Figure 134: Google Cardboard (Google 2016a)

Figure 135: Zeiss VR ONE Plus (OneButton 2016)

With *Cardboard, Google* delivered probably the simplest and cheapest *HMD* possible. Actually made of cardboard (see Figure 134), two plastic lenses, a magnet and a metal ring, it also serves as a reference design for various kinds of adaptations. The original is so simple, that consumers would need to punch out and fold the parts themselves. The resulting low-end *HMD* can take smartphones of various sizes in the front and the user can interact with compatible applications via sliding the metal ring on the side down (see Figure 134), like a virtual click. Not providing some sort of headband or a similar structure, the user would need to hold the device to his or her face at the time of use though.

In its cardboard material form, these *HMDs* tend to be given away for free as advertisement. Because of the bad durability and the little comfort to wear these *HMDs*, they tend not to be for long-term usage.

B.3.2 Zeiss VR ONE

One of the more high-end *HMDs* derived from the *Cardboard* design are the *VR ONE* and *VR ONE Plus HMDs* from the optics manufacturer *Zeiss* (see Figure 135). Built from robust plastic and providing a foam faceplate, adjustable head straps and relatively good optics, these devices are positioned at the other end of the spectrum of *Cardboard*-like devices.

B.3.3 Samsung Gear VR

Figure 136: Samsung Gear VR (Oculus 2016b)

Figure 137: Google Daydream View (Google 2016b)

Oculus in cooperation with *Samsung* released its first consumer version of the *Samsung Gear VR* (see Figure 136) in late 2015 (Wikipedia 2017a). In contrast to *Cardboard*, the *Gear VR* includes built-in electronics like various sensors and a multi-use touchpad (Wikipedia 2017a). By restricting compatibility to *Samsung* flagship smartphones, it was possible to create one of the best first wave *Mobile VR* experiences with low latency and low persistence (Carmack 2014), almost on-par with the *DK2.*

B.3.4 Google Daydream View

The late 2016 released and relatively inexpensive *Daydream View* by *Google* (see Figure 137) has learned a lot from the *Cardboard* movement and clearly took some inspiration of the *CV1* (Rubin 2016). Similar to the *CV1* it uses textile coverage and includes a companion controller, tracked only in orientation but not position.

Overall the *Daydream View* looks like a good quality first wave *Mobile VR HMD* that can provide interesting *VR* interactions (Rubin 2016).

B.3.5 Nintendo Labo VR

Figure 138: Nintendo Labo VR (Nintendo 2019)

Figure 139: Nintendo Labo VR with rifle application (Nintendo 2019)

With the very creative, extensible and inexpensive *Labo* system, *Nintendo* expanded its mobile gaming console *Switch* with cardboard based accessories of various kinds. One set of accessories is the *Labo VR* system (see Figure 138, Nintendo 2019), which uses the console in a similar way like the *Mobile VR* headsets. The *Switch* is slid into a cardboard frame, the console's internal sensors and computing power are used to render *VR* games and the player looks through special lenses onto its screen. The base system can be further extended with various types of cardboard controllers like e.g. a fishing rod or a rifle (see Figure 139).

There are certainly more sophisticated *VR* experiences, but the *Labo VR* system clearly shows how rather simply designed interactions in *VR* can lead to enjoyable experiences.

B.3.6 Oculus Quest

Figure 140: Oculus Quest (Oculus 2019b)

At the moment of this writing, the probably most exciting consumer *VR HMD* (including tethered headsets) is the all-in-one *Oculus Quest* (see Figure 140). It combines a mobile first approach with great visual quality in comparison, solid inside-out positional tracking, a sophisticated product design at an affordable price and the possibility to still run the most high-end applications via a cable connection to a *PC.*

The *Quest* uses two *PenTile OLED* panels, offering 1440 × 1600 pixels per eye (2880 × 1600 pixels total), running at 72 Hz (Wikipedia 2019g). It further includes special *Fresnel* lenses, almost completely eliminating *God Ray* artifacts. For the *Oculus Insight* tracking system, the *HMD* is equipped with four cameras, also providing a passthrough mode. This combination of wirelessness and robust inside-out tracking makes the device especially portable and leads to an extremely quick and simple setup process, consisting of only confirming the floor level and virtually painting the guardian boundaries via controller, within the passthrough mode. The *Quest* weighs 571 g and further includes integrated speakers in the comfortable three-strap head mounting structure, directing its high-quality audio to the user's ears (Wikipedia 2019g). To calculate the tracking and to render the native *Quest* applications, a *Qualcomm Snapdragon 835* processor is installed. The integrated battery supports approximately two hours of performance intensive usage but can be further extended by connecting an external battery via *USB* cable. The headset comes with two second-generation *Oculus Touch* controllers, providing a high-quality product design and a sophisticated feature set (see Figure 140), identical to the first-generation

Touch controllers. Two further features of the *Quest* have been integrated via software update: Via *Oculus Link* the *HMD* is able to connect to a *PC* and stream non-mobile high-end applications to the device (Oculus 2019d). Finally, by interpreting the camera image, the Quest further supports native hand and finger tracking, so it is possible to use certain applications with just the *HMD* itself (Oculus 2019e).

B.4 GAME PADS

Figure 141: Wireless PlayStation DualShock4 Controller (PlayStation 2016d)

Compared to a combination of keyboard and mouse, gamepads still have the advantages of a more limited set of buttons, sticks etc., a very distinct and relatively easily learnable layout of these and the fact that they are handheld and mostly wireless. In relation to *VR* though, their very abstract interaction principle seems to be not particularly contributing to the user's *Presence* in *VR* as properly tracked hand controllers do by comparison.

B.4.1 Xbox Controller

One of the most recognized and often referenced gamepads (Ulanoff 2013) is the *Xbox* controller (see Figure 8). Its well-crafted and meticulously designed hardware details make it a generally great interface (Ulanoff 2013), even when not being able to see it (e.g. because of wearing an *HMD).*

B.4.2 PlayStation DualShock Controller

Its closest competitor is the *PlayStation DualShock* controller (see Figure 141). In its current version 4 this controller provides a touchpad and is even tracking its rotation and position when using a *PlayStation Camera* (PlayStation 2016d). Though this tracking, for example within the *PSVR* system, seems to provide only limited use cases.

B.5 HAND CONTROLLERS

The previously illustrated studies showed that the design and functionality of controllers certainly affect the *UX* of *VR* applications and that using specialized *VR* hand controllers can lead to very sophisticated and naturally feeling experiences.

B.5.1 Oculus Touch Controller

In late 2016 *Oculus* released its feature packed first-generation *Touch* controllers (see Figure 10, Durbin 2016a). The two comfortable controllers each provide an ergonomic asymmetric design (see Figure 11) specialized for one left and one right hand. Similar to the *CV1* and the *Quest,* the materials and product design of the *Touch* controllers feel significant and elaborate, regarding its functionality.

Though being relatively light, to keep possible fatigue as low as possible, their center of mass feels very much in the center of the structure as "they simply melt away in your hands." (Durbin 2016a). Grabbing a virtual object in *VR* via the lightly moveable grab trigger on the handle, feels as natural as possible with a fixed structure hand controller.

The first-generation *Touch* controllers are tracked via the *Constellation* system. When the respective sensors are set up correctly, rotational and positional tracking of the controllers feels very robust (Lang 2016b). Drifting or judder will be immediately compensated without the user noticing it.

Triggers, buttons and analogue sticks all seem to have the right amount of resistance and feel very comfortable to reach and robust in their usage. Haptic feedback through vibrations covers the whole range from subtly reminding of picking up an object to almost kicking in, when firing a gun (Durbin 2016a).

Finally, via capacitive sensors every button, trigger and stick on the controller senses if it is touched without being pressed (Lang 2016b), which "should be a standard-setting innovation for the rest of the industry" (Durbin 2016a). The seemingly trivial gestures like giving a thumbs up to another character or extending an index finger to for example push a virtual button, can provide this extra bit of *Presence* in a *VR* application compared to other *VR* hand controllers without this functionality (Durbin 2016a).

The second-generation *Touch* controllers shipping with *Rift S and Quest* headsets (see Figure 125 and Figure 140) provide an identical feature set and are feeling very similar, only the tracking ring moved upwards. This is because the controllers are not tracked via external sensors, but via the *HMDs* built-in cameras and the *Oculus Insight* tracking system.

B.5.2 HTC Vive Hand Controller (Wands)

Even though less ergonomic, clunkier, heavier, shaped like wands and without any touch features, the original *HTC Vive* hand controllers (see Figure 126) nevertheless already made a huge difference in delivering *Presence* to users through their usage.

Using them in the *Vive* typical *Roomscale* setup, you are able to interact with the *VE* in a clearly more natural manner, than e.g. via a gamepad. Grabbing objects, firing arrows from a bow or pushing buttons (with your whole hand) and other actions like these, clearly expands the list of possible interactions within a *VE.* Compatible to the *Lighthouse* system, rotational and positional tracking of the controllers feels very solid.

Nevertheless, the *Vive Wands* feel quite outdated compared to the more modern and versatile *Oculus Touch* and *Valve Index* controllers (see from page 234ff.).

B.5.3 PlayStation Move Controller

The *PlayStation Move* controllers (see Figure 130) were originally not developed for *VR*, but for gesture-based interactions in front of a *TV* similar to the *Nintendo Wii.* As such, they feel a lot less sophisticated and clearly not optimized for a *VR* experience (Thang 2016).

Like the *PSVR HMD*, the tracking of the controllers shows the same issues with accuracy and robustness. Furthermore, the *Move* controllers do not provide either a D-pad or analogue stick, which drastically limits its versatility (Thang 2016).

Nevertheless, because of their more natural handling, even the *Move* controllers contribute more to creating *Presence* then for example the *DualShock* controllers do.

B.5.4 Tactical Haptics Reactive Grip Controllers

Figure 142: Tactical Haptics Reactive Grip controllers (Tactical Haptics 2019)

The *Reactive Grip* controllers from *Tacticle Haptics* are not yet released as a consumer product, but as a developer kit. Currently, the *Reactive Grip* controllers (see Figure 142) are compatible to the *Constellation* and *Lighthouse* tracking systems, by snapping in either *Oculus Touch* controllers or *Vive Trackers* (see page 237).

The developer kit implements two very interesting concepts. First, the controllers are equipped with several male and female *Multi-Pose* magnet sockets (see Figure 142, Tacticle Haptics 2019). With these, the controllers can be snapped into various stereotypical poses like a rifle, a steering wheel or a two-handed sword etc. Due to the connection being magnetic, it can be easily unsnapped again or switched during the *VR* experience, opening up diverse usage possibilities.

Second, the grips of the controllers include physically shifting plates. With these, haptic feedback can go beyond the traditional vibration techniques. By moving these plates in certain ways, the *Reactive Grip* system can provide *Shear Feedback.* Synched to a *VR* application, this gradual and versatile system can simulate e.g. the weight of a grabbed object, the friction of a dragged object or the resistance of the string of a bow etc. (Tacticle Haptics 2019).

B.5.5 ForceTubeVR

Figure 143: ForceTubeVR (ProTubeVR 2019)

Going a similar direction like *Tacticle Haptics*, with the *ForceTubeVR* device *ProTubeVR* does not provide a dedicated controller, but instead a mounting device for industry-leading *VR* hand controllers (see Figure 143). Like this, e.g. the *Oculus Touch* controllers can be snapped into respective sockets and in turn the whole structure feels more like a rifle to the user. Additionally, the *ForceTubeVR* device provides haptic feedback through relatively strong recoil effects.

Devices like these can create very convincing effects and improve the unique *UX* of certain applications, but they may be very specific in their use-cases and especially the *ForceTubeVR* device seems relatively expensive for its limited versatility.

B.5.6 Valve Index Controllers (Knuckles)

Figure 144: Valve Index HMD and controllers (Valve 2019)

The *Valve Index* or *"Knuckles"* controllers belong to the high-end *Valve Index HMD* (see Figure 144). Being compatible with the *Lighthouse* system, they can theoretically also be used with other headsets, too.

The controllers need to be fixed to the user's hands by tightening comfortable straps. Like this, one can open the hands and the controllers stay in place, without falling down. This is important, because the grips of the controllers are equipped with multiple capacitive sensors. With these, specialized *VR* applications can track the current grip pressures and the hand poses of the user, even if the fingers are extended, all while the hands' positions and orientations are tracked via the robust *Lighthouse* system. Although the hand and finger tracking is not perfect, it certainly adds to the user's *Presence*, providing a convincing enough effect, while opening up various possibilities for more fine-grained interactions than only using tipping fingers or grabbing objects. Nevertheless, the product design including buttons etc., seems slightly sub-par to the one of the *Oculus Touch* controllers, although the hand tracking should make up for this.

B.6 HAND & FINGER TRACKING

The previous study with *Gooze* (see from page 150ff.) showed that hand and finger tracking can certainly increase *Presence* in *VR*, compared to other input devices which do not support this feature. Hence, additionally to the hybrid *Valve Index* controllers, further hand and finger tracking devices will be illustrated in the following.

B.6.1 Leap Motion Controller

The previously introduced *Leap Motion* controller (see from page 39ff.) was also used and evaluated in the *Lab Experiment: UX Evaluation of VR Locomotion & Virtual Object Interaction Mechanics* (see from page 150ff.). Its optical *IR* tracking of the hand skeletons can create astonishing virtual hand representations but is lacking robustness in certain situations. Issues can occur due to e.g. occlusion, suboptimal lighting and the limited camera frustum.

Nevertheless, its *SDK* evolved over time and the latest version called *Orion* seems to lead to a lot better results (Heater 2016). Developed for *VR* from the ground up, *Orion* delivers less latency, longer range, better and faster hand and finger recognition and a greatly improved tracking robustness (Leap Motion 2016b and Heater 2016).

B.6.2 Intel RealSense

Figure 145: Intel RealSense set-top camera, produced by Creative (Intel 2016)

Figure 146: GloveOne by Neurodigital Technologies (Lang 2016c)

Among an extensive set of other features, *Intel's RealSense* technology (see Figure 145) can track hands and fingers similarly to the *Leap Motion* controller. The tracking technology is built into various form factors and devices (e.g. *Project Alloy* and dedicated set-top cameras).

Though other tasks of scanning and tracking work incredibly well (e.g. 3D object scanning and facial tracking), tracking of hands and fingers seems sub-par compared to that of the *Leap Motion* controller.

B.6.3 GloveOne

Various glove systems have been available for *VR* over the years, but a wider consumer adoption has been lacking so far. Compared to other hand and finger tracking devices gloves do not seem to have the same momentum in the industry at the moment, though this might change in the future, as they can possibly combine skeletal tracking with various haptic feedback techniques.

Exemplary for this device category, *GloveOne* by *Neurodigital Technologies* (see Figure 146) offers several vibration actuators, which are supposed to simulate haptics, though the quality of the experience very much depends on the content of demos as could be expected (Lang 2016c).

B.7 NODE TRACKING

Another very interesting area lies in the tracking of simple nodes. Being able to acquire rotational and positional tracking data through wireless small form factor devices, offers diverse possibilities. E.g. this could enable variably detailed limb tracking, special object tracking of physical objects and thus the ability to upgrade previously non-tracked interface devices to get compatible with *VR.*

B.7.1 Vive Tracker

Figure 147: HTC Vive Tracker (HTC 2016b)

The *Vive Tracker* (see Figure 147) is fully compatible to the *Lighthouse* tracking system. Its purpose is to act as a node in *VR* (HTC 2016b). Either tracked on its own to translate a single object or in combination with other *Vive Trackers*, possibly even linked in a network, these node trackers can be used for very diverse applications.

B.7.2 PrioVR

Figure 148: PrioVR Pro node tracking suit with 17 sensors (Yost Labs 2016a)

Figure 149: The VOID Rapture vest (The VOID 2016)

Specialized more on motion tracking of the human body, but nevertheless using a network of node trackers and two relatively simple hand controllers, *Yost Labs' PrioVR* "suit" development kit was released in late 2016 (Yost Labs 2016b) and can be seen as an example of the category of multi node body tracking suits. Coming in three different models with varying amounts of node trackers, these suits are supposed to translate the user's posture and movements into common 3D applications and *VR* (Yost Labs 2016b).

Most similar suits are aiming more at professionals and enterprises than home-customers, due to their relatively high prices.

B.7.3 The VOID Rapture Vest

Aiming at entertainment park visitors, *The VOID* provides its customers with their own *Rapture* vests (see Figure 149). These vests can offer detailed body tracking and several points for haptic feedback (The VOID 2016) through vibration actuators.

As *The VOID's* complete *Rapture* gear is developed for the usage in their venues, it is unlikely that this hardware will be available to home users in the near future.

B.8 LOCOMOTION TRACKING VIA OMNIDIRECTIONAL TREADMILLS

This section will elaborate on so called *Omnidirectional Treadmills.* Though their implementations certainly differ in various aspects, the following devices are all based on the same principle: Restricted through some sort of harness or other structure, the user rather naturally walks on the same spot and can freely turn by 360 degrees. Further actions like running, strafing, jumping, crouching and even sitting may be possible as well, depending on the device. These movements will be translated into *VR* and like this the user can traverse a possibly infinite virtual space, while staying in a confined physical space.

B.8.1 Virtuix Omni

Figure 150: Virtuix Omni (Virtuix 2017)

The *Omni* from *Virtuix* (see Figure 150) started off as a *Kickstarter* project for home customers but was later redirected for usage in gaming arcades (VR WORLD 2016), due to increased production costs and a change in business model. The treadmills can now be found in entertainment centers, including *Omni Arenas.* These specialized *Multiplayer* booths provide a *Virtuix* ecosystem of *Omni* centered *VR* setups, corresponding *Omni* compatible *VR* games and a whole system of managing time slots, onboarding and customer support etc. (Virtuix 2019).

A user needs to wear special shoes and strap him or herself into a harness, connected to two fixed arm structures (see Figure 150). Because of the usage of a very low-friction material, the shoes easily slide over the bowl-curved base. Sensors connected to the shoes track each foot's steps, which will be translated into virtual steps. Additional sensors in the ring holding the harness furthermore enables the more natural decoupling of movement and direction of sight, which means the user can walk in one direction, but look at another (Durbin 2016b).

This more natural approach to *Locomotion* supposedly results in a higher chance to create *Presence* in *VR* (Virtuix 2017) while at the same time exercises its users.

Though it was originally planned to use the *Omni* as a treadmill in *Gooze*, due to its shipping issues and the change in business model it was not feasible to integrate the device in the overall study.

B.8.2 Cyberith Virtualizer

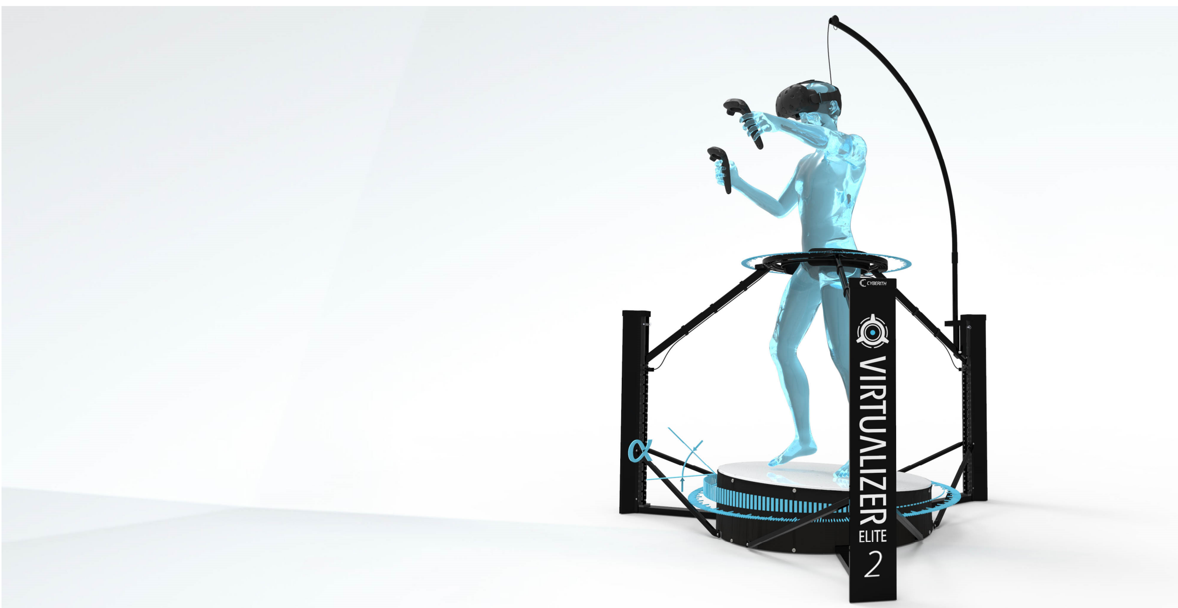

Figure 151: Cyberith Virtualizer Elite 2 (Cyberith 2019)

The *Virtualizer* from *Cyberith* (see Figure 151) is also currently aimed at professionals and commercial customers (Cyberith 2019). The basic principle is similar to the *Omni* and the *ROVR:* The user moves on the spot on a low-friction base, restricted by a structure. Instead of using separate shoes, *Cyberith* offers overshoes, to slip over the user's normal shoes. By using a flat base plate *Cyberith* claims walking feels more natural then on a curved surface (Cyberith 2019). Tracking is accomplished by "Three sets of sensors in the base plate, pillars and ring" (Cyberith 2019).

The *Virtualizer's* second generation, the *Elite 2,* additionally integrated a tilting base plate, which should further improve the walking movement, by automatically inclining towards the direction the user is currently moving at (Cyberith 2019).

B.8.3 Wizdish ROVR

Wizdish with its *ROVR* device (see Figure 12) is offering a more minimalistic and simple design. The *ROVR* does not offer any harness, but instead the user is supposed to hold onto the railing (Wizdish 2017). For obvious reasons this limits its usage to less interactive applications and focuses it more on walking/running only experiences, as the user is not comfortably able to hold any controllers. Still, it was integrated in the study with *Gooze* (see from page 150ff.), which provided an interesting interaction mode, combining the *ROVR* with *Controllerless Hand Tracking* via the *Leap Motion* controller.

Furthermore, *Wizdish* chose to use a headphone jack to transmit tracking data through a microphone input socket (Wizdish 2017). Choosing this nowadays-exotic input port seems unusual, though the *ROVR* can supposedly additionally communicate via *Bluetooth* (Wizdish 2017). Nevertheless, the very simple microphone tracking technique showed various disadvantages like only being able to move forward or its lack of tracking precision.

In terms of shoes, *Wizdish* offers both, special shoes and overshoes for a low-friction movement on a slightly curved base plate.

B.9 STEREOSCOPIC 3D PROJECTORS & TVS

There is a plethora of different *3D* capable *Projectors* and *TVs* available on the consumer market. As it was used in one of the artifacts of the overall study, the following will elaborate on the *Panasonic PT-AT6000E 3D Projector* (see Figure 13), exemplary for the whole category of *Non-VR Stereoscopic 3D* devices.

Though these specs might possibly differ for other devices, the *Panasonic* projector offers a resolution of 1920 x 1080 pixels in total, 480 Hz intelligent *3D* frame creation, 2400 ANSI-Lumes and a contrast of 500000:1 (Panasonic 2017a). With its relatively strong zoom, it is possible to get a large projection in a small room and thus several people can comfortably sit together while still being able to view a large screen at a relatively good angle.

Being an affordable home cinema projector without the need for any special screen or screen paint, active *Shutter Glasses* are required for *3D,* compared to for example passive polarization filter glasses, which are often used in *3D Cinemas.* The *Panasonic TY-EW3D3ME* glasses (see Figure 14) use an *IR* signal from the projector to synchronize their shutter effect. The glasses provide a very long battery life and can be easily recharged via a *USB* cable. Due to their dimensions, it is possible to wear medium sized prescription glasses underneath them. Finally, with the slide of a button, the glasses also offer to individually show a flat *Monoscopic* image to users who might prefer that.

B.10 LOCATION-BASED VR INSTALLATIONS

There are very immersive "holodeck-like" *VR* experiences, which are so complex and expensive to install, that these are largely not for home consumption, but set up for example by universities, professionals and entertainment park providers. Though the overall study is not concerned with these kinds of installations, they need to be mentioned to provide context.

B.10.1 CAVE

Figure 152: CAVE system (Strickland 2007)

Figure 153: The VOID debut at TED 2016 (Ha 2016)

The *CAVE Automatic Virtual Environment (CAVE,* Cruz-Neira et al. 1992 and Lugrin et al. 2013) is a system, which in principle uses several projectors to project a *VE* possibly on all walls, the roof and the floor of a room (see Figure 152). Additionally, the user needs to wear *3D* glasses (e.g. active *Shutter Glasses),* which are synced to the *3D* projections to establish *Stereoscopy.* Though the system can be viewed by multiple people only the user who is tracked will be able to automatically adjust the projected point of view (Strickland 2007). Via various tracking techniques the user's gaze, movements and possibly interactions with a *VE* are captured and manipulate it in turn.

B.10.2 The VOID

There are also *VR* entertainment parks like *The VOID* (see Figure 153, Ha 2016). In *The VOID* users will be equipped with a mobile gear set consisting of the *Rapture HMD,* vest (see Figure 149) and optionally special hand controllers. Multiple users can freely walk through a specially designed setup like an unpainted movie set (see Figure 153), including gimmicks like water sprinklers, fire bursts, artificial olfaction, moving floor panels and other special effects (Ha 2016). Using techniques like redirected walking (Bruder et al. 2012), the needed installation space can be reduced in comparison to its virtual equivalent (Road to VR 2016).

These location-based sceneries and effects in combination with the high-end *Rapture VR* gear create astonishingly realistic experiences (Road to VR 2016). Users are able to fight together or against each other in science fiction styled gun battles on a spaceship, or they can cast spells against a giant dragon in a fantasy scenery etc. What makes these experiences so compelling is the elaborately crafted and effect loaded physical space that users likewise need to physically traverse and interact with, with their whole body (Road to VR 2016).

B.10.3 Hologate

Figure 154: Hologate four player installation (Hologate 2019)

Hologate offers consumer-oriented location-based *Multiplayer VR* setups (see Figure 154) with a limited footprint. These installations use a combination of available high-end consumer *VR* hardware and additional custom devices like e.g. rifle controllers and haptic vests. Furthermore, *Hologate* provides custom *VR* games, also developing some of them in-house, and streamlined the player onboarding process and the end-consumer support for venue owners through custom solutions.

C. SOFTWARE DEVELOPMENTS FOR ARTIFACTS

As more complex game development commonly involves a great amount of software development and programming, this aspect of the creational process needed to be mentioned, too. Providing a quantitative metric of measuring the effort that went into coding the logic parts of the three artifacts, *Nicely Dicely* and *LizzE – And the Light of Dreams* each required over 8k lines of individual code and *Gooze* needed even more than 13k lines of code.

The following section will elaborate on the most prominent custom software solutions, developed for the three artifacts. Some *Unity Components* are too comprehensive to be presented in a single screenshot, so white arrows indicate when separated screenshots belong together. To avoid exceeding the scope of this thesis, only the feature set and selected underlying processes of certain developed systems will be outlined. This is by no means an exhaustive listing of all developed systems. Although the following solutions were specifically created for the corresponding artifacts, they were developed as modularly as possible, to be able to use them for future artifacts. Likewise, underlying approaches, concepts and processes may be extrapolated to be implemented in other projects.

C.1 NICELY DICELY

C.1.1 Screen Shake

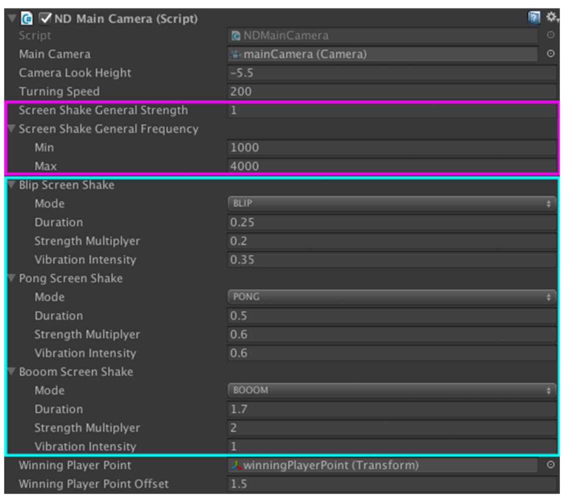

Figure 155: Screen Shake parameters in NDMainCamera Component

To increase the visual "impact" of various in-game events (e.g. the explosion of a mine) and thus make the game feel more dynamic, an adjustable *Screen Shake* system was added to the *NDMainCamera Component.*

The effect is based on simultaneous *Sine* and *Cosine* animations of the three dimensions of the camera's position. In the *NDMainCamera Component* one can configure the general strength and frequency of the effect animation (see pink highlight in Figure 155). Although adding more would be easy, for *Nicely Dicely* it was enough to add three *Screen Shake* templates. These were preconfigured starting in strength from a light *BLIP* over a stronger *PONG* to a rather pronounced *BOOOM.* Each template is set up with different values for effect *Duration, Strength*

Multiplier and *Vibration Intensity* (see light blue highlight in Figure 155). The latter affects how the system also triggers haptic feedback through gamepad vibrations. Finally, there is also a short delay implemented, which runs between triggering a *Screen Shake* and before the effect actually begins. This should subtly simulate the travel time of a shock wave and thus improve the feeling of the effect.

C.1.2 Animated Headline

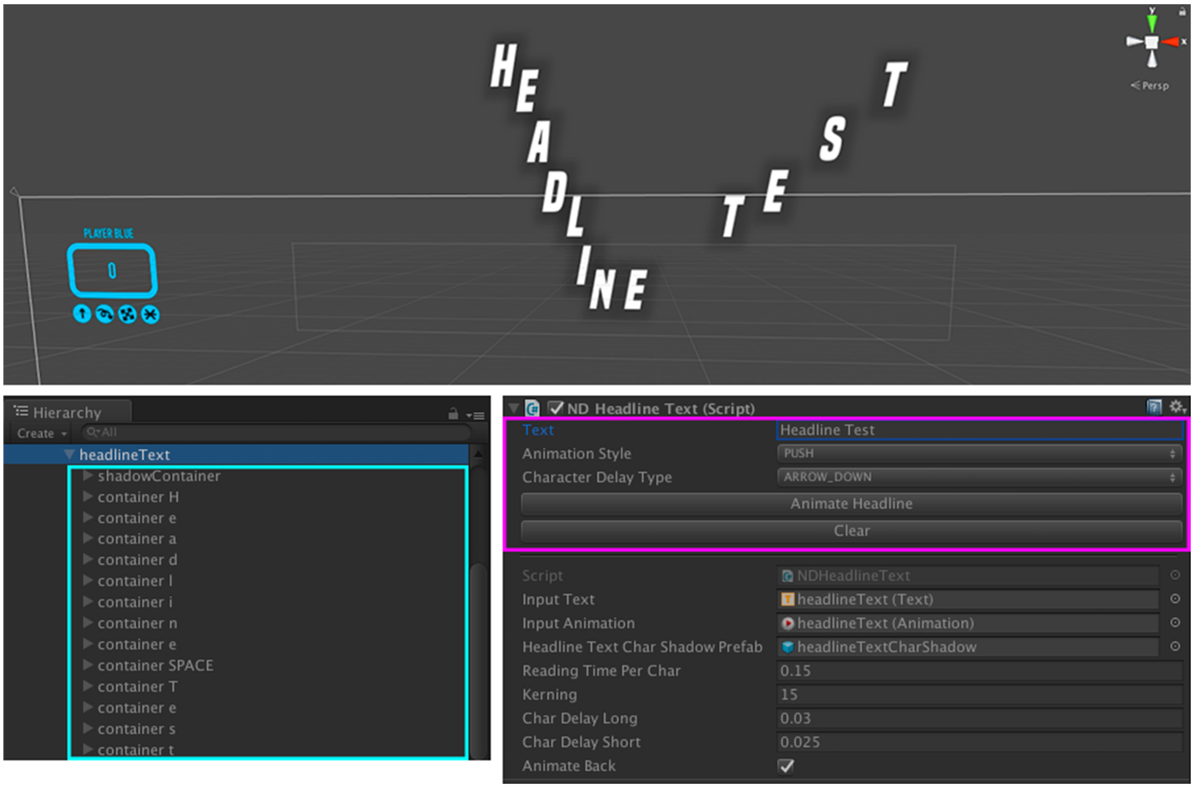

Figure 156: Headline during animation, Hierarchy showing dynamically created character objects and NDHeadlineText Component

To provide textual information accompanying in-game events in a visually versatile way, a corresponding headline system was developed.

It offers a diversely animatable headline design, while maintaining an easy development interface giving access to its full feature set. Using a single method call, a headline can be instantiated and animated into the visible screen area. After a certain reading time it can automatically rewind the animation back out of the screen. It is possible to set up a general *Reading Time Per Char* (see *NDHeadLineText Component* in Figure 156), which can automatically calculate the reading time for a headline, or one can specify a manual reading time, after which the headline should animate back. Each headline will be dynamically created by code, containing separately addressable characters and their blurred shadows for better readability (see light blue highlight in Figure 156).

Four *Animation Styles* were added: *Push In*, *Bounce In*, *Scale In* and *Fade In* (see pink highlight in Figure 156). Additionally, six *Character Delay Types* were implemented: no delay, iterative delays starting from the leftmost character or the rightmost, iterative delays starting from the center character going outwards *(ARROW_DOWN)* or vice versa or a completely random pattern of iterative delays (see *ARROW_DOWN* in pink highlight and the headline screenshot during a V shaped *Push In* animation in Figure 156). Like this, 24 different headline animations can be achieved, creating enough visual variety for informing on various game aspects in an appropriate manner. Finally, it is also possible to directly test an animation from the editor, to speed up development (see pink highlight in Figure 156).

Though this system proves how complex a rather simple element like a headline can be, it also shows that investing the required work for such a system can drastically benefit an application's development and visual versatility on the long run.

C.1.3 3D Stereoscopy System

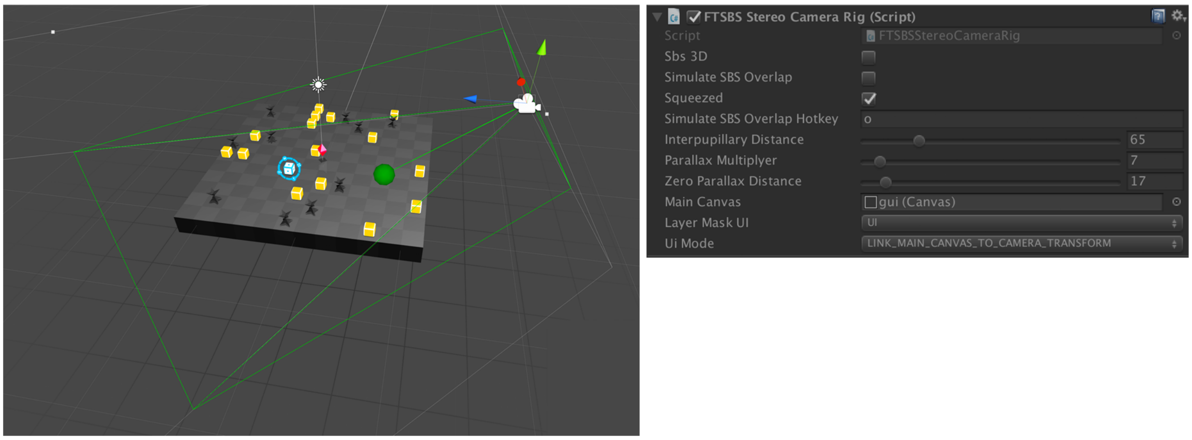

Figure 157: Scene View visualization of stereo camera rig: green rectangle and ball show zero parallax distance and FTSBSStereoCameraRig Component

Although in *LizzE* v2A a third-party plugin was used to add *SBS3D* support, due to discontinued support a similar but custom solution was developed for *Nicely Dicely*. This *FTSBSStereoCameraRig Component* (see Figure 157) can be added to a standard camera *GameObject* and it would automatically create all necessary child *GameObjects* and *Components*, while preserving the functionality of the base camera. It offers several settings including the real-time toggling of the *SBS3D* mode, a *3D Simulation Mode* overlaying the half transparent left and right images, an *IPD* adjustment, a parallax multiplier, a zero-parallax distance adjustment and a slot to link a *UI Canvas* object.

With the *3D Simulation Mode*, it is possible during development to quickly adjust various parallax settings without the need of an actual *Stereoscopic 3D* setup. Of course, this does not create the actual *Stereoscopic* effect, but provides a visual estimation of applied parallax shifting (see Figure 36, Figure 37, Figure 44 and Figure 45).

The zero-parallax distance is also visualized with a green frustrum gizmo (see Figure 157), so it is easy to identify the distance from the camera, where there is no parallax shift happening and the left and right image overlap perfectly. When a completely independent *UI Canvas* object is linked, the *Component* can automatically create a synchronized visual duplicate, while preserving the interactivity of the different *UI* elements, including mouse click targets etc. These two *SBS UIs* are automatically positioned at zero-parallax to always present a clear image. Like this, it is possible to maintain a game's overlaying *GUI* independent of and unaffected by the *Stereoscopic 3D Mode.*

C.2 LIZZE – AND THE LIGHT OF DREAMS

C.2.1 Spatialized HUD

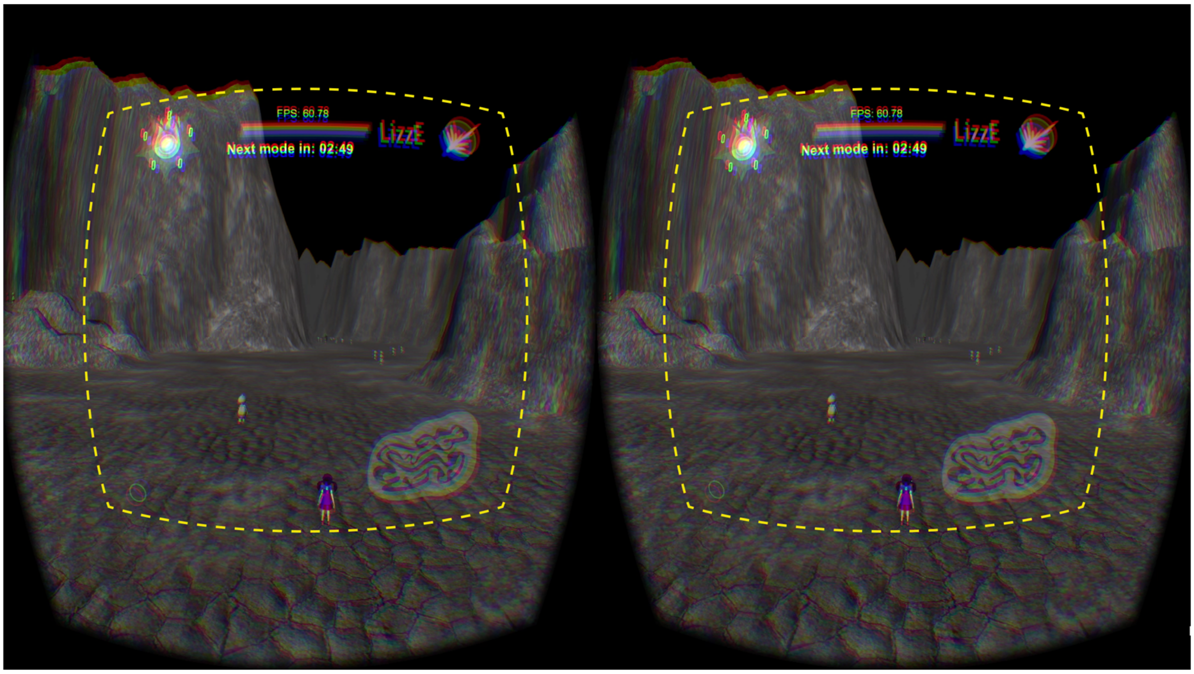

Figure 158: Visualization of spatialized HUD plane in LizzE

The *HUD* for *LizzE* was originally created using the rather outdated third-party plugin *NGUI* (Tasharen Entertainment 2012) in *Unity* v4.x. This *GUI* approach was based on using a separate *GUI* camera, which rendered *2D* images to an overlaying layer on top of the *3D* rendered image. During the development of v2A/B it became clear, that this behavior was completely incompatible to *3D Stereoscopy* and *VR* in terms of technique as well as design. In order to overcome this issue, without needing to re-develop everything from scratch, I developed the following trade-off solution: The original *GUI* camera setup was kept, but the render target was changed from the viewport to a special render texture. This render texture was then placed on a semi-transparent plane, which was parented to the *3D* camera rig and placed slightly in front of it, so the *3D* camera rig would always "look through" it (see yellow highlighted distorted squares in Figure 158). The downsides of this approach were a mandatory square aspect ratio for the *HUD*, the enemy health bars needed to be disabled as they would have required a complete re-development, players would need to adjust their focus depth back and forth between the *HUD* and the *3D* scenery and the edges of the *GUI* plane became visible, i.e. certain *GUI* effects like the red fade-ins when taking damage started off in mid-air. Nevertheless, this approach was good enough for an experimental prototype.

C.3 GOOZE

C.3.1 Interactive Object

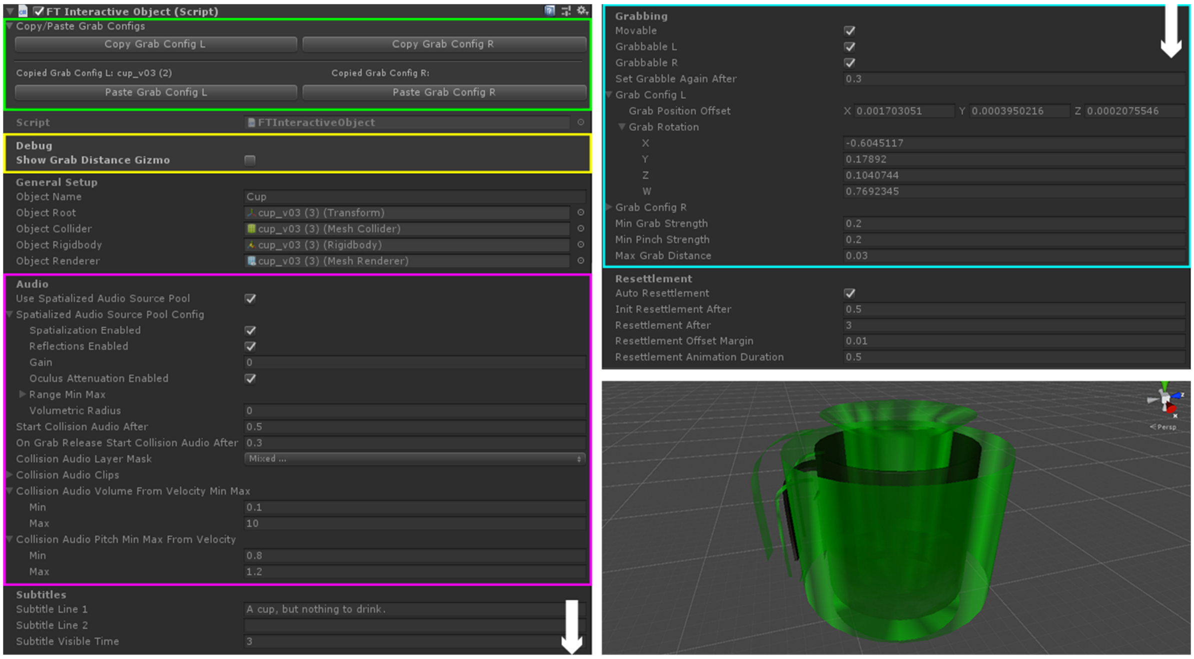

Figure 159: FTInteractiveObject Component and Grab Distance Gizmo visualization

The *FTInteractiveObject Component* is the base class for all interactive objects in the game. These include e.g. the cup, the polaroids and the ceiling light, but also the invisible hole in the wall etc. The *Component* provides various options to configure the object for the diverse sub-systems of the application, like spatialized audio, thought subtitles, object grabbing and object resettlement (i.e. the sub-system, which automatically places the object back at its initial position, when moved and released). To simplify adjusting the maximum distance from a hand's grab point to the object's *Collider,* inside which it can be grabbed, a *Grab Distance Gizmo* was implemented (see yellow highlight in Figure 159). To roughly visualize this distance, the gizmo automatically renders a semi-transparent dynamic duplicate of the mesh, in which all surfaces are outwards scaled by the respective distance (see screenshot of cup with green gizmo in Figure 159).

The following elaborations on further sub-systems will refer back to this *Component.*

C.3.2 Posing Skeletons and Objects

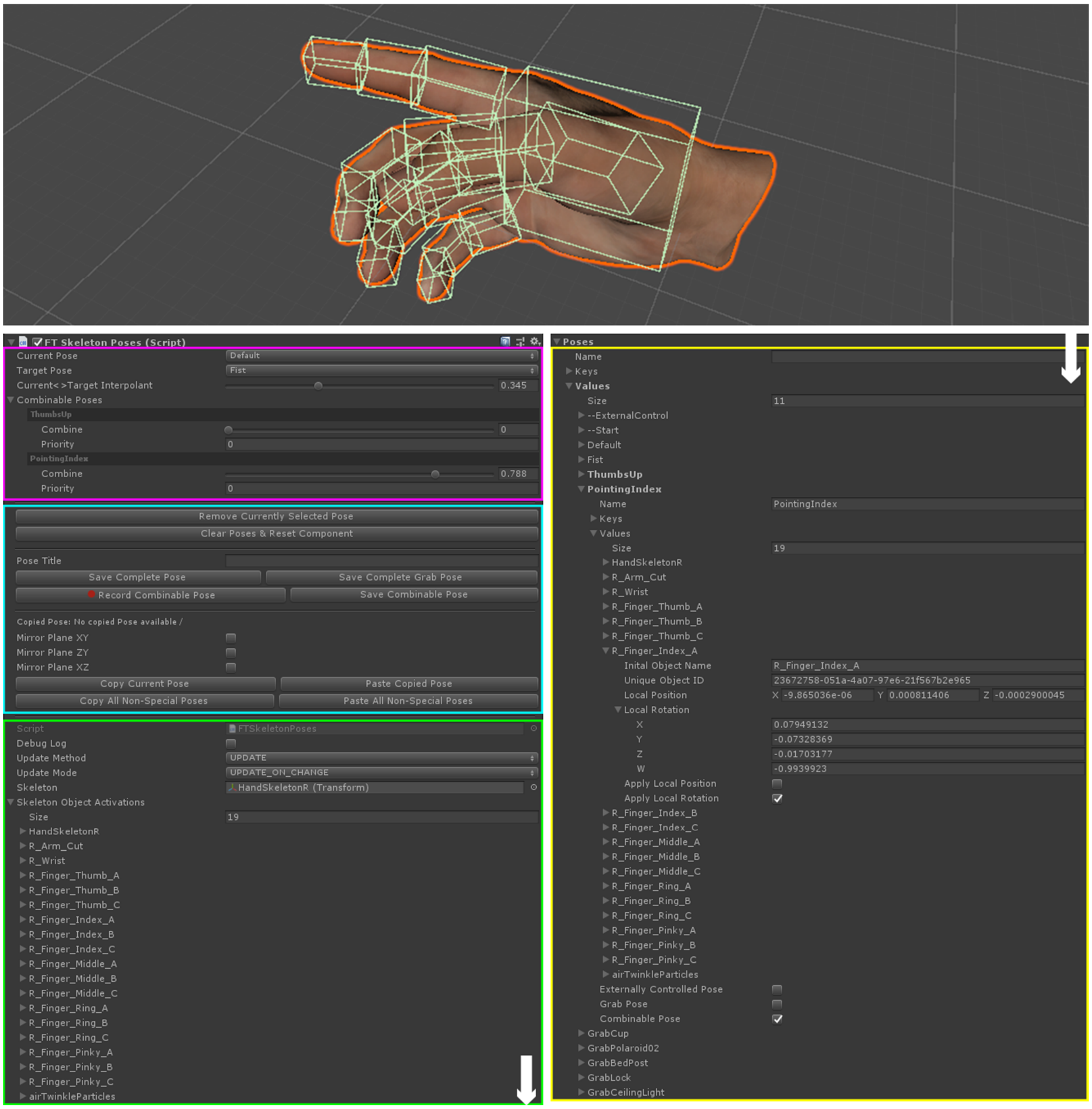

Figure 160: Posed hand and FTSkeletonPoses Component

To achieve a precisely controllable animation of the hand skeletons and thus the hands, a *Universal Skeleton Poses* system was developed. This system includes the three *Components FTSkeletonPoses* (see Figure 160), *FTDevHandObjectPoser* (see Figure 161) and *FTUniqueObjectID*, several further sub-systems, tools and is tightly integrated with other *Components* like *FTInteractiveObject.*

Once *FTSkeletonPoses* is added to a *GameObject* (e.g. a rigged hand), one can link any other possibly subordinated *GameObject* into the *Skeleton* slot. This automatically recursively creates a list of all respective child *GameObjects* and the skeleton parent object itself (see green highlight in Figure 160) and applies an *FTUniqueObjectID Component* to each of them, in turn assigning a *GUID* styled unique *ID* to each skeleton

GameObject. Additionally, the *--Start* pose is created from this initial configuration of the skeleton and added to the list of poses.

A "pose" basically stores the local position and rotation values as well as further properties for all skeleton objects in a list (see yellow highlight in Figure 160). There are three types, i.e. complete, grab and combinable poses. As the name suggests, a complete pose applies corresponding values to the complete skeleton. A grab pose is a special version of the complete pose, which is individually configured for each hand and each grabbable object. A combinable pose applies only a specific subset of local position and/or rotation values to the skeleton and multiple combinable poses can be applied on top of complete or grab poses.

A precisely controllable script-based interpolation system can then animate, in a *Forward Kinematic* fashion (Softimage 2011), between multiple poses and mix them in various degrees. Due to the setup of the skeleton, this in principle "simple" interpolation of local position and rotation values of the skeleton *GameObjects* results in believable animations. Only the caching of animation states and pre-calculations for mixing poses and precisely controlling and prioritizing them added a certain complexity to the animation system.

In simplified terms, this system is based on a "current" and a "target" pose, which can be freely switched and between which the skeleton can be precisely interpolated. On top, the combinable poses can also be interpolated into these mixed values and possible overlapping pose instructions can be controlled via setting up priorities. In code, timed animations can be triggered in real-time and when a pose is switched the system automatically applies a custom animation from the current possibly mixed pose to the new configuration. The current configuration of poses, interpolants and priorities can also be manually adjusted in the editor (see pink highlight in Figure 160). The right hand in Figure 160 is posed according to the pose configuration shown in the pink highlighted area: The hand is posed in-between the *Default* and the *Fist* pose and the combinable *PointingIndex* pose (affecting only the index finger) is calculated into this mix of values, too. To provide flexible usage in various situations, the animation system can be further configured to animate during *Update* and/or *FixedUpdate* steps. Additionally, it can continually animate on every corresponding frame or process animation only, if there are pose changes scheduled (see green highlight in Figure 160), to reduce its impact on performance.

As many poses needed to be configured and stored for the demo – e.g. two poses per grabbable object, one for each hand – and a pose consisted of a rather huge amount of values, a comprehensive editor workflow was required. This workflow should automize as much of the process as possible.

To create a complete or combinable pose, only the *FTSkeletonPoses Component* is needed. In case of a complete pose, one needs to manually adjust the skeleton objects (the local positions and rotations), so the skinned mesh is posed as needed, enter a *Pose Title* and click the *Save Complete Pose* button (see light blue highlight in Figure 160). The pose will then be added to the lists of selectable poses and can be freely interpolated to and from. To create a combinable pose the *Record Combinable Pose* button needs to be clicked initially. Once this mode is started, each individual parameter change of the skeleton objects is recorded. When the skeleton is posed as needed and a *Pose Title* was entered, a click on the *Save Combinable Pose* button (see light blue highlight in Figure 160) will internally store a complete pose but set up corresponding flags only for the actually changed parameters (see yellow highlight in Figure 160).

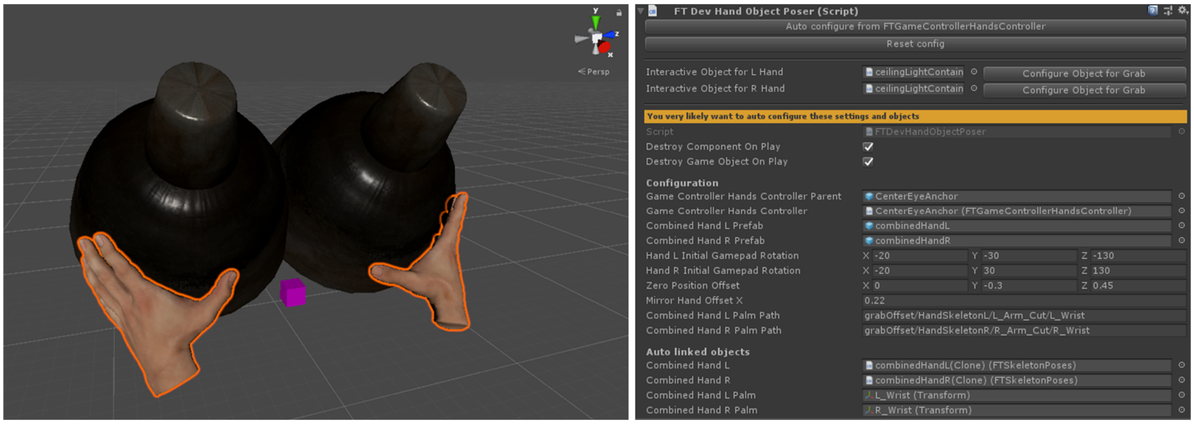

Figure 161: Scene View showing left/right grab pose configuration process for the ceiling light and FTDevHandObjectPoser Component

The workflow of creating a grab pose is slightly more elaborate and involves the editor only *FTDevHandObjectPoser Component*, which was developed purely for this purpose. Once *FTDevHandObjectPoser* is added to an empty *GameObject*, by clicking the respective button, it can automatically acquire its configuration from an *FTGameControllerHandsController Component* present in the scene. This creates duplicates of the correctly configured hand objects and parents them to the empty *GameObject*. This is to avoid breaking any prefabs or other configurations. For similar reasons one needs to create two further duplicates of the grabbable object and link them to the corresponding slots (see Figure 161). In the following, one needs to pose and position the object and the hand for one side, so they seem to be naturally set up. By typing in a correct *Pose Title* and clicking on *Save Complete Grab Pose* in the respective *FTSkeletonPoses Component*, the grab pose specific to this grabbable object will be saved in the duplicate hand object. Likewise, clicking on the respective *Configure Object for Grab* button in *FTDevHandObjectPoser* will save the grabbable object's position and rotation relative to the hand in the corresponding section in *FTInteractiveObject* (see light blue highlight in Figure 159).

It is possible to configure two completely different grab poses, when grabbing the same object with the left or right hand. E.g. the cup is either held at its handle or its body, depending on which hand is grabbing it. Nevertheless, most objects in Gooze were supposed to be grabbed in similar but mirrored poses. To avoid needing to pose the hands twice, a respective feature set was implemented. Using the corresponding buttons in *FTSkeletonPoses* one can not only copy and paste poses from one *Component* instance to another, but also automatically mirror these poses alongside three mirror planes (X-Y, Z-Y and X-Z, see light blue highlight in Figure 160).

So, once both hands and objects are posed, and the respective poses and grab configurations are saved in the duplicate *GameObjects*, they need to be transferred to the original *GameObjects* in a convenient way. For that reason and as already mentioned, *FTSkeletonPoses* offers a feature to copy and paste single or several poses between *Component* instances (see light blue highlight in Figure 160). Likewise, it is also possible to copy and paste left and right hand grab configurations between *FTInteractiveObject* instances (see green highlight in Figure 159).

C.3.3 Spatialized Dynamic Audio

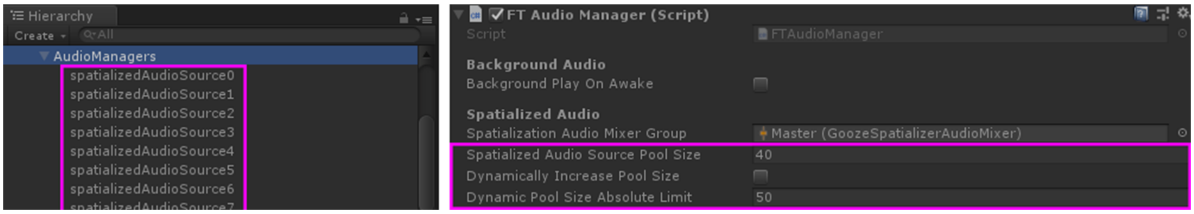

Figure 162: Hierarchy showing AudioManagers and automatic pool of spatialized audio sources and FTAudioManager Component

Although a naive user most likely does not consciously notice a well-implemented spatialized audio system, it will nevertheless very likely contribute to a more immersed and naturally feeling experience. In *VR,* due to commonly using some sort of headphones, a good spatialized audio implementation is even more important. The binaural setup and the constantly changing individual viewpoint and hearing directions of a *VR* user are a perfect fit for spatialized audio and the resulting immersive experience.

The audio system in *Gooze* is based on the *ONSP* framework (v1.29.0) from *Oculus* (Oculus 2019c). Correctly configured, the framework already handles audio spatialization topics like head related occlusion, direct sound, reflections, reverb and dynamic room modelling (Oculus 2019c). To include spatialized sound effects, e.g. for object collisions, a custom *Dynamic Audio* system was implemented on top of it. Requiring a working *ONSP* setup, *FTAudioManager* creates a pool of reusable, automatically ad-hoc configured and positioned audio sources (see pink highlight in hierarchy in Figure 162). The initial pool size can be adjusted and if needed it can be dynamically increased until an absolute limit is reached (see pink highlight in *FTAudioManager* in Figure 162). Using a pool of reusable audio sources, instead of always dynamically creating and destroying them, was implemented to minimize the performance costs of the system.

By invoking a specific method of the *FTAudioManager* singleton, the manager will be instructed to automatically acquire an audio source *GameObject* from the pool, which is preferably not in use or the one which is already playing the longest time of the stack of currently active audio sources. The selected audio source will then be configured with individual settings, three-dimensionally positioned and a respective audio clip will start to play. If not re-assigned prematurely, once the playback is finished, it will be treated as inactive and ready to be re-used again.

When a movable *FTInteractiveObject* collides with the level geometry or another object, the above process is invoked. The speed of the collision will be used to calculate the audio effect's desired volume and pitch. This and the *FTInteractiveObject's* individual audio configuration with a randomly selected audio clip from a pool of pre-configured collision effects (see pink highlight in Figure 159) will be send to the *FTAudioManager.*

So, the implemented audio system simulates spatialized audio in a performant way, including sound reflections (and optionally reverb). Additionally, e.g. in *Gooze,* when moving your head from the main room into the corridor, the system dynamically adjusts its internal audio environment, which in turn accordingly adjusts the sound of audio effects, creating a more believable *VE.* This is further enhanced by not only triggering audio effects precisely positioned at object collision points, but also adjusting their volume and pitch in relation to the collision speed. In other words, one can actually hear where a sound is coming from, audio effects sound according to the room the player is in and e.g. if you just slightly tap the metal door with another object, you hear a gentle >bing<. Whereas if you pound it hard, you hear a loud >BONG<, and everything in-between is possible without the need of multiple pre-rendered audio files.

C.3.4 Universal Input Manager

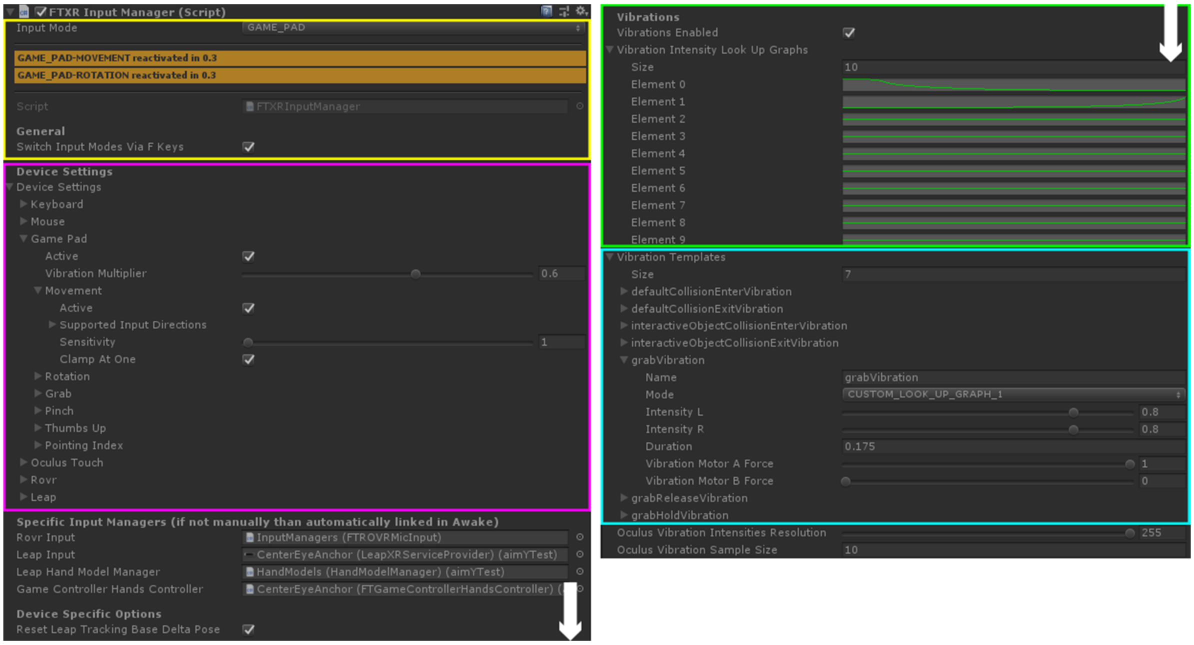

Figure 163: FTXRInputManager Component

The biggest challenge in developing *Gooze* was to provide compatibility for very diverse input devices, while maintaining an almost identical set of possible interactions for the player. On the one side, this challenge required a sophisticated interaction design. On the other side it also required a technical approach, which needed to modularize device dependent code and separate it from the other game systems as well as possible. These systems should instead access an abstracted interface, the *FTXRInputManager* singleton (see Figure 163). Although this *Universal Input Manager* could not abstract all device specific features, it is nevertheless an essential solution to unifying the majority of possible input actions and haptic feedback options.

FTXRInputManager offers a standardized but extendable way of implementing any number of diverse input devices (see *Keyboard, Mouse* and *Gamepad* etc. in pink highlight in Figure 163). This is feasible by providing a set of abstract internal interfaces and rules, which the device specific code needs to conform to.

It is further possible to add an arbitrary number of abstracted input actions (see *Movement, Rotation* and *Grab* etc. in pink highlight in Figure 163) and each input device should provide device specific implementations for as many of them as possible. Nevertheless, the system pragmatically accepts that different input devices do not offer the same number of sub-controls or output parameters. E.g. a gamepad provides various buttons, triggers and sticks, whereas the ROVR treadmill only outputs a single one-dimensional parameter. In turn, for every device, individual general device settings and all input actions can be individually fine-tuned and configured (e.g. device *Vibration Multiplier* and action *Sensitivity).* This includes completely or partially deactivating an action or setting it up to fully support a specific device.

Regarding the other game systems though, *FTXRInputManager* works as a central access point for all input related matters with a standardized interface for most of the possible input actions. When there is an exception it can also provide direct access, by passing through the specific device controller instance (see *Specific Input Managers* in Figure 163). Additionally, it internally handles setting up and possibly switching the *Input Mode*, via hotkeys, too (see yellow highlight in Figure 163). An *Input Mode* is a certain configuration of active and inactive devices and/or actions.

Furthermore, *FTXRInputManager* includes a sophisticated haptic feedback system using the vibration capabilities of the input devices. A vibration effect consists of several parameters, including an intensity graph, a duration and several more device dependent options. Additionally to typical graphs like full vibration and sine wave, it is possible to define custom vibration intensity look up graphs, to create very individually feeling vibrations (see green highlight in Figure 163). A haptic effect will then adjust its intensity according to the graph over a freely configurable effect duration. Selecting from these graphs, it is possible to create *Vibration Templates*, which can be easily triggered as a vibration effect from anywhere in code (see light blue highlight in Figure 163). These effects can be applied to either the left and/or right vibration channel/s, to provide possibly hand specific haptic feedback.

C.3.5 Controlling Hands via Gamepad: Automatic Height Adjustment

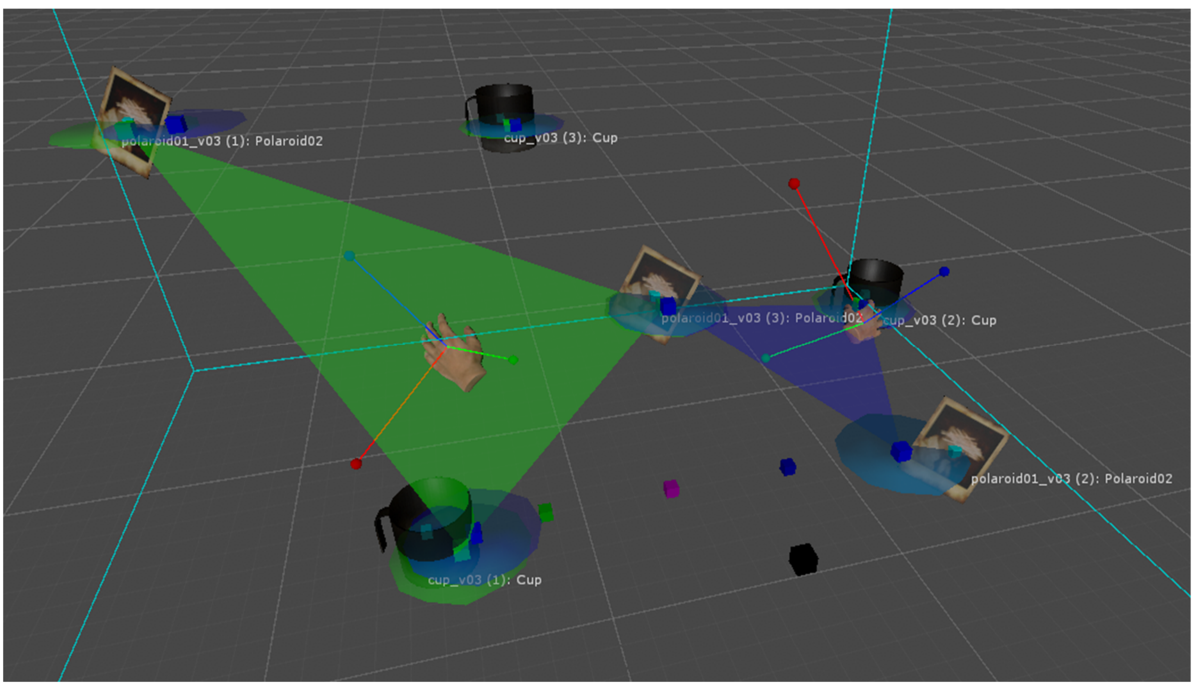

Figure 164: Scene View visualization of automatic height interpolation of hands between grabbable objects, with development gizmos visible

Due to the analogue sticks of a gamepad providing only two-dimensional inputs, a special approach was needed to three-dimensionally control the hands with such an input device. The respective input approach is based on the player controlling the translation of a hand via an analogue stick on the X-Z plane only and using an algorithm to automatically adjust the hands Y position according to grabbable objects. So, the player can actively move his virtual hands forwards/backwards and sideways in a certain range, but the algorithm adjusts the upwards/downwards movement automatically, if grabbable objects are in range.

The latter is not a trivial behavior though, if it should feel rather unnoticeable and natural to the player. To achieve this feature the corresponding algorithm is based on several phases, which need to be rerun on every frame, as the three-dimensional constellation of objects and player hands can constantly change. In turn the corresponding code needed to be specifically optimized to run as performance efficient as possible.

In the first phase the system checks if and which grabbable objects are in grabbing range (see cups and polaroids in truncated light blue box in Figure 164). Next, instead of just using the center points of the objects for further calculations, the two "optimal" grab points (one for each hand) are calculated for each object. This means the closest point on an object *Collider* (see green and blue cubes around objects in Figure 164, green for left and blue for right hand) to the initial hand position (see isolated smaller green and blue cubes in Figure 164) is acquired. Including the current hand positions and the four corner points of the grab range box positioned at the height of the initial hand positions, this three-dimensional constellation of hand positions and "aim points" is then cached. For further calculations, it is flattened to two dimensions on the X-Z plane. Next, the space around each hand's current position is separated into four sectors and the closest and second closest aim point per sector are determined. In a sort of reverse triangulation process, the "tightest" triangle of aim points around a hand position is identified. Relative to the hand's position, the barycentric weights of the corresponding triangle corner points are then cached. Next, these barycentric weights are used to project the hand's two-dimensional position back onto the three-dimensional version of the triangle surrounding it (see green and blue triangles in Figure 164). Hence, when actively controlling the X-Z position of a hand, the system automatically interpolates its height relative to the currently tightest surrounding three aim points. Or in other words, when moving the hands, they automatically slide along a triangulated "mountain range", whose peak and valley constellation is defined by the different aim points. Like this, when moving a hand from one grabbable object to another, it automatically interpolates its height, like one would expect from a real hand reaching between objects. To further increase the usability of the system and to avoid unintendedly "overshooting" the very precise grab points, an additional close-range zone check is performed. In turn, when a hand is inside the close-range zone of a grab point (see green and blue discs around grab points in Figure 164), it will automatically translate to the optimal height for grabbing the respective object (see right hand in Figure 164). When an object is then grabbed, it will be temporarily excluded from the list of grabbable objects and the whole aiming process. Exceptions to the latter are objects like the ceiling light, which have an additional grab constraint space applied. This three-dimensionally defined space controls when a grabbed object needs to be automatically released and additionally it is used to guide the hands along its delimiting edges. Finally, a constant global height interpolation rather unnoticeably interlaces the different sub-systems of the overall aiming system.

This seemingly complicated approach was not conceived at the beginning of working on the issue but was established over developing various simpler but rather unusable implementations. In the end though, this more complex approach led to a rather naturally feeling and unobtrusive interface for three-dimensionally controlling hands with the two-dimensional sub-controls of a gamepad.

C.3.6 Wizdish ROVR Implementation

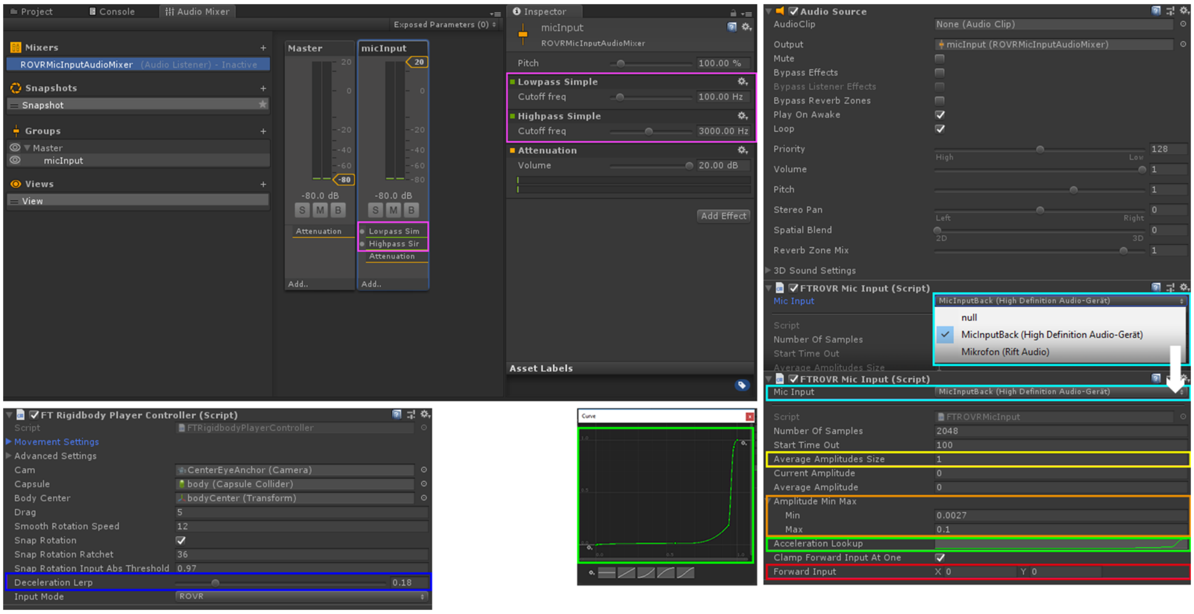

Figure 165: Components for ROVR implementation: AudioMixer with Low and Highpass filters, FTRigidbodyPlayerController, FTROVRMicInput with various configuration and fine-tuning options

The integration code snippets supplied by the manufacturer of the *ROVR* treadmill were neither modular, nor did they provide any fine-tuning options for the device. So, to implement the *ROVR* treadmill in a more accurate, adjustable and usable way, a custom solution was developed.

To achieve a modular structure, the provided code snippets were cleaned up and placed into *FTROVRMicInput.* This singleton is accessible from anywhere in the code and works as a controller for the *ROVR,* but still provides the convenience of adjusting settings via the editor.

Because the *ROVR* is connected to a *PC* as a microphone and multiple microphones can be connected at once, an editor dropdown was implemented to select the correct input for signal interpretation (see light blue highlights in Figure 165). A commercial application would additionally need a corresponding option in a settings menu, but this was not implemented for the artifact.

To minimize the influence of possibly recording unwanted loud external noises, the corresponding *Audio Mixer* group for the *ROVR* was equipped with *Low* and *Highpass* filters, which would still let most of the sliding noises through (see pink highlights in Figure 165). The passable frequency band (100-3000 Hz) was determined through trial and error and is by no means exact, but nevertheless worked as a good tradeoff.

Several previously hardcoded parameters concerning the microphone signal processing were made easily adjustable through the editor interface. E.g. the *Average Amplitude Size* – the size of an array, which stores several amplitude values to be averaged – was set very low (to 1), to achieve a more direct input interpretation (see yellow highlight in Figure 165).

Issues with unwanted but possible peaks in the sound could be mitigated by adding the *Amplitude Min Max* range, which would be used to normalize the amplitude value to a 0-1 range for further processing (see orange highlight in Figure 165). Additionally, the *Min* threshold is used to avoid unintended *Locomotion* while a user physically turns and thus produces noise. The tradeoff to this approach is, that it prohibits a more fine-grained tracking of the user movements.

As the sliding sound's amplitude is not direct proportional to the user's actual movement speed, another transformation is required. Hence, the *Acceleration Lookup* curve was added as a fine-tuning option against this issue, providing more accurate forward motion values (see green highlights in Figure 165). Again, the applied curve was established through trial and error. According to the graph, the previously normalized amplitude values are mapped to a normalized *Forward Input* parameter (see red highlight in Figure 165), which can be accessed by other systems like the *FTXRInputManager* (see Figure 163). Though, during the *Lab* experiment with *Gooze* (see from page 150ff.), it became clear that this single general curve is not optimal for all the different movement styles of various users, although it worked as a reasonable tradeoff. Nevertheless, an individually calibrated curve would likely result in more accurately translated movements of that specific user.

Finally, a *Deceleration Lerp* parameter was added to the *FTRigidbodyPlayerController,* to configure how smooth the movement should be and how quick the user should be stopped, when there is no physical movement (see dark blue highlight in Figure 165). This decelerating parameter adjusts the short delay at the end of a physical movement, when the virtual player still pushes forward one last bit. That last inaccurate virtual movement is a tradeoff again and may induce some *Simulator Sickness* in players on the one hand, but on the other hand it smoothens the virtual movement, instead of resulting in chopped up separate movements.

D. RESEARCH TOOLS

The following section will outline custom software tools, specifically developed for this research.

D.1 XML EXCEL EXPORT OF IN-GAME PARAMETERS

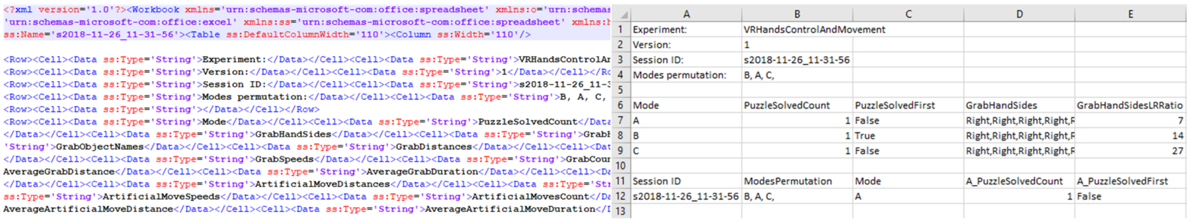

Figure 166: Exported XML snippet of an experiment session and the MS Excel spreadsheet after the import

Each of the three conducted *Lab* experiments incorporated the tracking of diverse in-game parameters of the respective artifact. E.g. in the case of *Gooze* and its *Lab Experiment: UX Evaluation of VR Locomotion & Virtual Object Interaction Mechanics* (see from page 150ff.), the experiment application tracked the general meta data of a session, including the individual session ID and the pseudo random modes order. The former was used to link the in-game data set with other data sources like video recordings and questionnaire data, whereas the latter was needed to analyze related individual player behavior and to look for order effects. Mainly though, several predefined events and their respective data, separated for all three interaction modes, were tracked per session. Among many more, these events included e.g. if the puzzle was solved in a mode, how often it was solved and if it was the first time it was solved in a session. Further events were concerned with tracking all object grabs, including data on which object was grabbed, which hand grabbed the object, for how long it was grabbed and how far it was carried.

Often the tracking system was developed in such a way, to also automatically calculate mean averages or other possibly relevant values for certain parameters, so the manual work on the tracked data after the experiment could be minimized as much as possible. Over the course of the three experiments, the tracked parameters obviously changed respectively to the experiment and the content of the game. Furthermore, internal processes and the exported data layout were improved with each iteration of the system. Nevertheless, the basic procedure stayed the same for all three experiments: The application would acquire specific data, fill a structured database and at the end of a session it would export this data set to an *XML* file, which could be directly imported with *MS Excel* for further processing (see Figure 166).

Although all experiment applications were developed to run their procedure rather automatically, an additional set of features was implemented and extended only over time. Specifically, the ability to manually control the flow of modes during a session and to export the data of the current session, without actually finishing it. Only experience with conducting experiments showed that various unforeseeable things can happen during a session and that one always needs to be able to manually save the current data set, as well as start a specific experimental mode in an otherwise automatic procedure.

D.2 TEXT CLUSTERS GENERATOR

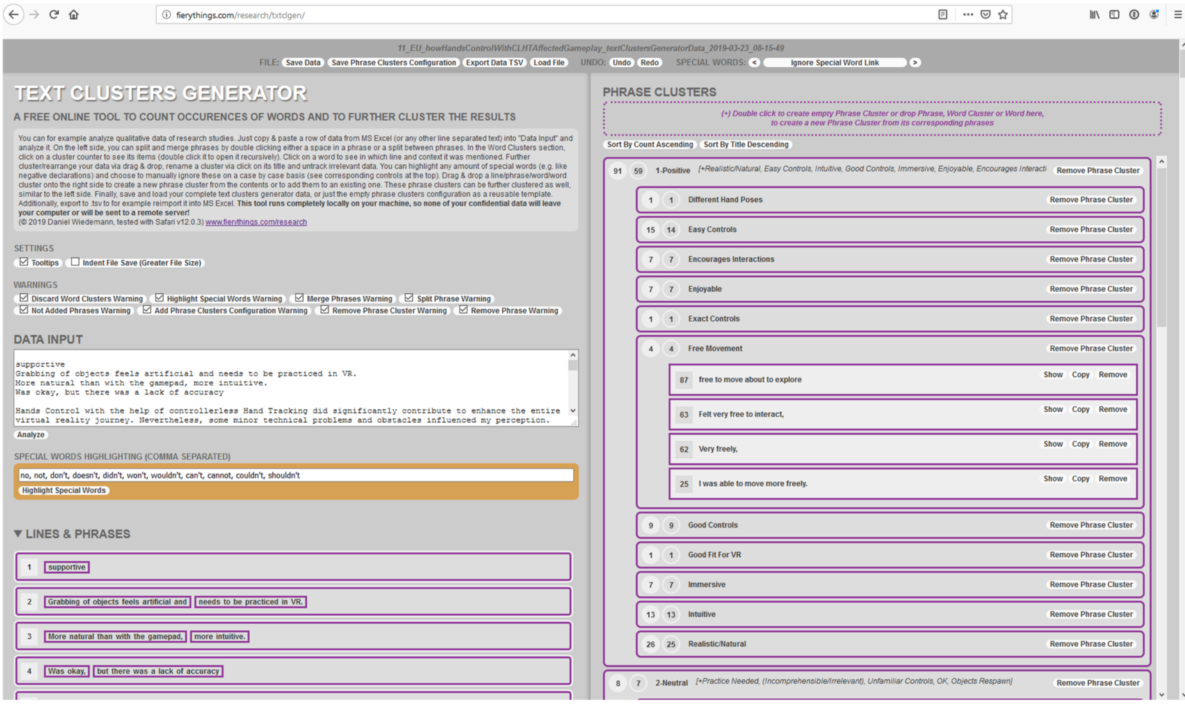

Figure 167: Text Clusters Generator website

Due to the complexity and the rather large number of participants in the last *Lab Experiment: UX Evaluation of VR Locomotion & Virtual Object Interaction Mechanics* (see from page 150ff.), a very big collection of qualitative data was collected. In contrast to the two preceding *Lab* experiments, it became clear, that simple manual splitting and clustering of the huge number of participant comments, seemed inefficient. Especially, when retraceable references to the original data sources should be maintained.

In turn, to streamline the condensed approach on *"Thematic Analysis"* (Braun and Clarke 2006), which included to "split the comments into thematically separated phrases or words, accumulate these phrases or words in thematic clusters and structure them hierarchically on the fly" (Wiedemann et al. 2020), I developed the free online tool *Text Clusters Generator* (see Figure 167): http://www.daniel-wiedemann.de/research/txtclgen/

To exclude any data security and privacy issues, it runs completely locally in a browser and accepts any line-separated text data, including the copy/pasting of a data row from *MS Excel*. The automatic analysis sorts all words into counted word clusters and in a separate section splits the lines into likely correctly delimited phrases, while maintaining internal references to the source data. One can then manually adjust the phrases (via split or merge) and create phrase clusters from them or sort them into previously created ones via drag and drop. The phrase clusters themselves maintain references to the phrases and vice versa, as well as provide phrase counts of absolute numbers and unique lines (i.e. participants). Additionally, the phrase clusters can be manually organized in hierarchies and freely named according to their content, resulting in a clear thematically structured overall hierarchy of qualitative comments.

The tool is equipped with several productivity features, which include the saving and loading of *Text Cluster Generator* files, to locally and permanently store whole clustered data sets or just cluster configurations, which can be reused as templates for other data sets. Furthermore, lists can be sorted in different ways and it is possible to perform undo and redo actions as well as several keyboard shortcuts. Finally, a processed data set can be exported as a sharable offline *TSV* file, which can be imported into *MS Excel* again to see a table structured overview of the data.

E. DISTINCTIONS

E.1 NOISE FESTIVAL 2014 EXCELLENT GAMES & NEW MEDIA AWARDS FOR LIZZE – AND THE LIGHT OF DREAMS AND ITS INTRO VIDEO

E.2 GAME-ON'2016 INTERNATIONAL CONFERENCE BEST PAPER AWARD

EUROSIS UNIVERSIDADE NOVA DE LISBOA Game-On

We, the Conference Committee of the GAMEON'2016 Conference, which was held in Lisbon, Portugal from September 13-15, 2016, hereby declare that after a peer review

Daniel P.O.Wiedemann, Peter Passmore and Magnus Moar

were selected with their paper entitled

Virtual Reality 3rd Person Camera Behavior Modes

As Best Paper of the aforementioned conference

Helena Barbas
GAMEON'2016
General Conference Chair

E.3 LEAP MOTION 3D JAM 2014 POWERED BY INDIECADE SEMIFINALIST WITH GOOZE (12TH PLACE OF 155 ENTRIES)

E.4 SCIFI-IT'2020 INTERNATIONAL CONFERENCE BEST PAPER AWARD


EUROSIS SCIFI-IT KU LEUVEN BioTeC BIOPROCESS TECHNOLOGY & CONTROL

We, the conference Committee of the SCIFI-IT'2020 Conference, which was held in Ghent, Belgium from September 6-8, 2020, hereby declare that after a peer review

Daniel P.O. Wiedemann, Peter Passmore and Magnus Moar

were selected with their paper entitled

UX Evaluation of VR Locomotion &Virtual Object Interaction Mechanics

As Best Paper of the aforementioned conference

Monika Polańska
SCIFI-IT'2020 General Conference Chair

Philippe Geril
SCIFI-IT'2020 Conference Chair

F. DOCUMENTARY VIDEOS

F.1 NICELY DICELY

F.1.1 In-Game Footage

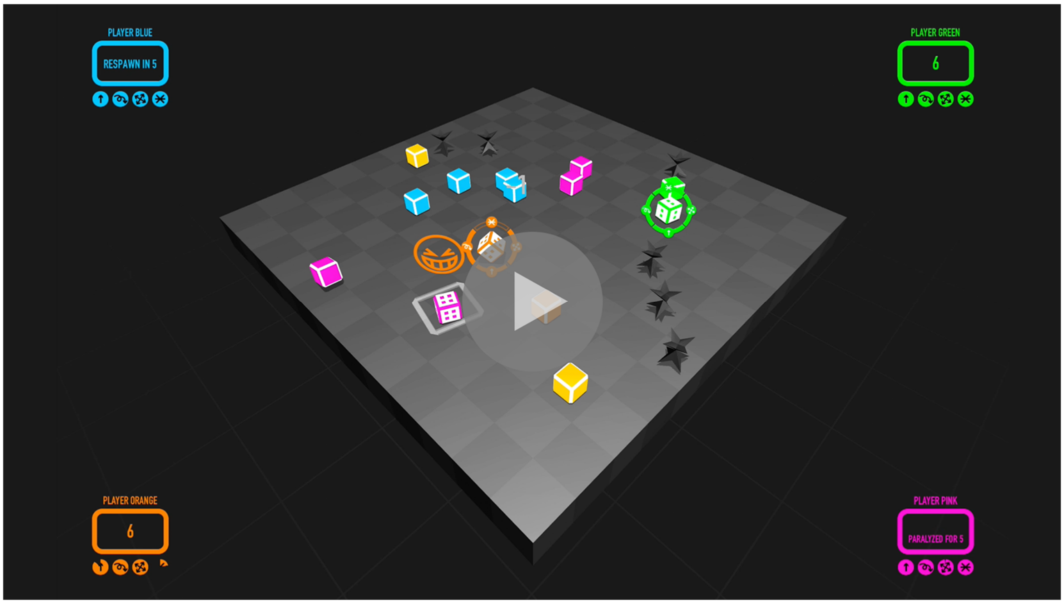

Figure 168: https://vimeo.com/wiedemannd/nicelydicely

F.1.2 Local Multiplayer Immersion Affected by 3D Stereoscopy – Experiment Overview

Figure 169: https://vimeo.com/wiedemannd/immersionaffectedby3dstereoscopyexperimentoverview

F.2 LIZZE – AND THE LIGHT OF DREAMS

F.2.1 Intro

Figure 170: https://vimeo.com/wiedemannd/lizzeintro

F.2.2 In-Game Footage

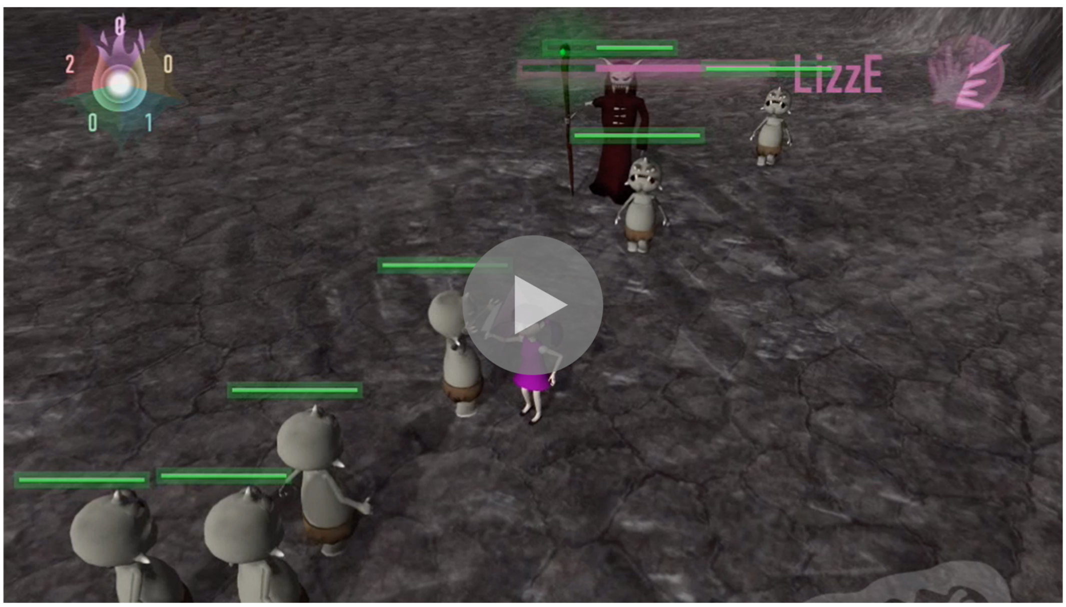

Figure 171: https://vimeo.com/wiedemannd/lizzeingame

F.2.3 Virtual Reality 3rd Person Camera Behavior Modes – Experiment Overview

Figure 172: https://vimeo.com/wiedemannd/vr3rdpersoncamerabehaviormodesexperimentoverview

F.2.4 Virtual Reality 3rd Person Camera Behavior Modes – Experiment Procedure

Figure 173: https://vimeo.com/wiedemannd/vr3rdpersoncamerabehaviors

F.3 GOOZE

F.3.1 Intro

Figure 174: https://vimeo.com/wiedemannd/goozeintro

F.3.2 In-Game Footage

Figure 175: https://vimeo.com/wiedemannd/goozeingame

F.3.3 Informal Prestudy at Super Warehouse Gaming Party

Figure 176: https://vimeo.com/wiedemannd/goozesuperwarehousegamingparty

F.3.4 UX Evaluation of VR Locomotion & Virtual Object Interaction Mechanics – Exp. Overview

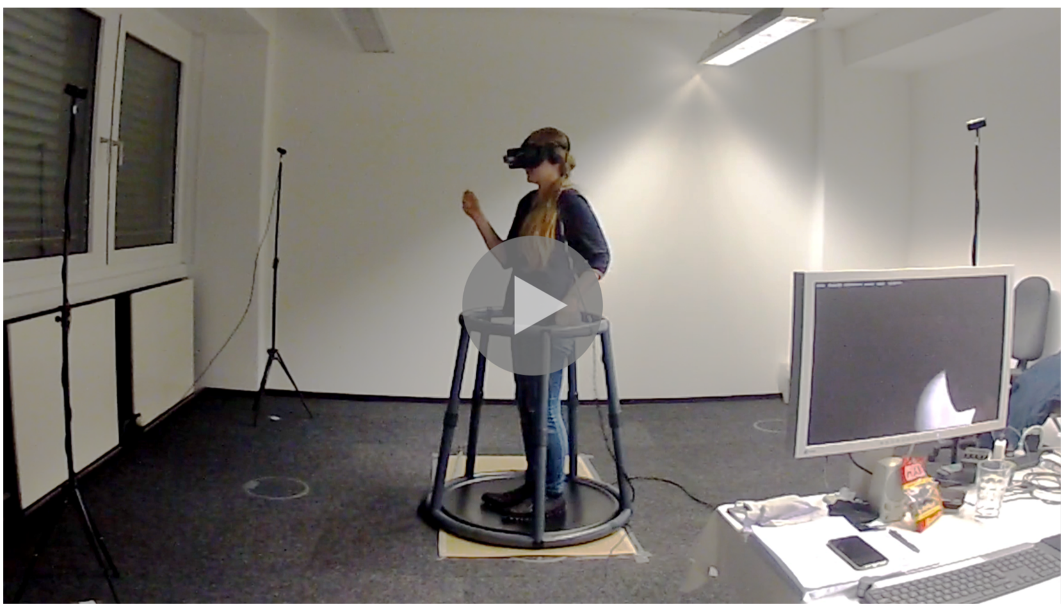

Figure 177: https://vimeo.com/wiedemannd/uxevalvrlocvoi

F.3.5 Interview on Gooze Submission to Leap Motion 3D Jam at Inition

Figure 178: https://vimeo.com/wiedemannd/goozeinitioninterview

G. PUBLICATIONS

Parts of this thesis were also released in the following publications:

Wiedemann, D.P.O., Passmore, P. and Moar, M. 2016. *"Virtual Reality 3rd Person Camera Behavior Modes".* In Proceedings of Game-On'2016 the 17th International Conference on intelligent Games and Simulation, 09/2016. EUROSIS-ETI, 57-64.
ISBN: 9789077381946, URL http://eprints.mdx.ac.uk/25245/
Abstract: [I] describe and evaluate five different level design independent modes of handling camera behavior in the 3rd Person game LizzE – And the Light of Dreams in Virtual Reality. The behavior of the different modes will each be illustrated in detail. To evaluate the modes A: Fast Circling, B: Lazy Circling, C: No Circling, D: Blink Circling and E: Buffered Pulling, an experimental study with 33 subjects was conducted. An analysis of the resulting data will show why Buffered Pulling seems to be the most promising of the examined modes. [I] elaborate on the quantitative and qualitative hybrid experiment design and methodology. Eventually the advantages and disadvantages of the five tested modes are discussed in terms of supporting the gameplay, Player Enjoyment, in game performance and the tendency to induce nausea.

Wiedemann, D.P.O., Passmore, P. and Moar, M. 2017a. *"'VRification': Applying Virtual Reality to Digital Games".* In Proceedings of SciFi-It'2017 the International Science Fiction Prototyping Conference, 04/2017. EUROSIS-ETI, 55-58.
ISBN 9789077381977, URL http://eprints.mdx.ac.uk/25249/
Abstract: In the following, [I] discuss the process of applying Virtual Reality to digital games. [I] named this process "VRification" and will elaborate on some of its opportunities and issues. Based on a literature survey and professional practice, this work covers several examples of VR games, which were intended as such from the beginning (Job Simulator and Lucky's Tale) and others, which were ported to VR after their initial release (DOOM VR and LizzE). [I] conclude that, for VR games, it is essential to be optimized for the full potential of targeted interface technologies. Furthermore, porting Former-Non-VR games to VR can create successful user experiences, when aiming for the same high standard of optimization, especially regarding Simulator Sickness.

Wiedemann, D.P.O., Passmore, P. and Moar, M. 2017b. *"An Experiment Design: Investigating VR Locomotion & Virtual Object Interaction Mechanics".* In Proceedings of Game-On'2017 the 18th International Conference on intelligent Games and Simulation, 09/2017. EUROSIS-ETI, 80-83. ISBN 9789077381991, URL http://eprints.mdx.ac.uk/25248/
Abstract: In this paper, [I] describe an experiment outline on investigating design and User Experience related aspects of several Virtual Reality Locomotion and Virtual Object Interaction mechanics. These mechanics will be based on consumer hardware like a common game controller, an infrared hand and finger tracking device, VR hand controllers and an Omnidirectional Treadmill. Corresponding related work will contextualize and motivate this research. The projected experimental study will be based on user test sessions with a specifically developed 1st Person VR puzzle horror game, called Gooze. A hybrid approach of self-assessment, in-game parameter tracking and session observations will be proposed for the investigation. Statistical analysis methods will be suggested to evaluate results. Furthermore, this paper will give an overview of the game and elaborate on design, gameplay and User Experience related insights of already conducted informal pre-studies with it.

Wiedemann, D.P.O., Passmore, P. and Moar, M. 2017c. *"Local Multiplayer Immersion affected by 3D Stereoscopy".* In Proceedings of the 2017 ACM SIGCHI Annual Symposium on Computer-Human Interaction in Play (CHI PLAY 2017).
ISBN 9781450351119, DOI 10.1145/3130859.3131429
Abstract: In this paper, [I] describe an experimental study, which evaluates how 3D Stereoscopy affects Player Immersion in a possibly very distracting Local Multiplayer game. The game "Nicely Dicely" was specifically developed for this purpose, with 3D Stereoscopy in mind, right from the beginning. Groups of participants were competitively playing the game in Non-3D Monoscopic and 3D Stereoscopic Presentations via a 3D compatible projector and corresponding active Shutter Glasses. In the following, [I] elaborate on the game and [the] quantitative and qualitative hybrid experiment design and methodology. An analysis of the resulting data will show that, indeed 3D Stereoscopy significantly increases Spatial Presence, Involvement and Player Immersion, even in a Local Multiplayer situation. Furthermore, some guiding insights relating to the game's design will be illustrated.

Wiedemann, D.P.O., Passmore, P. and Moar, M. 2020. *"UX Evaluation of VR Locomotion & Virtual Object Interaction Mechanics".* Will be published in Proceedings of SciFi-It'2020 the 4th International Science Fiction Prototyping Conference, 09/2020. EUROSIS-ETI, 49-57.
ISBN 9789492859105
Abstract: Virtual Reality (VR) Interactions like in Ready Player One? Locomotion (LOC) and Virtual Object Interaction (VOI) are two key areas of concern, when designing and developing VR games and other VR applications. This paper describes a study of three interaction modes and their underlying VOI and LOC mechanics, using a range of consumer-oriented VR input setups, spanning from gamepad, over Spatially Tracked Hand Controllers, to Controllerless Hand Tracking and Omnidirectional Treadmill. All corresponding mechanics were implemented in the specifically developed, optimized and polished "real-world" game Gooze, to test them in a real-world scenario with corresponding challenges in gaming and Human Computer Interaction. A within-subjects experiment with 89 participants using qualitative and quantitative analysis methods was conducted. The interaction modes and their mechanics were evaluated based on the four User Experience aspects: Player Enjoyment, Support of Gameplay, Simulator Sickness and Presence, with the latter being subdivided into the four sub-parameters: General Presence, Spatial Presence, Involvement and Experienced Realism, according to the igroup Presence Questionnaire. The paper concludes with summarizing the individual advantages and disadvantages of the assessed interaction modes.

H. CURRICULUM VITAE

Name:	Daniel Peter Otto Wiedemann
Date of birth:	25^{th} of December 1985
Nationality:	German

Education

01/2014 – 09/2020	Research for the PhD dissertation at hand, directed by Dr. Magnus Moar and additionally supervised by Dr. Peter Passmore *Faculty of Arts and Creative Industries* at *Middlesex University*, *London*, *United Kingdom*
10/2012 – 10/2013	Master of Science in Creative Technology *"'LizzE – And the Light of Dreams' Creating a game, combining modern with common interaction methods"* *Faculty of Arts and Creative Industries* at *Middlesex University*, *London*, *United Kingdom*
03/2006 – 02/2009	Diploma in Communication Design *Akademie an der Einsteinstraße U5*, *Munich*, *Germany*
03/2008 – 07/2008	Basics in Advertising Copy Writing *Text-College München*, *Munich*, *Germany*
06/2005 – 08/2005	Courses in Principles of Graphic Design and Advanced Webdevelopment *Harvard University*, *Cambridge*, *MA*, *USA*
1996 – 2005	University-entrance diploma with advanced courses in Arts and Physics *Feodor-Lynen-Gymnasium*, *Planegg*, *Germany*
1992 – 1996	Elementary school *Grundschule*, *Gräfelfing*, *Germany*