

Towards Developing an Eye-tracker Based Virtual Reality Application for Supporting Vision Screening

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Abstract

Statistics from 2014 show that 35 to 75 percent of school age children suffer from some sort of vision problem. Of these children, around 25% have normal visual acuity, however, their problems relate to low performance of their vision system. This low performance can be due to, e.g., eye musculature, nerve problems, cognitive problems etc. Such deficiencies may get worse as the person gets older, and it is important that we strive to treat these issues while the person afflicted is still young. Standardized vision control is performed on children at the age of 4 or 5 in most European countries. This screening can miss functional vision problems. The identification of these requires additional expertise and resources. By providing better aids supporting vision screening, we can help to catch problems that standardized screenings do not prioritize. A previously developed laptop application (C&Look) managed to target certain aspects of the screening battery identifying oculomotor problems (OMDs), a usual functional vision problem. However, C&Look's functionalities are limited by the size of the screen and the lack of depth, two important issues influencing how our vision functions. Separation of vision problems and the lack of focus from the test person is another not addressed issue, as there is currently no way to distinguish between these.

This thesis addresses these issues by developing a Virtual Reality (VR) version of C&Look with the possibility of identifying the lack of focus before measuring functional vision problems. Evaluation with a vision expert indicates that VR technology provides great promise for further assisting the current vision screening battery, however, focus was deemed too correlated with functional vision fatigue for an attention test to be used for separating the issues. User experience evaluation from seven possible end-users shows that the Virtual Reality version of the screening application is considered usable compared to the original version. This process also helps to highlight the benefits and weaknesses of a transition from 2D to 3D. A simulated environment makes the process feel more like a real screening process which can increase participants' focus. A clear drawback is the limitation of head-mounted displays (HMDs) capability of measuring distances of the gaze, but also less confidence in results and worse performance. Creating a screening application is feasible in VR and can help cover more parts of the vision screening battery than a laptop application allows.

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Acronyms

2D two-dimensional. 12–14, 31, 33, 38, 40, 45, 91

3D three-dimensional. 12, 13, 19, 24–27, 33, 40, 45, 56, 57, 88, 91

CI Convergence Insufficiency. 11

DSR Design Science Research. 30, 33

HMD Head Mounted Display. 2, 12, 14, 15, 21, 22, 32, 36–41, 44, 49, 53, 69, 76, 77, 88–92

HVL Western Norway University of Applied Sciences. 11, 14

MVS Manual Vision Screening. 12

OMD Oculomotor Dysfunction. 11, 12, 19, 85, 91

SDK Software Development Kit. 22, 38, 44, 51, 53, 80, 87

SUS System Usability Scale. 34

UEQ User Experience Questionnaire. 28, 34

UI User Interface. 20, 26, 43, 54

UX user experience. 28, 29, 74, 87, 91

VR Virtual Reality. 2, 12–15, 18, 21, 23–25, 30–42, 47, 49, 50, 52–54, 57, 59–62, 64, 65, 68–70, 72, 73, 75–77, 79–81, 83, 84, 86–88, 90–92

XR Extended Reality. 44, 53, 87

Chapter 1

Introduction

Motivation and context for the thesis are presented in this chapter, which provides context to the following research questions and expected results.

1.1 Motivation

Reduced sight can limit a person's daily life, and is generally difficult to discover unless the person affected notices something is wrong themselves. Some eye-related diseases or visual disabilities may also progress slowly, where vision is gradually degrading without noticeable rapid change. Some such diseases or disabilities may be treatable using the correct vision therapy, or by assigning appropriate vision correction tools such as glasses or lenses. Convergence Insufficiency (CI) is an example of one such disability. CI is described as "a highly treatable binocular vision condition that affects near vision and eye muscle coordination. Convergence of the eyes occurs when two eyes need to focus on a close object, such as a book, computer, tablet, smartphone, etc" [38]. Convergence Insufficiency is an example of an Oculomotor Dysfunction (OMD), a grouping of vision impairments that can be treated using correct vision therapy if discovered at an early age. Problems like these are very common in children, and if not treated, the condition may worsen when the person gets older. This can lead to diseases such as amblyopia (lazy eye) or strabismus (eye turn).

To catch these vision impairments early it is common to perform vision screenings on children at an early age. These screenings are used to detect problems related to OMD in children, as well as problems such as near- or farsightedness and astigmatism. If a potential problem is found, a diagnosis is not given at the screening but rather a referral to an eye care specialist for proper treatment [24].

A previous study into training oculomotor problems in children using eye-tracking devices and serious games has been performed at the Western Norway University of Applied Sciences (HVL). This included a software named C&Look developed to record the user's eye movements when performing tasks on a computer screen based on software. Locating the users in front of a computer screen and letting them follow moving objects in a structural, predetermined way on

the screen or letting them read displayed texts, certain measurements can be done. The measurements are based on recording eye movements separately from the left and the right eyes, and knowing what the user should focus on on the screen. This data gives us important information about the major eye movements such as saccades, fixation, and pursuits. In this study, eye movements were recorded using the commercial grade Tobii 4C eye-tracker developed by Tobii, with a sampling rate of 90Hz [27]. Limited laptop screen sizes exclude certain elements of the Manual Vision Screening (MVS) battery, as well as a lack of ability to measure a patient's depth perception. MVS is screening done by professionals without computer aided tools measuring small eye movements.

Another area of interest for this study is attention span. Some of the most important tasks for detecting visual problems that exist in C&Look are tasks that involve reading. Subjects may perform worse on these tasks, not due to a vision impairment, but rather as a result of lacking interest or unknown learning disorders [53]. By being able to distinguish between people with such disorders we can avoid incorrectly attributing their low results to visual problems. In such cases, other tasks that don't include text or are more interactive might be better suited.

This thesis considers how we can extend C&Look to better support detection and rehabilitation of functional vision problems during a vision screening. By converting tasks from this software into three-dimensional (3D) space, we can measure eye movements in space through a Head Mounted Display (HMD) with integrated eye-tracking hardware. This presents a unique opportunity to compare results and possibilities of different environments and display methods. The inclusion of a tool for estimating focus of attention during screening is also analyzed as part of this project, with the goal of separate cases of eye musculature fatigue from those where poor results stem from a lack of focus.

1.2 Research Question

The 2D implementation of C&Look is well suited for the detection of pursuit movements, which is a good indicator when testing for OMD. However, a multitude of other tasks performed during screenings was either impossible or posed great difficulty to implement. Some of these tasks such as tests for stereo vision require a 3D space, and are better suited for Virtual Reality (VR) environments [18]. Attention span can also be an important measurement, as a lack of attention might affect the results of tasks independently of visual problems. This bringing motivation to examine possible measuring techniques of this in VR as a complement to C&Look. So in what way can VR help aid the detection and rehabilitation of functional vision problems when assisting the current vision screening battery?

By detecting vision disorders early to start treatment rapidly we can reduce the overall impact these problems will have long term. For this, it is essential to develop an objective vision screening. Studies show that visual disabilities such as myopia, or nearsightedness are associated with changes to visual functions [22]. Therefore it is important that we pay more attention to these areas.

This illuminates the thesis' main research questions:

- How can Virtual Reality technology be utilized to assist the current vision screening battery?
- How can we measure attention to verify that poor results from vision tests are correctly attributed to vision problems?

1.3 Expected Results

With the goal of answering the research question above, this thesis goes into how vision screenings are currently being performed, and in what ways VR technology can improve the quality of such screenings. Analyzing and comparing results and possibilities from using a laptop screening application with a mobile eye tracking device with experiments done in VR should give insight into the possibilities of VR, motivated by aiding vision screening.

The expected results of this master thesis are as follows:

- Contribute to demonstrating the added value of technologies, such as eye-tracking and VR complementing the screening battery the vision experts use today.
- Develop three-dimensional exercises in VR to gather relevant information on eye movements for a vision screening, based on the 2D exercises implemented in the C&Look software.
- Highlight how the inclusion of estimations for focus of attention can assist vision screening.
- Explore differences in the experience gained by utilizing different technologies in complementing manual vision screening.

1.4 Research Methodology

This study focuses on utilizing Virtual Reality technology to assist the current vision screening battery. This consists of developing a system for VR which includes exercises for recording eye movement data, as well as exploring other possibilities of VR for this purpose. An essential part of the study will be the exploration of prospects and limitations that the use of head-mounted displays brings. Such an approach will require analysis, explanation, argumentation, justification, and critical evaluation of the implementation on how it serves to aid the goal of this project.

Based on this background, the project utilizes the Design Science Research Paradigm. The artifact produced is an instantiation that demonstrates how the theory behind vision screening can be implemented on a system in Virtual Reality, and what advantages and disadvantages this brings. The evaluation methodology for this thesis is unique, combining different aspects of human-computer interaction evaluation techniques, with focus on usability, user experiences and presence. As a result, a detailed explanation of the evaluation method and its integration with artifacts is necessary. For a full explanation of the methodology, see chapter3.

1.5 Prior Work

The application developed for this project is based on two original implementations, the laptop version of C&Look and an attention test designed to be run in a browser. Understanding these original implementations is important for this thesis, with the design of the new application being based heavily on its compatibility with elements of C&Look.

The C&Look application was developed by Ruben Watanabe and Mads G. Eide as part of an MSc project at HVL [17]. The implementation aims to assist vision teachers during screening via a laptop application with a connected eye-tracking device. This is done by having participants perform predetermined tasks with their eyes, while an eye-tracker collects positional data of where they are currently looking. Once all tasks have been performed, users can review their results in the form of replays with visualization of where each eye was looking. The application also includes graphs depicting each eye's distance from the desired target. Additional research on implementing training exercises was made after the original MSc study [27], as well as large-scale testing of the application's performance when screening children [75]. A more detailed description of the original version of C&Look can be found in section 2.1.

To be able to produce estimations for the focus of attention concerning vision screening, an application for measuring attention was used. This is a preexisting implementation of the D2 Test of Attention designed to be run in a web browser. It is a two-dimensional implementation of the test and is well suited for testing attention together with the original vision screening application as it can run on the same machine. It was developed by Henrik Laxhuber, who was subsequently hired by HVL to further develop this solution to measure attention within the context of vision screening. This application was evaluated as part of this project, as the compatibility of measuring focus of attention as a part of vision screening is not well documented. Before proper evaluation on performing such a test in VR can be made, it must first be evaluated concerning the original C&Look implementation. More background information on the browser version and a description of the D2 Test's structure is found in section 2.2.

1.6 Related Work

To get a better understanding of how other researchers have approached VR solutions within the vision science domain, studying these approaches help guide study direction and implementation details. Enthusiasm for utilizing VR and gaze data has seen a huge growth in the last couple of years, as commercial grade HMDs with the possibility of eye-tracking have become more available [8]. This has led to recent academic research taking a greater interest in this technology for treating and identifying visual problems.

1.6.1 Utilizing VR and eye-tracking for rehabilitation of visual problems

As the application developed for this project aims to assist the current vision screening battery, it is important to have some insight into how VR has previously been utilized for rehabilitation and testing of vision. While a lot of these approaches do not take advantage of gaze data for measuring problems related to vision functions as C&Look does, they often make use of immersive VR technologies. This information helps to validate the usage of VR and its potential.

A study into amblyopia treatment using mixed reality focuses on the advantages of treating this disease using the Microsoft HoloLens mixed reality technology rather than earlier VR methods for therapy [46]. This approach maintains the high eye involvement and immersive experience that VR offers, in addition to adding the convenience of mobile solutions. Other factors such as reduced motion sickness, less possibility of eye strain syndromes, and increased comfort, elevate this study within the rehabilitation of visual problems. Some problems are apparent, however, regarding improvements on gamification aspects and lack of quality data due to a lack of gaze data collection. This study[46] presents a well-documented and researched solution to the specific task of amblyopia therapy for both children and adults.

VR has also been used to identify eye movements in combination with wearable electronic sensors [44]. To detect eye movements unobtrusively with high accuracy, this study focuses on the creation of skin-conformable sensors for detecting eye vergence while the user is wearing a VR headset. Eye vergence is defined as the movement of both eyes in opposite directions, used to get or hold single binocular vision on a point. This steps away from the built-in eye-tracking of HMDs, and rather distributes data collection of eye movement data to sensors. Such an approach still maintains the simulated virtual world which allows for a controlled and stable testing environment, while avoiding some of the negatives included in HMD based eye-tracking. With the assistance of a classification algorithm, eye vergence can be determined, leading to the possibility of detecting visual problems that relate to this movement. The study also includes two therapeutic programs which contain tasks for the user to complete while data is being collected. One of these programs is an implementation of the Brock String, a common vision therapy tool used to treat visual problems such as convergence insufficiency, amblyopia, and strabismus [72]. The other is the implementation of the eccentric circles, another regular tool in vision therapy, widely used for vergence therapy [3]. The combination of these systems leads to a portable solution for real-time classification of eye vergence, usable in an office setting. It does, however, lack testing of long-term therapeutic effects and usage in a home setting. A combination of electronic sensors for data collection, a VR headset to introduce therapeutic software, and a classification system to determine eye vergence, gives insight into how a combination of different technologies can produce satisfying results when it comes to vision therapy.

1.6.2 The usage of gaze data and its potential

For a vision expert to be able to successfully determine whether a patient has visual problems, C&Look uses gaze data to visualize where the test subject was looking during the performance of tasks. Contemporary research on the usage of eye-tracking technology help illuminates its potential.

In recent years, the utilization of machine learning systems combined with eye-tracking devices has grown more popular, and a lot of research on classification systems combined with eye-tracking data has been done. One such system was developed for event detection in eye movement data [78]. Event detection is the process of extracting events related to certain eye movements from raw eye-tracking data. The study focused on the detection of fixations, saccades, and post-saccadic oscillations within the raw data using a random forest classifier. Using machine learning techniques, the algorithm developed outperformed two other state-of-the-art hand-crafted event detection algorithms. This study illuminates the possibilities of the use of machine learning in the field of event detection.

Using machine learning in unison with eye-tracking data has also yielded promising results in other areas. These include detecting task demand and cognitive load [55], identifying gaze error patterns in eye-tracking datasets collected under different operating conditions [33], and a study combining these approaches with the Internet of Things technologies for evolving eye-tracking applications [34]. Many other studies handle this topic, and the combination of eye-tracking hardware and machine learning technologies is well documented to be a good fit.

The solutions mentioned above are only sufficient for the detection of a handful of visual problems, and only cover some of the aspects in which eye-tracking hardware and machine learning can be used together. Many of these approaches also suffer from poor performance when the data contains large amounts of noise. With eyesight being such an essential part of everyday life, early identification and treatment of related issues can improve a person's daily life and mitigate or even eliminate the possibility of more severe disabilities. By utilizing machine learning's good compatibility with eye-tracking data, we have the opportunity to achieve accurate and objective results from vision screenings. This could make the process both faster and more reliable. This however requires data of high quality and with low levels of noise. To ensure proper classification of results, the quality of data collection from different eye-tracking hardware needs to be examined.

Chapter 2

Background

This chapter presents some of the knowledge that the research is built upon. This theory is important to know to understand the following chapters. Background sections 2.1 and 2.2 are important for a fundamental understanding of the implementations the developed application takes inspiration from, while sections 2.3-2.8 are focusing to existing research necessary to understand results and evaluations.

2.1 C & Look

The C&Look Software was developed for a study into how eye-tracking technologies can complement manual vision screening for the detection of oculomotor dysfunction [18]. This software aimed to implement tasks performed during manual vision screenings while collecting objective data presented in an easily understandable way.

2.1.1 Application components

This implementation is comprised of three main components. A user and group registration part with a task set editor, eye-tracking calibration and the tasks themselves, and the results overview with replays for performed tasks and related graphs. When registering a new user, they must first be assigned to a group. If no relevant group exists, one should be created. This approach allows for vision teachers to separate sets of test subjects into groups, which is useful when testing a primary school class. Task sets to be used during testing can be constructed within the application, allowing a vision expert to quickly construct a set of tasks necessary for a given patient. The task editing is limited to three different tasks:

- A task where an object moves instantly from one point to another. This is designed to measure the quality of a patient's fixations.
- A task where an object moves smoothly between two points. This task measures smooth pursuit movements.

- A task where the user is instructed to read displayed text. Multiple experiments show a connection between visual function and reading ability [32], therefore being able to visualize where a patient is looking when reading can vision experts identify visual problems.

These tasks all contain several settings, including options such as speed, total duration, focus object sprite, and what text a reading task contains. Some options are unique to each task, and all possible settings are described in 5.1 as this aspect becomes relevant to the VR implementation.

Once a user and relevant task set have been registered, eye-tracking calibration may commence. The calibration method used is custom-made, involving five dots that should be focused on in a specified order. Once this base calibration step is complete, a calibration assessment is presented and if the results are not sufficient calibration should be done again. Once a satisfactory calibration assessment has been reached, the user moves on to perform all tasks in the selected task set. All tasks are performed in order, with no breaks in between. Gaze data is recorded as tasks are being executed.

When all tasks in the set have been completed, a list of results is presented to the user. Replays for each task are available within the result page, which visualizes the position of gaze points for each eye during testing. Graphs depicting eye movements in relation to the desired target are also available. Figure 2.1 shows an example of the result section of the application for a fixation task. The blue dot and graph represent the left eye, while the red dot and graph represent the right eye movements on the screen while following the object (the cat). Background colors range from green to red, where green shows that gaze point results in that section were close to the desired target and red represents poor fixation accuracy.

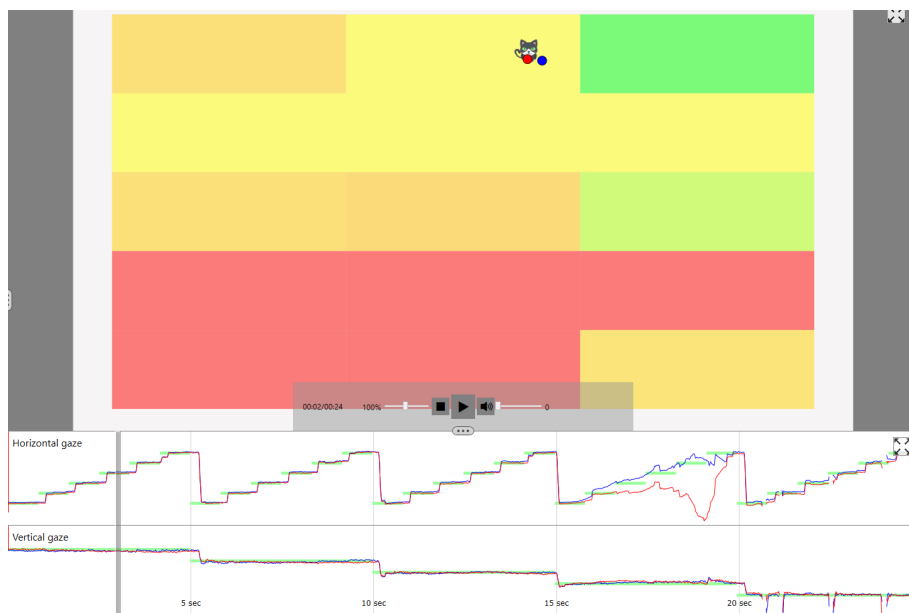


Figure 2.1: A screenshot of the result page related to a fixation task.

2.1.2 Current limitations of laptop based C&Look

At the present stage of eye-tracking technologies, a multitude of tasks performed during screenings was either impossible or posed great difficulty to implement. These include tests for visual acuity, eye dominance, accommodation, and color vision. However, tests for pursuit movements are a good indicator when testing for OMD and are very suitable with eye-tracking technologies. The gaze data collected during C&Look is also suitable for the convergence test to a certain extent since indicators of convergence insufficiency can be calculated via the distance between the gaze points of both eyes. Similarly, some of the problems detectable using the cover test can be seen if gaze points travel upwards, downwards, inwards, or outwards abnormally during the test. An important advantage of eye-tracking hardware in combination with vision screening comes from its compatibility with the reading test. Ability to record eye movements while the patient is reading provides information on how they follow text, an important part of the vision screening battery.

2.2 The D2 Test of Attention

Visual attention is required to select and filter the area of information and is needed to plan motor movement. Visual attention impairment appears to be the primary problem in children with dyslexia and it is most often accompanied by deficits in visual abilities such as visual perception, visual temporal processing, and the rapid engagement of attention [58].

The D2 Test is a well-documented test with verifiable metrics that can be used to measure a person's attention. Early digital implementations of the D2 test were constructed based on the final revised pen and paper version created in 1994 [41]. The browser version used as part of evaluation and inspiration for the 3D implementation during the project inherits its structure from a slightly more recent version of the test, described by Merten et al. (1997) [42]. This background section presents this version of the D2 Test's structure while also giving insight into the browser base application.

2.2.1 Test Structure

The structure of the test consists of rows of letters with associated lines, where each letter is either a d or a p and can have at most 4 lines. Rows are shown one at a time, and the number of lines is randomized for each letter. Figure 2.2 shows an example row of the D2 Test. A user's goal is to click each d with a



Figure 2.2: Sample Row of the D2 Test.

total of two lines. This is then repeated for each row, and over a total of 12

series. Each series consists of 14 rows with 9 letters, and a series ends when the current series timer hits 30 seconds or the user completes all associated rows. The test is designed to take approximately 6 minutes. From the number of correctly marked letters known as *D2* in different series, metrics for measuring attention can be calculated. These metrics are as follows:

- **TN**: This is the total number of letters seen while performing the test. This includes both D2 and non-D2 letters and changes based on how many rows were completed in total.
- **D2**: The total number of D2 letters seen.
- **E**: The total number of errors. This includes both marked non-D2 letters and D2 letters which were not marked.
- **TN-E**: TN-E represents the total number of correct letters, meaning both correctly marked D2 and non-D2 letters not marked.
- **E1**: The number of D2 letters not marked.
- **E2**: The number of non-D2 letters marked.
- **E%**: E/TN as a percentage representing the number of errors in the set of seen letters.
- **CP**: CP stands for concentration performance, a metric represented by the number of correctly marked D2 minus E2. A high CP value indicates a lot of D2 were marked while considering non-D2 letters, and a low CP value indicates that a user did not concentrate on marking correct letters.
- **FR**: FR stands for fluctuation rate. It is the minimum number of letters seen in a series, versus the maximum number of letters seen. This value indicates the fluctuation in attention experienced during the test concerning the speed of execution.
- **ED**: Error Density, which indicates the difference in the number of errors made during early series and late series.

2.2.2 The browser implementation of the D2 Test

The browser version of the D2 Test of Attention was developed for the Node.js runtime environment and written in JavaScript. The application consists of two components. A client web page that involves all logic for the test itself, and a server that runs on a host machine with access to the database. The client can be run on the server hosting machine or separate machines if desired, and multiple clients can connect to the hosted server at the same time. This allows for the application to be used on a large number of participants simultaneously, and since clients are web browser based they can run on devices such as tablets or phones with an Android operating system using the Android JS runtime environment.

The client allows for different languages, including both English and Norwegian. Additional language options allow for testing of participants from different backgrounds, however, no User Interface (UI) interaction for language selection is currently available and must be done through the command line during setup.

This is also the case for all other application setup steps, requiring the use of a terminal that can exclude interested parties with no computer science background. A ReadMe with detailed setup directions is available within the GitHub repository, so users with a particular interest in the application should be able to use the application regardless¹.

2.3 Previous research on Virtual Reality Aided Vision Therapy

Although VR has seen growing interest in multiple fields of research, as stated in 9, its application within the field of vision therapy remains limited. A bibliometric analysis of virtual reality aided vision therapy by Ali et al. [2] discovered that after filtering an original pool of 336 articles, by their relevance to VR and vision therapy, only 47 of those articles remain. Figure 2.3 shows the annual publication rate (on the left) and the most relevant research fields (on the right) for this area. This figure comes directly from the article itself, and its usage in this thesis has been approved by the author.

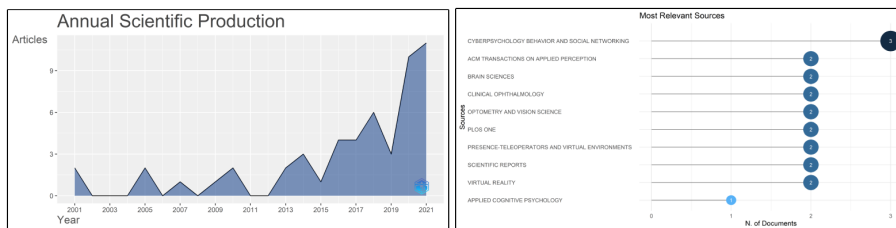


Figure 2.3: Annual publications rate of two decades (left), and the top 10 most relevant sources of documents (right).

Although VR has seen increased recent attention within research, publications related to vision therapy and screening are still few when compared to related domains.

2.4 Varjo and the VR2-Pro Head Mounted Display

VR2-Pro was the selected Head Mounted Display to be utilized for this research, and some background on the headset and its provider is relevant to this study. Varjo is a company that develops Virtual Reality headsets and accompanying software, focusing on its use in research with high-quality data collection and display resolution. Lockheed Martin, Volvo, and other large-scale companies utilize Varjo headsets for their high fidelity [67]. Varjo also specializes in integrated eye-tracking technology, with their newest models featuring the world's

¹Github link to the D2 Test application: <https://github.com/he-1a/d2test-candlook>. It is worth mentioning that the repository for this application is private, and as the author of the thesis is not the developer they cannot grant readers access to this repository.

highest-speed HMD integrated eye-tracking with a sampling rate of 200Hz [65]. The older model VR2-Pro was selected as the HMD for this research, as newer headsets come at a considerable cost due to their leading-edge technology. A sampling rate of 100Hz is available here, which is good compared to commercial-grade mobile eye trackers which typically reach a sampling rate of 90Hz. The resolution available in this headset is 1440x1600 pixels per eye, which is equivalent to or higher than that of other well-known HMDs such as the HTC VIVE Pro and Oculus Rift.



Figure 2.4: The Varjo VR2-Pro Head Mounted Display used for this study.

2.4.1 Varjo Base

Software for running and managing the headset is necessary for Varjo specific HMDs. This software is called Varjo Base and is used to calibrate controllers through SteamVR, as well as enable specific settings and runtime environments for the VR2. Calibration of eye-tracking can be done through this application, or through calling their API via engine-specific Software Development Kit (SDK)s. A live feed of the headset view can be seen in Figure 2.5, a screenshot of Varjo Base while the HMD is connected, and a camera feed of the user's eyes can also be viewed within the software. Varjo provides SDKs for Unity, Unreal Engine 4 and 5, and a native Varjo SDK.

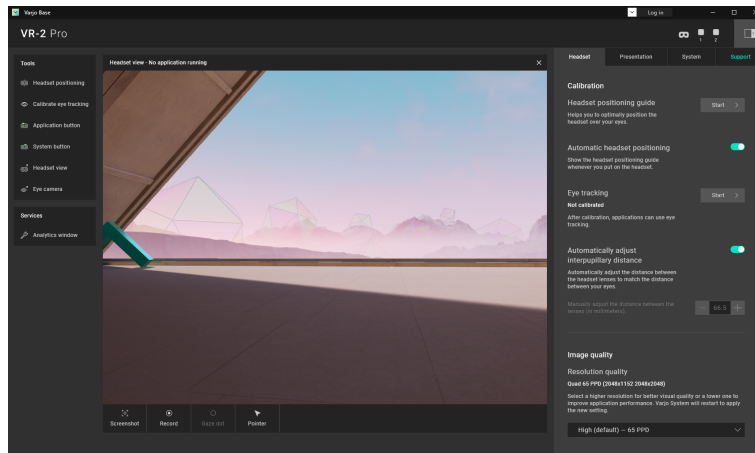


Figure 2.5: A screenshot of the Varjo Base software while the VR-2 is connected.

2.5 Eye-tracking

Eye movements can tell us a lot about a person, and gaze is a stable indicator of visual attention [36]. For this reason, eye-tracking has become a popular field of research in many different domains. This includes medical application [23] with focus on both mental and physical health, marketing to optimize advertisement strategies [74], human-computer interaction for interface evaluation [47], along with other areas [15]. This documentation on wide interest in eye-tracking shows promise in the technology, and with vision being such an essential part of how we perceive our surroundings it is apparent that gaze data could lead to many discoveries in different fields.

As a result of the proven usefulness of eye data, it is important that the way of collecting this data is well understood and that different eye-tracking hardware is described properly. These next two sections go into more detail on the eye-tracker used for the original C&Look application, and the possibilities of eye-tracking in VR.

2.5.1 Tobii 4C and limitations of mobile eye-trackers

The current C&Look application utilizes the commercial grade Tobii 4C eye-tracker, which has a sampling rate of 90Hz. This is a mobile eye-tracker that is attached to the bottom of a laptop computer's display. Comparisons between expensive and more cost-effective eye-trackers show that oculomotor problems can be identified using relatively cheap hardware, with noticeable differences being the amount of data loss, frequency, and precision [20]. This validates the use of an inexpensive mobile eye-tracker such as the Tobii 4C, making it suitable for vision experts to use during screening. Mobile eye trackers require the user to sit at a specific distance from the screen. This introduces the limiting factor that users need to sit relatively still to gather gaze data of high enough quality to be used for accurate measurements. This can often lead to data loss when

the user moves too far away or too close, a problem which is difficult to catch while tests are being performed [16].

2.5.2 HMD integrated eye-tracking

VR technologies offer a unique approach for the collection of eye-tracking data, using infrared cameras filming the eyes and transmitting the visible spectrum [39]. As VR is becoming more accessible to the average consumer, the hardware is turning into a reliable research tool. This introduces new techniques for well-controlled experiments within immersive natural environments for subjects. One of the reasons VR is well suited for eye-tracking lies in the definition of areas of interest. Since the 3D space contains only artificially created objects, certain points of interest can be established. The time when these points are looked at can be determined based on the gaze vector from the eye-tracker and can help control data collection [9]. The limitation of correct user positioning seen in mobile eye-trackers is another advantage of integrated eye-tracking, as the cameras recording eye movements are a part of the headset which follows the user around, as we pointed out in an earlier publication [10]. A lot of recent VR hardware comes with eye-tracking support, which is a promising sign of growing interest in the combination of eye movement data and Virtual Reality.

2.6 The Vision Screening Battery

There exist multiple screening batteries that vision experts use today, containing a plethora of tests designed to evaluate different aspects of a person's vision. The original C&Look application targets a screening battery proposed by Udén [61] and further developed by Wilhelmsen [76] and implemented by Eide and Watanabe [17], mainly targeting suitable implementations of the pursuit movement test and reading test.

This thesis contains attempts at covering the stereo acuity test and hand-eye coordination tests from the same screening battery, by extending the current C&Look application from the laptops to VR and some new functionalities described below.

2.6.1 Measuring hand-eye coordination

Popular methods of measuring and training hand-eye coordination include techniques such as cup stacking exercises and drawing tasks. A cup stacking exercise includes forming a pyramid of cups by balancing them on top of each other within a specified time limit. It is a validated form of training for hand-eye coordination and reaction time [62]. Measurements consist of the total time used before all cups are stacked, which makes it easy to notice improvement as completion time lowers. Drawing tasks take many forms, such as drawing from memory, writing, or completing a predetermined description. The impact of experience with pen and paper improving hand-eye coordination is well documented, while also being suitable for measurements when combined with eye-tracking technologies [45]. When selecting what parts of the vision screening battery to attempt implementation for in VR, hand-eye coordination was

selected as suitable for 3D with limited research on existing implementations [35].

2.6.2 Stereo Acuity Testing

Visual perception of depth is identified through a person's stereo acuity level. This is measured in arc seconds, with 1 second of arc being 1/3600 of a degree. Normal stereo acuity is defined by a person being able to notice 20 seconds of arc or better, while borderline is 25 to 40 and reduced stereopsis is 50 to 400 [13]. Popular measuring techniques for stereo acuity levels include contour tests such as the circle test and Titmus Fly test². Contour tests are exercises where an object has a set depth of arc seconds in angle relational to the background, and the subject is asked if they can visually perceive that the object is sticking out.

The circle test involves having the test subject look at four circles on a piece of paper. One circle protrudes slightly from the background, and the participant is asked to point out which one. If the participant is correct, the next four circles show a circle with less visible depth. Once a participant selects the wrong circle, visible depth is increased. Once enough iterations of this process have been completed and it is clear that the patient will not get the next one right outside of luck, stereo acuity level can be calculated by the angle of depth in the last correct selection.

Another contour test relevant to a screening of stereo acuity is the Titmus Fly test, which involves a highly detailed fly sticking out of a background with a maximum angle of 400 seconds of arc. The patient is asked to try and pick up the wings of the fly without touching the surface behind it. If the patient is unsuccessful, by either not reaching the fly or hitting the surface, their stereo acuity level is below 400 indicating reduced stereopsis. This technique is commonly used for screening and is not suitable for measuring the levels of stereo acuity.

2.7 Unity Game Engine

Unity was selected as the game engine for developing the VR version of C&Look. This section introduces concepts and terminology used during the implementation description, providing necessary background information to understand how the application works as a whole.

²No royalty-free images representing stereo acuity tests could be found for this thesis. For a visual representation, a YouTube video on the Titmus Stereoacuity Test uploaded on 2017-09-14 by user Taha Chucky can be found here: https://www.youtube.com/watch?v=AjUXLFz3VjA&t=1s&ab_channel=TahaChucky



Figure 2.6: The Unity Editor displaying a scene from the application.

2.7.1 The Unity Editor and Scenes

The most important tool that Unity provides for game development is the graphical user interface, known as the Unity Editor [63]. Figure 2.6 shows the editor while working on a selected scene. A scene in Unity can be described as an environment or *level* present in the application. Games can have multiple scenes, and the user can be transitioned between them when necessary. The center of the editor displays the scene view, giving a visual representation and allowing for repositioning of elements in the scene. The list on the left side is known as the Scene Hierarchy. All GameObjects present in a Scene are listed here, and the right-hand side shows the selected object's properties and attached Components.

2.7.2 Game-Objects and Components

GameObjects and Components are key elements of Unity's architecture, with all objects in any given scene being GameObjects, the base class which all other entities inherit from. These objects contain Components, which are their functional pieces. An example of this can be seen in Figure 2.6, where the selected GameObject is Controller with the attached components: Transform, Practice, and DatabaseUtil.

Transform is a base component for all GameObjects, containing information on their positioning and scale. The last two components are custom C# scripts, Practice containing the class which handles events on startup, during each frame, and on-scene exit. Database Util contains helper methods for database transactions. Scene entities can also inherit other types of components, such as 3D models, textures, and UI elements. Each GameObject contains an instance of the classes related to its components, and any of these can be attached to a different GameObject as a new component. The properties seen under Practice are the class' public attributes and can receive input from the editor, such as other GameObjects. The separation of different functionality into unique components helps to enforce the design principle of low coupling, as component

structures can easily be reused later.

To further emphasize this approach, Unity allows for a combination of `GameObject`s with defined components to be saved as *Prefabs*. The prefab structure can then be reused for other parts of the application and is a common approach seen when downloading assets from the Unity Asset Store. This makes using features from other developers easy, as little to no understanding of implementation details is needed. All blue elements in the scene hierarchy of Figure 2.6 are examples of prefabs. The house model is a collection of different 3D models within `GameObject` entities as children of the prefab.

2.7.3 Event Functions, Order of Execution, and Coroutines

All Unity scripts derive from the base class `MonoBehaviour`, allowing for core Unity features such as event functions. Event functions are called in a predetermined order during a scene's life cycle. Specifying when code should be executed during execution is done by putting it in the correct event function. Many different event functions are available from `MonoBehaviour`³; however, only the ones essential for the developed application are described here.

The `Start()` event function should contain all code to be run on the first frame of scene execution. This is not to be confused with the `Awake()` method, which is the very first element of the pipeline and is called as soon as its related `GameObject` is instantiated. The update is executed once every frame and should therefore contain code related to active scene updates. This includes elements such as object movement and data collection for this project's developed application. The final event function of importance for this project is the `OnDestroy()` function.

The `Start()` event function should contain all code to be run on the first frame of scene execution. This is not to be confused with the `Awake()` method, which is the very first element of the pipeline and is called as soon as its related `GameObject` is instantiated. The `Update()` is executed once every frame and should therefore contain code related to active scene updates. This includes elements such as object movement and data collection for this project's developed application. The final event function of importance for this project is the `OnDestroy()` function.

`OnDestroy()` is called once the related `GameObject` is destroyed, most commonly due to changing scenes. All `GameObjects` in a scene are disposed of when it no longer becomes the active scene.

Another element used frequently in the developed application is the Unity Coroutine feature. Coroutines are methods that do not finish their execution until they have returned their specified type or value, allowing certain tasks to be spread over the course of multiple frames. Regular methods do not stop execution until they have run to their completion, which in Unity must be done in a single frame. Coroutines provide a solution for when a sequence of events should happen over time. This is relevant when needing to wait for responses

³Unity documentation on events functions and their order of execution: <https://docs.unity3d.com/Manual/ExecutionOrder.html>

during database transactions, or when needing to wait a certain amount of time before enabling features.

2.8 A Benchmark for the User Experience Questionnaire

When performing user experience evaluation, questionnaires present an effective way to collect data used to produce a quantitative measure of user experience (UX). This measure offers a way to compare two applications' UX, providing valid data on which is better or worse in that regard [51]. This comparison of products is important to this thesis' evaluation, including deciding on a type of questionnaire and analysis approach. Analysis technique and a benchmark for the User Experience Questionnaire (UEQ) were used together, as proposed by Schrepp, Thomaschewski, and Hinderks [52]. An advantage of these techniques is a fast and direct measure of user experience, with the questionnaire designed to be filled out quickly after the exposure. Equally, to continue with filling in questions inspired by the "presence questionnaire," as suggested by Heldal for evaluating user experiences in immersive virtual environments[25] and for comparing immersive VR with desktop VR systems[26]. This helps in making sure the participant fills out questions intuitively and allows checking the quality by comparing quantitative data with qualitative data.

2.8.1 Questionnaire structure

Each question consists of two statements of opposite meanings. Seven options are available between these statements, resulting in a score from 1 to 7. These answers result in a score ranging from -3(closest to the negative term) to +3(closest to the positive term). Figure 2.7 shows an example of three lines from the UEQ, Positioning of the positive and negative terms is randomized, and a total of 26 pairs are predefined. These pairs are grouped into six different categories:

- Attractiveness: Overall impression of the product. Is it attractive, enjoyable, and pleasing to the user? (6 pairs)
- Perspicuity: Is it easy to understand and learn the product? Are usage and design clear to the user? (4 pairs)
- Efficiency: Are tasks presented easy to perform? Is unnecessary effort required? Is the product fast and interactions responsive? (4 pairs)
- Dependability: Is system behavior predictable? Does the user feel safe and in control? (4 pairs)
- Stimulation: Is the product fun, exciting, and motivating to use? (4 pairs)
- Novelty: Is the user's attention captured by the product? Is it creative and innovative? (4 pairs)

Which category each item belongs to is not displayed to the test subject when filling out the questionnaire, and the ordering of pairs is randomized. These categories are necessary as scales for the analysis of results and give insight into different aspects of the product.

6. Please assess your overall experience of the product by ticking one circle per line:

	1	2	3	4	5	6	7		
annoying								Enjoyable	1
not understandable								Understandable	2
creative								Dull	3

Figure 2.7: Example from the user experience questionnaire.

2.8.2 Feedback Analysis

By calculating the mean of all participant's answers within a category (ranging from -3 to +3), we get a resulting measure of each scale. These scales are then classified as excellent, good, above average, below average, or bad. This method of analyzing UX scores provides a stable measurement for the product's possible success with users in practice. Which value corresponds to each classification is shown in table 2.1. As the benchmark strives to provide a comparison between

	Att.	Eff.	Per.	Dep.	Sti.	Nov.
Excellent	≥ 1.75	≥ 1.78	≥ 1.9	≥ 1.68	≥ 1.55	≥ 1.4
Good	≥ 1.52	≥ 1.47	≥ 1.56	≥ 1.48	≥ 1.31	≥ 1.05
	< 1.75	< 1.78	< 1.9	< 1.65	< 1.55	< 1.4
Above average	≥ 1.17	≥ 0.98	≥ 1.08	≥ 1.14	≥ 0.99	≥ 0.71
	< 1.52	< 1.47	< 1.56	< 1.48	< 1.31	< 1.05
Below Average	≥ 0.7	≥ 0.54	≥ 0.64	≥ 0.78	≥ 0.5	≥ 0.3
	< 1.17	< 0.98	< 1.08	< 1.14	< 0.99	< 0.71
Bad	< 0.7	< 0.54	< 0.64	< 0.78	< 0.5	< 0.3

Table 2.1: Table of Intervals for UEQ Scales as described by Schrepp, Thomaschewski, and Hinderks.

an evaluated product and those available on the market, each classification has an attached description. These descriptions give an impression of which percentile the product lands in, compared to those used for the construction of the benchmark.

- Excellent: The product's score is within the top 10% of results.
- Good: 10% of evaluated products in the benchmark are classified as better, 75% of these results are worse.
- Above average: The product lands between the top 25% of results in the benchmark, and above 50%.
- Below average: 50% of the benchmark was evaluated as better, while 25% was evaluated as worse.
- Bad: The result for the evaluated product lands among the bottom 25% of results.

Chapter 3

Methodology

A relevant research methodology must be selected to properly answer the research questions presented in section 1.2. As mentioned in section 1.4, this thesis utilizes the Design Science Research (DSR) paradigm. This chapter contains information on DSR and why it was chosen as the relevant methodology, as well as presenting an overview of the research steps undertaken for this study. The evaluation method is also of importance here. This research utilizes a combination of evaluation techniques for human-computer interaction, and a thorough explanation of this new evaluation method must be described.

3.1 The Application of the Design Science Research Paradigm

DSR focuses on the aspect of problem-solving to complement an existing knowledge base. This is accomplished through the creation of innovative artifacts, designed to solve real-world problems [6]. This study would ideally result in a stable VR implementation of a vision screening system, which would require an iterative development methodology to ensure its compatibility with real-life screening. When attempting to answer RQ2 (see section 1.2), the feasibility of separating visual issues with focus-related issues through an artifact would have to be analyzed before committing to a specific implementation. These requirements lead to a realization of the problem's compatibility with Design Science Research. Figure 3.1 shows the framework for DSR.

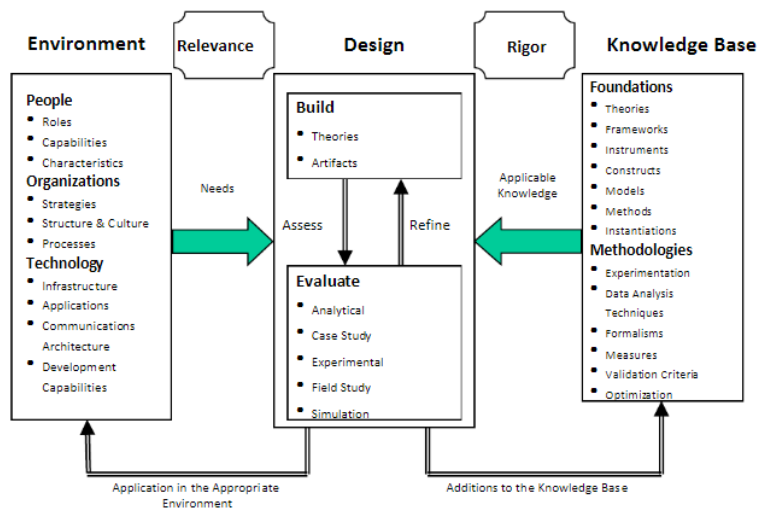


Figure 3.1: The Design Science Research Framework by Hevner et al. [29].

The relevant environments for this research are vision experts that perform regular vision screenings, as well as the Laptop version of C&Look with a need to extend its coverage of the existing screening battery. Our design includes two artifacts, the VR screening application, and an application for including estimations for the focus of attention. In accordance to design science research, these artifacts must be thoroughly evaluated, with results being used to refine their design and further inform research on connecting requirements for design with concrete measurements from eye movements. Evaluation methodology for the different artifacts is introduced in 3.3. The knowledge base for this study includes previous work on Virtual Reality Aided Vision Therapy, described in section 2.3. Results of previous validation and limitations of C&Look on laptop and the D2 Test of Attention are also components of the relevant knowledge base(see section 2.1 and 2.2).

3.2 Overview of study steps and their relevance

This study includes the following steps. Justification for their requirement and related chapters/sections are also described here. Mentions of the current screening application in this chapter and beyond refer to the two-dimensional C&Look application presented in Section 2.1.

1. Investigating how the current vision screening application can be made better by extending the application. The focus is on:
 - (a) Including estimations for the focus of attention for screening. This is done by evaluating an existing application designed to measure attention, based on the D2 Test of Attention.
 - (b) Investigating current limitations and possibilities to define a more general application. The current screening application is limited by

its inability to represent three-dimensional space, which eliminates the possibility of measuring stereo vision and hand-eye coordination. To define a more general application, experimental implementations of tests designed for stereo vision and hand-eye coordination are developed for VR.

2. Examining the advantages of VR for vision screening from current literature.
3. Investigating how the current application can be transferred to a VR environment by creating a VR prototype
 - (a) Examining the focus of attention and how this can work (and be measured) in VR. For this purpose, an implementation of the D2 Test of Attention is developed for VR as part of the VR version of C&Look.
 - (b) Creating and implementing exercises in virtual reality based on exercises from the C&Look software. This is done by developing a new application where tasks from the original screening application are presented in three dimensions using an HMD with integrated eye-tracking.
 - (c) Creating and evaluating possibilities of new exercises that were not possible to implement in the two-dimensional version. For this step, new tasks are developed based on the limitations of the current screening application. This includes a test for stereo vision and attempts at measuring hand-eye coordination using hand-tracking technologies.
 - (d) An iterative development methodology. The product is revised according to how its results benefit the solution of the thesis' problem statement and what is possible within the limited time frame. This includes two unique tests, the first on a vision expert and the second on possible end users. Changes are made to the application based on results from the first test.
 - (e) Comparison between the two-dimensional and three-dimensional tools that assist vision screening. Through testing both the current vision screening application and the VR vision screening application on end users, a comparison between two-dimensional and three-dimensional tools is highlighted. Evaluation of the application with a vision expert that has experience in the original screening application also highlights a comparison between two-dimensional and three-dimensional tools for vision screening purposes.

For point 1a, evaluating the inclusion of estimations for the focus of attention is accomplished through testing on a vision expert, to better realize its potential in the domain. More information on the evaluation methodology can be found in section 3.3.1.

1b requires the implementation of defined methods for measuring stereo acuity and hand-eye coordination. Before these aspects can be evaluated, the feasibility of their implementation must first be assessed. Chapter 5.1.5 details their

implementation attempts, which is necessary to illustrate feasibility. This point is further emphasized in 3c, however, the possibility of evaluation hinges on implementation being successful within the limited time frame of the project.

Examination of relevant literature, stated in point 2, is crucial for a better understanding of the current knowledge base. Following Design Science Research, an artifact's addition to the knowledge base is essential to the rigor of its design. Relevant literature on implementation, evaluation, and results is referenced throughout the thesis to inform decisions and validate results.

Step 3 includes the creation of a VR prototype, and a description of design and implementation is necessary to understand evaluation techniques and the context of results from this thesis. Point 3a, 3b, and 3c are all described in Chapter 5. As stated in 3e, an iterative development methodology is utilized in accordance with the DSR framework, and the necessary changes are also described in this chapter. As a lot of different technologies and techniques are used for the artifact, argumentation for why these technologies were chosen is necessary. Chapter 4 aims to justify these choices.

3.3 Evaluation Methodology

When evaluating artifacts, a proper evaluation methodology has to be used. Important aspects to evaluate for the VR C&Look artifact are the added sense of presence and depth that Virtual Reality can bring. This has to be tightly connected to the laptop version, as a comparison of these two applications highlights the differences of 2D and 3D for vision screening [25]. To target the second research question, expert opinions on the integration of measurement for the focus of attention with screening must be gathered.

Ilona Heldal defined the battery for evaluating the project results by incorporating existing evaluation methods for user's presence and user experiences and considering the main benefits and limitations of new technologies for extending C&Look for better screening. The battery focuses on combining evaluations with three different stakeholder groups: 1) the end-users, 2) developers responsible for technology development, and 3) key actors enabling technology use (vision experts, for this work) based on semi-structured interviews and questionnaires (see Appendix D). It investigates extensions of the current screening application and a comparative analysis of C&Look in VR and on a laptop, as described in Chapter 6.

The following sections serve as an introduction to the evaluation methodology for each test. The essential testing steps are described here briefly, as well as the purpose of these tests and their methodology. Since a new combination of evaluation methodologies was devised for this project, the integration of artifacts is thoroughly described in Chapter 6. Presentation and analysis of the data collected from this new evaluation method are found in Chapter 7. Chapter 8 provides a further discussion on the collected data with relevant literature and limitations of the project.

3.3.1 Test 1: Testing C&Look in VR and a 2D implementation of the D2 Test on a Vision Expert

The idea for the first evaluation test was initially to utilize the SUS questionnaire. Results from these questionnaires can be calculated to produce a SUS score, a reliable measure of system satisfaction [50]. As the project went on, the limitation of not being able to test the applications on more than one vision expert became apparent, and collecting multiple participants with specialized knowledge is difficult. Evaluation techniques using only one participant are scarce, and a custom semi-structured interview was designed as an alternate solution for evaluating extensions of the original screening application. This provides qualitative results, with the possibility of collecting detailed statements on feasibility and future directions. The set of steps for testing are as follows:

- Have the vision expert perform the D2 Test of Attention in the application.
- Ask the vision expert open-ended questions about the D2 test application.
- A short demonstration of how to use the VR equipment for the vision expert.
- Have the vision expert perform some tasks within the C&Look VR application and test out other available functionality.
- Ask the vision expert open-ended questions about C&Look in VR.

The purpose of this test was to evaluate the benefits and weaknesses of the D2 test in the context of vision screening, as well as the benefits and weaknesses of screening using C&Look in VR. Through open-ended answers from a vision expert, we get insight into the validity of extending the original vision screening application with an attention test. We also get input on possibilities and limitations of screening in VR from a domain expert. By including some questions related to usability and user experience, we also acquire feedback necessary for the iterative development strategy. Questions for both semi-structured interviews can be found in Appendix C. For a full overview of the test and how artifacts were integrated, see section 6.1.

3.3.2 Test 2: Comparing the user experience of C&Look in VR and on a laptop

The second test involved testing both the current screening application and the VR application on possible end users. For this evaluation test, 7 participants were available. This provides the option of collecting data to calculate a SUS score. However, to answer the research questions posed by this thesis, user experience related to the sense of presence and depth is more relevant than metrics for how they can accomplish specific goals. For this purpose, a benchmark analysis for the User Experience Questionnaire (UEQ) was utilized (see section 2.8). Although this method is well suited for the comparison of products, it does not produce necessary results related to the advantages of VR for vision screening and for evaluating the added value of immersiveness for higher user experiences. Custom questionnaires related to each application's similarity with regular screening procedures were used to measure this aspect, as well as semi-structured interviews for each participant. A full description of the evaluation

methodology and how the artifacts were incorporated can be found in section 6.2, and the results of the test are presented in section 7.2. The testing steps are as follows:

- Briefly explain the purpose of the applications and the study to the participant.
- Have the subject fill out a consent form.
- The subject fills out a form regarding their background in technology, eye-tracking, and vision screening.
- Have the subject perform a set of predefined actions in either the current vision screening application or the VR vision screening application. These predefined actions involve performing three tasks designed for screening vision. Which application they should be experiencing in this step was decided at random before testing started using a random number generator.
- The subject fills out a questionnaire regarding the presence and performance of the experienced application.
- Have the subject perform a set of predefined actions in the application they have not yet experienced. The tasks they perform in this step are identical to those they performed in the earlier application.
- The subject fills out a questionnaire regarding the presence and performance of the experienced, also the randomly assigned, application.
- The subject fills out a questionnaire comparing the presence and performance of both applications.
- The subject is interviewed about both applications, focusing on comparisons of their usability and the subject's experience.

This test was performed to evaluate the current state of the VR application compared to the current screening application when used on possible end users. Feedback from this test gives insight into how the VR application would work on the target demographic in practice, and what could be done to improve the user experience of the applications in the future. By measuring the VR application up against the current screening application, we can understand what needs to be done for the VR version to be used in practice. It also highlights the advantages and disadvantages of converting the screening application to VR. Blank versions of the forms used for the testing battery can be found in Appendix D.

Chapter 4

Technology Stack

This chapter presents the technologies chosen for the study. Argumentation for the used technologies are described here, as well as techniques used during development. Some of the technologies presented in this chapter were not used for the final product but tested along the way to measure the feasibility of implementing certain features. For an overview of implementation details for the finished product, see chapter 5.

As this project utilizes multiple technologies during different stages of development, technologies are presented in sections related to their origin and purpose. For example, hand-tracking was tested during development and is a built-in feature of the Varjo VR-2 Pro Head Mounted Display. It is therefore presented in the HMD section. This chapter argues why each chosen technology was used over other possible options. For more background information on a given topic, see chapter 2.

4.1 Hardware

4.1.1 Varjo VR-2 Pro HMD

Since the VR version of C&Look aims to implement the same tasks as the laptop screening application, an important factor when selecting an HMD for development was its eye-tracking capabilities. Other HMDs such as the Vive Focus 3¹ and HTC Vive Pro 2² support eye-tracking, but require an add-on device for this purpose. The Varjo VR-2 Pro also features measuring eye-tracking data from each eye separately, as well as being able to track the user's head position when wearing the HMD. These features lead to the Varjo VR-2 Pro being selected as the primary HMD for this study³. For more background information on Varjo and the headset, see section 2.4.

¹Vive Focus 3 Specs: <https://www.vive.com/us/product/vive-focus3/specs/>

²HTC Vive Pro 2 Specs: <https://www.vive.com/us/product/vive-pro2/specs/>

³Varjo VR-2 Pro Specs: <https://imotions.com/hardware/varjo-vr-2/>

4.1.2 Leap Motion Hand-Tracking

An important aspect of this study was to examine the feasibility of implementing tests for parts of the vision screening battery that a two-dimensional version could not measure results for. Hand-eye coordination is one such part of the vision screening battery and can be measured using hand-tracking technology. For this study, Leap Motion Hand-Tracking was utilized, as the Varjo VR-2 Pro HMD has external-facing infrared cameras developed by Leap Motion integrated into the headset.

4.1.3 Vive Controllers

To interact with a VR application, a set of VR controllers are needed. These controllers must be compatible with the used HMD, and Varjo works with any SteamVR-compatible controller. Varjo's referenced controller for setup is the HTC VIVE Controller⁴. To ensure compatibility between HMD and controllers, HTC VIVE Controllers were selected for this study.

4.1.4 Vive Focus 3

During the development of the VR C&Look application, multiple issues pairing HTC Vive Controllers with the VR-2 Pro headset occurred. While waiting for updates from Varjo, the Vive Focus 3 HMD was utilized to prototype interactions. The Focus 3 does not support eye-tracking, however, it is a mobile headset that does not need a direct connection to a computer. This provides more freedom for the user, and a separate VR version of the D2 Test of Attention was developed for Focus 3, as eye-tracking is not needed in this application.

4.2 Software

4.2.1 Unity Game Engine

When starting development on a game, one question must be answered before any development can begin; which game engine should be used during development? Building a game engine from the ground up is time-consuming work, and considering the limited time frame of this study, such an undertaking would not be feasible. The two most popular game engines today are Unity and Unreal Engine. They have also been identified as the two most powerful game engines which serve a wide range of user profiles and needs [7]. As the original two-dimensional vision screening application was developed using the Unity game engine, this was chosen as the game engine for the VR version. Additionally, the same version of Unity was used, 2020.3.9f1, allowing the applications to easily be merged if requested in the future. For more background and an introduction to the Unity architecture, see section 2.7

⁴Varjo setup guide with HTC Vive Controllers as the example: <https://varjo.com/user-center/get-started/varjo-headsets/setting-up-tracking/setting-up-tracking-old/>

4.2.2 Varjo Unity SDK

To be able to utilize the different tools that the Varjo HMD provides, Software Development Kits (SDKs) for different environments are available on the Varjo developer page⁵. For this project, the Varjo Unity SDK was used for purposes such as retrieving and recording eye-tracking data and getting the relative head position at runtime.

4.2.3 SteamVR Plugin and Vive Input Utility

Some plugins necessary for certain aspects of VR development are present in the application. These include the Vive Input Utility Plugin, which allows for user input through the Vive Controllers. This plugin comes with multiple components and prefabs which make interaction through controllers easy to implement.

The other plugin used by the application is the Unity SteamVR plugin. This plugin offers complex interactions with objects and some high-quality assets. For this project's application, the plugin is used to enable an overlay keyboard when interacting with text input fields.

4.2.4 Leap Motion Unity SDK

As mentioned in section 4.1.2, Leap Motion Hand-Tracking is made use of in the application for exploring the possibilities of VR for vision screening. To make use of this technology in the application, the Leap Motion Unity SDK is integrated. The official Varjo LeapMotion Unity package does not work on recent versions of Unity, so instead, version 4.8.0 of the Unity compatible SDK from LeapMotion is imported into the application. This version was the latest available release at the start of development.

4.2.5 Data Storage

When creating a larger application, an important aspect that needs to be decided on early in development is how necessary data should be stored. For this study's application, two main groups of data need to be saved. The groups are user information and gaze data. This section provides an overview of the different tools used to store data gathered at runtime, and the project code itself.

4.2.5.1 PostgreSQL

PostgreSQL is a widely used object-relational database system that has been in active development for over 30 years [48]. The original 2D vision screening application utilized this database system for storing results and users, so it was natural for the VR application to save its results to that same database. For more details on the database, see section 5.1.6.

⁵Varjo Developer Page: <https://developer.varjo.com/>

4.2.5.2 Entity Framework Core

The structure of the received gaze data when data collection is actively happening in the application is complex, and storing that data in the database from the application needs to be handled efficiently. By using an object-relational mapper, objects created from collected gaze data can be manipulated and stored in the relational database without having to manually construct specific SQL queries. Entity Framework Core supplies object-relational mapping tools and helped save development time when storing objects of the complex gaze data structure in the database. For more information on the use of Entity Framework Core in the application, see section 5.1.6.1

4.2.5.3 WAMP and Unity Web Requests

Local server hosting became necessary during the development of the D2 Test in VR, as the Focus 3 does not directly connect to a computer. To run the application it must first be built, then loaded into the headset and run from there. The database is hosted locally on the development machine, meaning there was no way to fetch or commit data without communicating over the internet. WAMP⁶ was chosen as the virtual server hosting environment, allowing for swift implementation where only PHP scrips for database queries were needed. This allowed the application running on the HMD to communicate with the local server through HTTP requests and responses. Unity Web Requests is a Unity feature designed for composing HTTP requests and receiving HTTP responses and was used to communicate with the database hosting machine from the Focus 3. The same approach is also used in the login section of the VR vision screening application, as user registration and selection for the D2 test was made first and all code could be reused.

4.2.5.4 Github

To safely store the project files, Github was used for online file storage. As there was only one active developer on the project, a feature-branch workflow was not established. If more developers were to inherit this project and work on it simultaneously, such development strategies should be considered. The repository for the project including a ReadMe with setup instructions can be found in Appendix A.

⁶Wampserver download and more information can be found here: <https://www.wampserver.com/en/>

Chapter 5

Design and Implementation

This part of the thesis describes the implementation of the main application developed for this project, a VR version of C&Look containing a version of the D2 Test of Attention designed to be run on a Head Mounted Display. This application is made in the Unity game engine, and it is advised to read section 2.7 for an introduction to the engine and its editor. Implementation of C&Look elements and the D2 Test is based on two-dimensional versions, the original screening application described in section 2.1 and the D2 Test of Attention implementation in section 2.2.

5.1 C&Look VR

For this thesis, it was essential to develop a prototype to examine how C&Look can be transferred to VR. This included basic functionality such as a login system with user registration, conversion of 2D tasks designed to gather information on specific eye movements to 3D, and a replay system where results from performing those tasks can be reviewed. The software architecture diagram depicted in Figure 5.1 shows how different technologies utilized for the system work together.

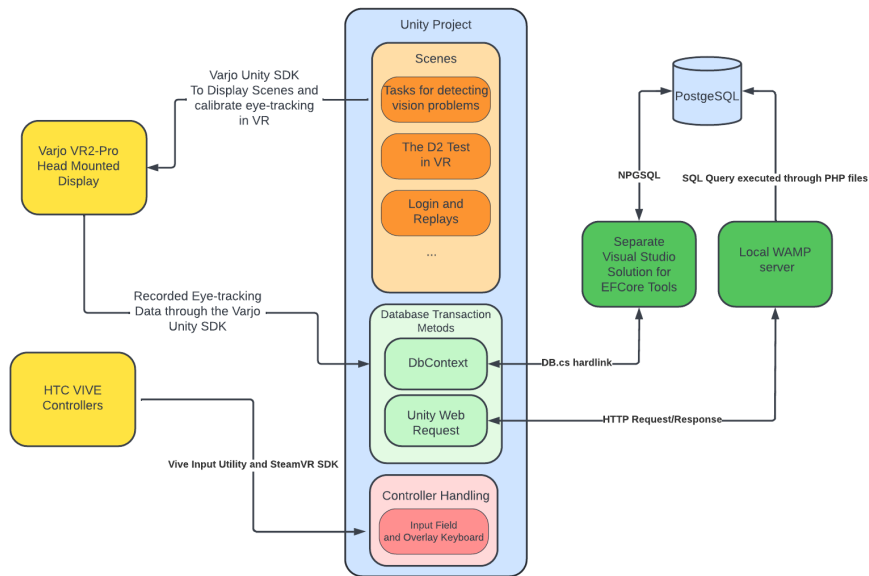


Figure 5.1: Software Architecture Diagram for the VR version of C&Look.

As this study also aims to analyze how VR can extend the current screening application, experimentation on utilizing technologies unique to HMD's for vision screening was done. This includes a prototype task for measuring stereo acuity, as well as experimentation with hand-tracking technology for measuring hand-eye coordination. The following sections go through scenes relevant to the user experience for the VR version of C&Look, as shown in Figure 5.2. Sections 5.1.5 and 5.1.6 are not part of the user experience flowchart, however, they describe implementation relevant to the rest of the application and details relevant for chapter 8. Appendix B contains a table listing all assets used for this application. The source code relating to VR C&Look and a demonstration video can be found in Appendix A.

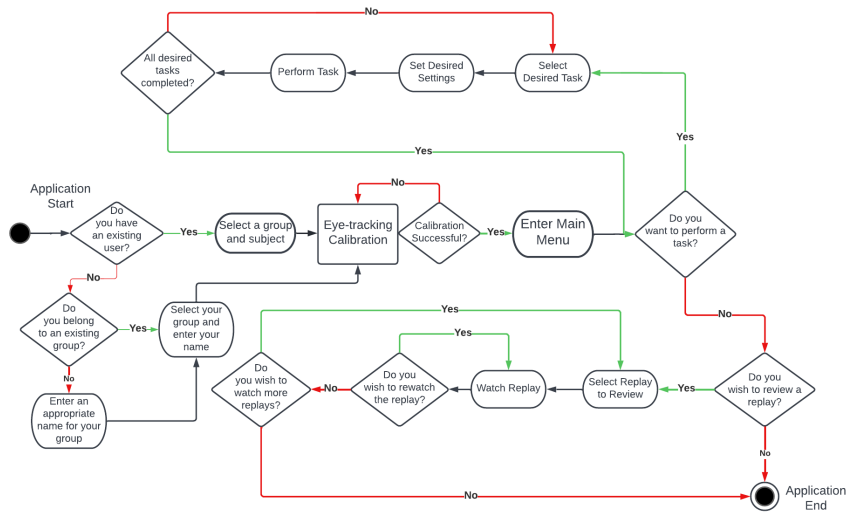


Figure 5.2: User Experience Flowchart related the final version of VR C&Look.

5.1.1 The login scene and eye-tracking calibration

Following the original screening application's structure, a user must first select a group and attached subject profile before testing can begin. If present groups and profiles are not relevant to the user, both can be created within the application. Profile selection in VR involves the user selecting a group from the dropdown menu on the left, as seen in Figure 5.3. Once a group is selected, the subject dropdown menu is populated with the subjects related to the selected group. To achieve this a callback that queries the database for available users in the selected group is created at scene startup and runs whenever a new group is selected as part of a coroutine. To initially populate these dropdown lists, the database is queried for all available groups, and the first element of the group dropdown list is used to construct a query for its users.

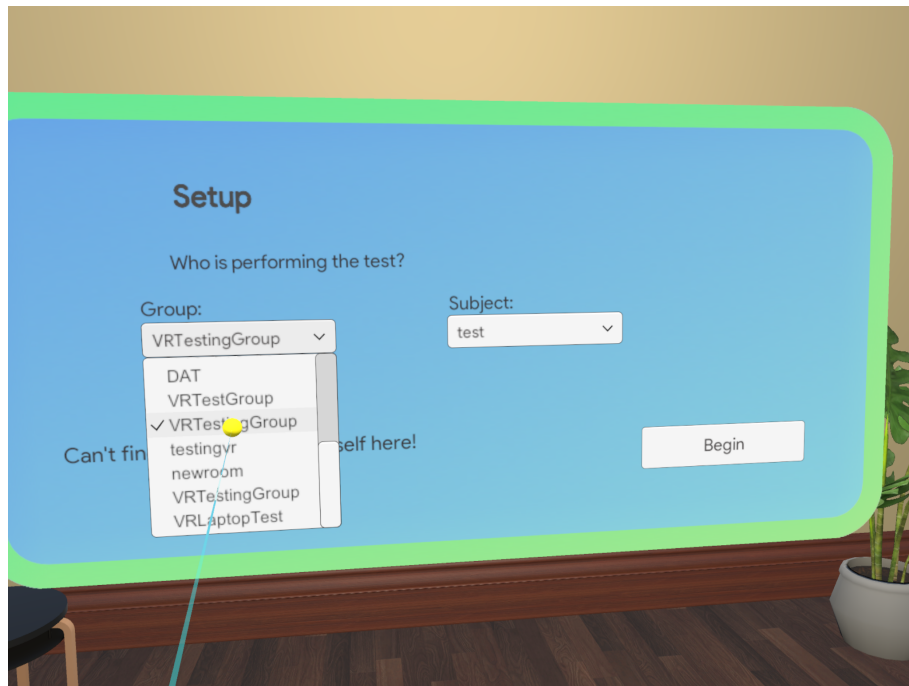


Figure 5.3: User selection in VR C&Look.

All interactable GameObjects are UI elements, which are children of a Canvas object. The VIVE Input Utility extension [73] provides an attachable script, `CanvasRaycastTarget.cs`, allowing for controller interaction with canvas elements. It also includes Prefabs for locating controllers and visualizing pointers. The login scene contains three different canvas objects in total, representing three different menus. If a user decides to create their subject profile, the original selection canvas is hidden, and the subject registration canvas is displayed instead. The same is true if a user wishes to create a group. Both of these new menus include an input field, where text can be entered via an overlay keyboard as seen in Figure 5.4. The overlay keyboard and its logic come from the SteamVR plugin for Unity [64]. If the user submits a new group, that group name is stored in the database and a new id is generated. Once the group has been saved, the group selection dropdown elements are repopulated. Similarly, when submitting a new user the name is stored in the database and an id is generated.

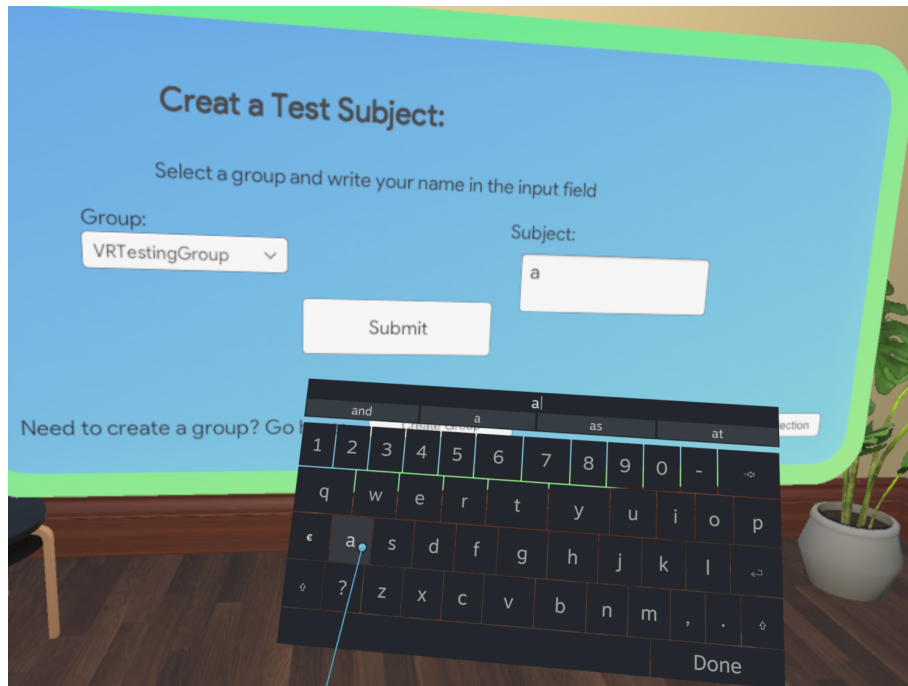


Figure 5.4: User registration and overlay keyboard.

After selecting or submitting a user, eye-tracking calibration begins. The eye-tracking calibration method used for this application is the Varjo Unity SDK’s Legacy Calibration [70]. This calibration is slower than the standard option available, however, when testing the different calibration methods legacy yielded better results. Calibration is initiated by calling the `RequestGazeCalibration(gazeCalibrationMode)` method, where the parameter is an integer of either 0 for standard or 1 for legacy. While eye-tracking calibration is being performed by the user, they are moved to the Main Menu scene. For future necessary reference to subject and group id, these values are stored in a `GameObject` calling the `DontDestroyOnLoad()` method on `Awake()`. This ensures that the object persists on scene change, making the data accessible in the future. This is relevant when saving and fetching gaze data related to a specific user, and when getting a user’s replays. Scripts related to login can be found at this location: `Assets\Scenes\CandLookHomologues\LoginScripts`.

5.1.1.1 XR plugin providers, eye-tracking and input fields

For the overlay keyboard to be displayed when gathering user input for text fields, the currently initialized XR management plugin provider for the application must be set to the OpenVR Loader. This is a result of the SteamVR unity plugin being dependent on this provider. An XR plugin provider handles displaying the application on the connected HMD, as well as providing relevant subsystems. To utilize Varjo-specific features, such as eye-tracking and hand-tracking, the active plugin provider must be set to Varjo or other compatible plugins. The SteamVR plugin has limited compatibility with the Varjo SDK

[69], as a result of relying on the OpenVR Loader. The only free overlay keyboard for receiving user input that was found during development came with the SteamVR plugin, so a temporary solution to this issue was implemented by manually initializing the Varjo loader and its subsystems. This makes eye-tracking and hand-tracking features accessible, however, comes at the cost of the application crashing when exiting play mode. Loader management is a complicated topic, and this temporary solution adds a large amount of technical debt.

5.1.2 The Main Menu

The main menu offers five choices to the user. The recalibrate eye-tracking button starts eye-tracking calibration in legacy mode and should be selected if calibration initially fails. Each other button relocates the user to different scenes. The "Follow the Soccerball Task" takes the user to the task for measuring fixations, the "Follow the basketball task" leads to a task for measuring smooth pursuit movements, and the "Reading Task" moves the user to a scene where gaze data is collected while they read displayed text. Replays of completed tasks can be found by clicking on the "Replays" button.



Figure 5.5: The main menu of the VR C&Look application.

5.1.3 Original screening tasks converted from 2D to 3D

The three main tasks available in the original screening application were converted from 2D to 3D. A myriad of settings can be selected for each task in 2D, making the total task set larger. Recording area can be set for all tasks as a percentage, defining the area for the task to take place in based on the original

canvas shown in Figure 5.6. The available tasks and settings are:

- The fixation task: Measures the user’s ability to fixate on a given point. The target for fixation moves in steps from one point to another. Available settings for this task are:
 - Duration: The total duration of the entire task measured in milliseconds.
 - Direction: Movement direction for the object to be fixated on. Can be either horizontal, vertical, or diagonal. Origin point can also be set, as either top, bottom left, or right.
 - Number of Steps: Number of steps executed for the duration. If a task is vertical or horizontal, the number of steps in each direction can be set.
 - Target Graphic: Graphical representation of the object of interest. Selections are sprites of a frog, cat, or soccer ball.
- The smooth pursuit task: Collects data of a user’s pursuit movements. This involves following an object with your eyes while it moves smoothly from one point to another. Settings for this task are identical to those available for fixation, except for the number of steps being removed. The duration of smooth pursuits is based on total task duration.
- The reading task: Gaze data is gathered while the user reads some displayed text. A reading test is itself a part of the manual vision screening battery [19], calculating the speed and accuracy of reading ability. Available settings for this task are as follows:
 - Text: Any text can be entered for this task in the form of a .txt file.
 - Font Size: The font size used for the test.
 - Font Family: Decided what font type for the text to be displayed as.
 - Line height: The distance between lines of text measured in centimeters.

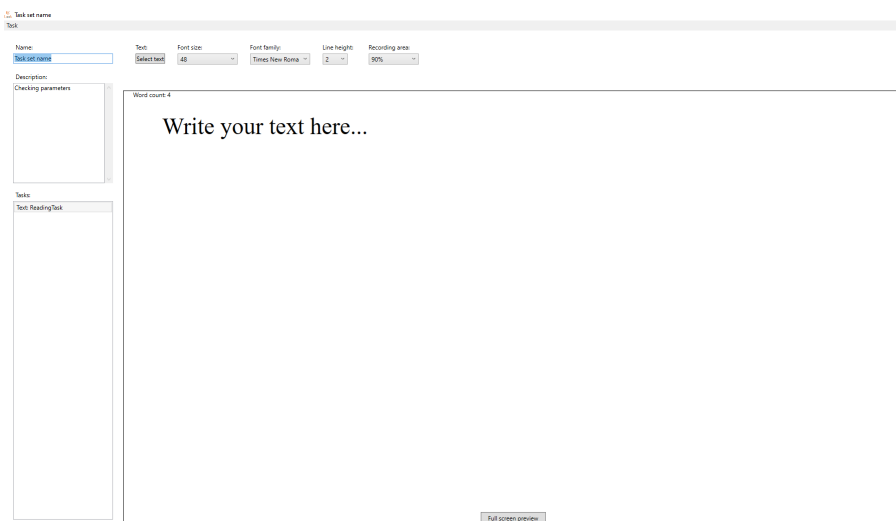


Figure 5.6: A screenshot of the task set editor from the laptop version of C&Look while constructing a reading task.

5.1.3.1 Fixation Task

For the VR version of the fixation task, the object to fixate on is presented as a soccer ball moving from one position to a given destination. The ball will reach its destination and return a total of two times. This was the first task implemented, and the design of the fixation target is directly related to the original screening application where a soccer ball is available as an option. The scene contains a canvas where settings can be adjusted before starting the task. Upon clicking the "Start Game" button, slider values and direction options are read from their respective GameObjects and used to set starting points and values influencing movement logic. A coroutine also starts when clicking the button, initiating a timer counting down from three. Once the countdown reaches zero, the task begins and movement logic is executed within the update loop. The frame seen in Figure 5.7 indicates the area in which the ball will move. Settings available for this version of the task are:

- **Direction:** Influences the start and endpoint of the ball. Available options are diagonal movement left to right, diagonal movement right to left, and vertical movement left to right. When the direction is set to vertical, a slider for horizontal steps is available. This influences the number of left to right cycles before the starting point reaches the bottom of the frame.
- **Time Per Fixation(Seconds):** Lets the user decide how long each fixation should last. For example, if the time per fixation is set to 2, the ball will maintain its position for 2 seconds before moving to its next location.
- **Number of Steps:** Indicates how many steps it should take the ball to reach each destination, meaning how many fixations need to be made.

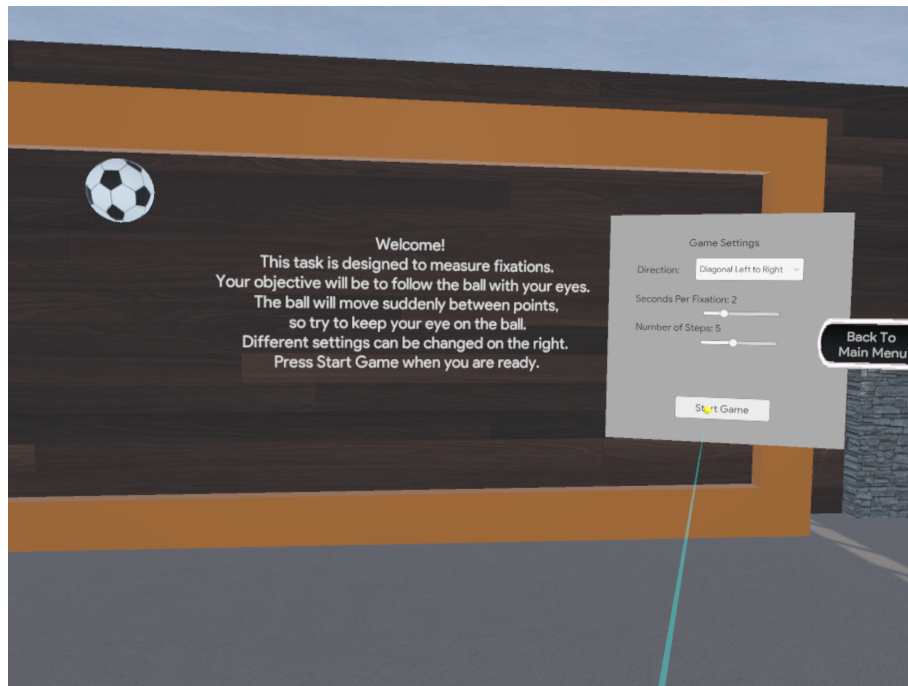


Figure 5.7: A screenshot from the fixation task scene.

Recording of gaze data is handled by the GameRecorder object. When settings have been confirmed, an instance of this object is created, containing task description, subject id, the current local time, and the Varjo eye-tracking instance. The GameRecorder class handles database transactions for eye-tracking data, which is reusable for all tasks. By calling the Update method on the instantiated GameRecorder object, all (if any) gaze data since the last frame is recorded. Once the task is finished, calling the Commit method will store all recorded gaze data in the database. For more information on data storage, see section 5.1.6.1. The main script for this task is located here: `Assets\Scenes\CandLookHomologues \DiagFixController.cs`.

5.1.3.2 Smooth Pursuit Task

The smooth pursuit task shares many similarities with the fixation task, and the scene structure remains mostly the same. Notable exceptions are the use of a basketball texture on the sphere to differentiate the scenes, and different settings being available. Movement logic is also different, as this task involves the ball moving smoothly from one destination to another. Recording of gaze data is accomplished in the same way as mentioned previously. The settings available for smooth pursuit are:

- **Direction:** Influences the start and endpoint of the ball. Available options for this task are left to right and right to left.
- **Repetitions:** Changing this value will change how many times the ball will reach its destination and return.

- Speed(Duration of Saccadic Movement): This value dictates how many seconds it will take for the ball to reach its next destination. For example, a task with 4 repetitions and 5 in speed value will last for 20 seconds.
- Movement Type: Movement type contains two options, diagonal or horizontal. This has been split up into a new setting from the fixation task, meaning both left to right and right to left horizontal tasks are now available.

Task structure remains the same as during fixations, where confirming settings will lead to a three-second countdown and calculation of values related to movement logic. The main script for this task can be found here: `Assets\Scenes\CandLookHomologues \SmoothPursuitScript.cs`.

5.1.3.3 Reading Task

VR implementation of the reading task maintains the gaze data collection method, however, scene structure changes slightly. Fewer settings are available, a language option and a length option. Language can be either English or Norwegian, and length selections include short, medium, and long. Text is predetermined based on the combination of these two options, and a long text only extends the same text as displayed when the medium option is selected. Equal lengths for each language have the same number of characters, ensuring consistency of testing regardless of selected options. The ideal solution for deciding what text should be displayed would have been selecting a text file as part of the settings menu, or the inclusion of a different menu where a custom text could be added similarly to what is available on the laptop version. The problem with this approach is that browsing through files while in VR would be cumbersome for the user, and the same goes for manually writing text using an overlay keyboard. This prompted the decision to use predefined text instead. Figure 5.8 shows the reading task while running on a HMD. For controller code related to this task, see `Assets\Scenes\CandLookHomologues \ReadingTaskScript.cs`.

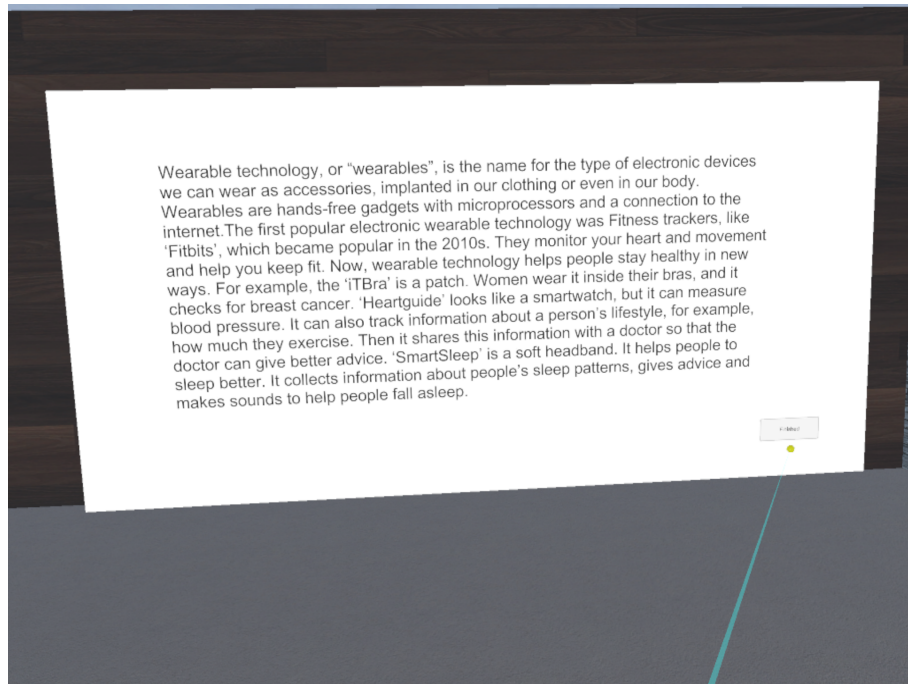


Figure 5.8: A screenshot from the reading task scene.

5.1.4 Replay implementation

The replays scene contains a list of all recordings made by the active user, with each button on the left part of the canvas in Figure 5.9 representing a replay. To generate these buttons, the database is queried on scene startup for recordings related to the user id stored in the global instance. The returned JSON is parsed to a list of `GameInfo` objects, containing task names, recording time, and game version for each task. A button is generated for each object in this list, their representative text being a combination of task names and the timestamp in which the task was performed. Whenever one of these buttons is clicked by a user, the right side of the canvas displays relevant settings used during the recording of the task. As an example, the selected replay in Figure 5.9 is a replay for a fixation task, recorded on 26/07/2022 at 11:44 am. The task was recorded with direction diagonal left to right, 2 seconds per fixation, and 5 fixation steps. All information on settings is stored in the recording's `game_name` attribute, each value being separated by an underscore. By splitting the name string on each underscore, we get a list of all task settings. Once a replay has been selected, a "View Replay" button appears, which can take the user to the active replay scene. An overview of users' results from the VR version of the D2 test is also available here, but no "View Replay" feature is implemented. The main scripts used during the replay menu can be found in this folder: `Assets\Scenes\CandLookHomologues\ReplayScripts`.

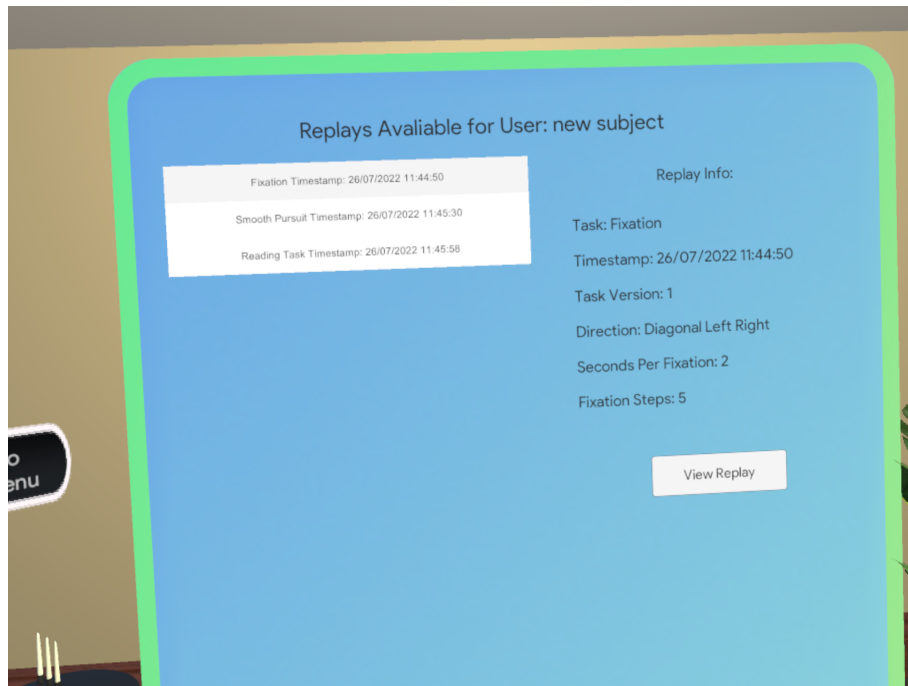


Figure 5.9: A screenshot of the replay scene with a fixation replay selected.

Once a replay has been selected for viewing, the user is moved to the task scene related to the recording. To maintain information on task settings after changing scenes, a `GameObject` with settings is instantiated, defining a `DontDestroyOnLoad()` call in its `Awake()` method. These settings are retrieved on scene startup, ensuring identical task execution. In this version of task scenes, the `Start()` method queries the database for gaze data relevant to the user id and timestamp, deserializing the JSON to a `Recording` object. This object contains gaze data available for each frame during recording, which can be synchronized with the current execution via the `TimestampNS` value, indicating the time in nanoseconds since task startup. Visualization of gaze data at runtime is based on the Varjo SDK's `GazeVisualizer.spawn(EyeTracker et)` method, which displays red and green orbs based on where you are looking at runtime. Since replays use specific gaze data, not data currently available through the eye-tracker, retrieved recording data was used to initialize objects of the `EyeData` data structure. This enables the use of additional helper methods, allowing for features such as displaying the average gaze point between both eyes. The positions of visualized gaze points are updated every frame, using gaze data synchronized with the execution by the timestamp value. Figure 5.10 presents a replay in action, where the red orb represents the left eye and the green orb represents the right eye. Visual differences in a replay and regular task scene consist of the settings canvas being removed and replaced by "Start Replay" and "Exit Replay" buttons. Once a task has started, the "Pause" button will halt task execution and gaze point visualization, giving the user the ability to more closely examine specific results.

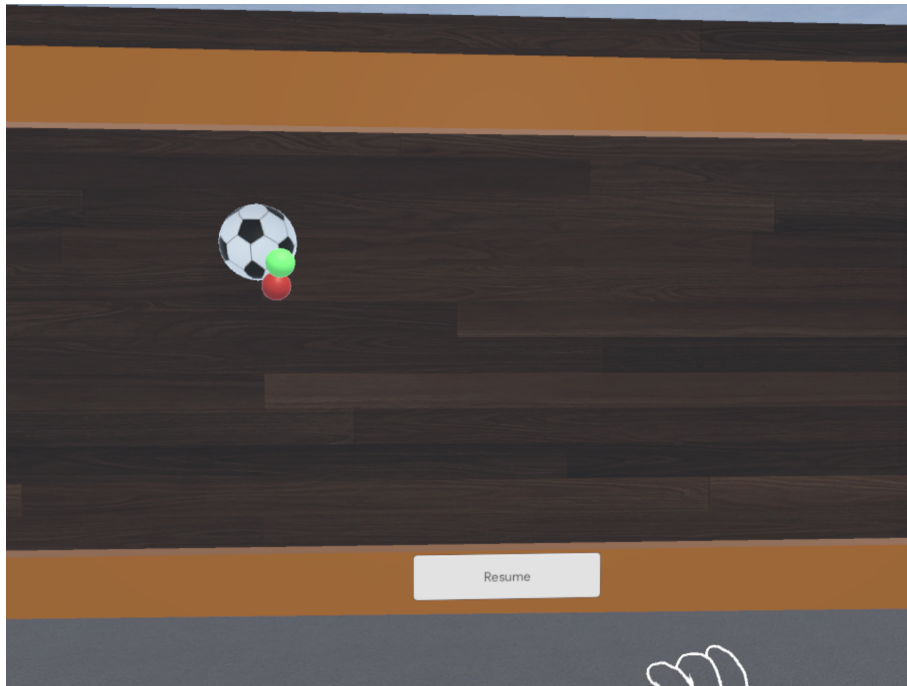


Figure 5.10: Screenshot of an active replay.

5.1.5 Experimental tasks for testing VR capabilities

This section revolves around experimental development and testing that was done to better realize the feasibility of implementing tasks designed to extend the current screening application. The viability of implementing a stereo acuity test was explored in form of an experiment implementation of the circle test. Possibilities of measuring hand-eye coordination were also tested, focusing on hand-tracking technology.

5.1.5.1 Testing the possibility of implementing the circle test

The circle test was selected for experiment implementation, as a stereo acuity test designed for VR has been developed previously by Vivid Vision. This testing method is discussed in a conference presentation about the standardization of stereo acuity testing in VR, presented by Backus [4]. The talk presents a VR version of the circle test, describing the different elements needed to maintain validity when testing measuring stereo acuity levels in Virtual Reality. As a result of this talk, the circle test seemed like a solid choice for experimental implementation. For more information on the circle test, see section 2.6.2.

After implementing a rough solution, one problem became apparent. Stereo acuity level is measured in seconds of arc, with manual testing going as low as 40 arc seconds. An arc second is $1/3600$ of a degree, requiring a very detailed sphere to represent such shallow angles. Blender was used to attempt high-quality sphere generation, focusing on placing a high number of vertices around one vertex of the sphere at a close distance. This limits file size and improve

optimization since the entirety of the sphere does not need to contain high levels of detail. Figure 5.11 shows an image of a high-quality sphere with over 145 000 vertices displaying 300 seconds of arc from the background. Some edges are visibly vanishing behind the grey surface, meaning the quality of the sphere is not high enough. This scene will not even run on the HMD, and generation of this sphere via the script, found at `SphereGenerationScript\SphereGeneration.txt`, took around 2 hours. Better optimization of the sphere generation algorithm might be possible, but combining the time of generation with the issue of not being able to run the scene in VR because of the sphere’s complexity makes this implementation method beyond the scope of this project.

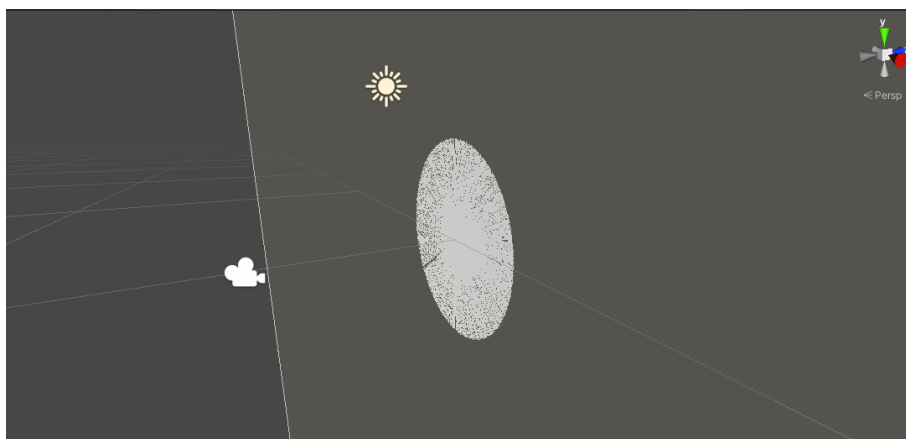


Figure 5.11: The high-quality sphere, with 300 seconds of arc being displayed.

5.1.5.2 Experimental hand-eye coordination testing

The Varjo VR2-Pro features external-facing infrared cameras which allow hand-tracking when using the headset. As mentioned in 4.2.4, the Leap Motion Unity SDK was utilized for exploring hand-tracking possibilities. As of version 4.8.0, the shaders used for rendering hands did not work with instanced GPU rendering¹, meaning that the hand will only appear on one eye but not the other. A solution to this is changing render mode to multi-pass, however, this sacrifices performance significantly. The implemented fix which does not come with a performance cost was to make changes to the provided hand shader from the LeapMotion SDK. To enable hand-tracking in any given scene, a **Leap XR Service Provider** component can be attached to the main camera object. Prefabs for displaying hands when using the HMD were available as part of the SDK, however, some additional setup is required to enable interaction and proper tracking. Details on setup for hand-tracking and necessary changes to the hand shader can be found in the GitHub repository’s ReadMe file, see Appendix A. For more information on hand-eye coordination tasks used by vision experts, see section 2.6.1.

A simple air hockey game was developed to experiment with hand-tracking and

¹More information on GPU instancing can be found here: <https://docs.unity3d.com/Manual/GPUInstancing.html>

its interactions. Interacting with menus and UI elements work by pinching with the thumb and index finger, which brings up a targeting ray. When the fingers are separated, an interaction occurs where the ray is pointed. To pick up objects in a scene, performing a grabbing motion with your hands will pick up the item. A wide variety of motions are inconsistent for picking up objects, however, a pinching motion with all fingers is relatively reliable. A problem discovered from testing the hand-tracking was the unreliability of continuous tracking when hands were facing down towards the floor. This seems to stem from the front of your hand blocking the infrared camera's vision, leading to often accidentally dropping objects that you are holding. As the main task performed during manual vision screening for measuring hand-eye coordination involves drawing or precision stacking, the current state of hand-tracking felt too unreliable for users to not get frustrated by the technology during testing.

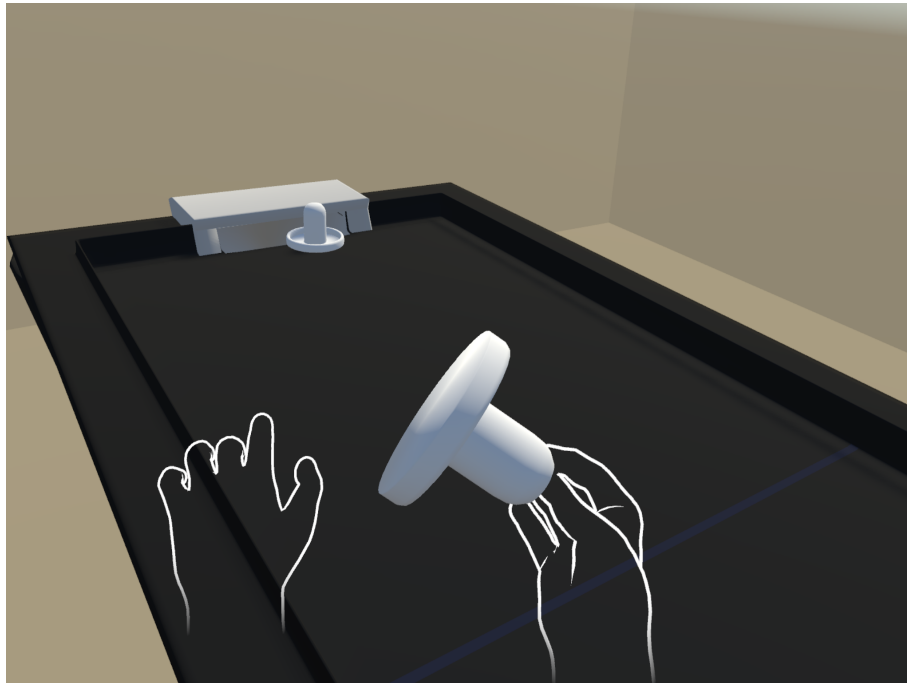


Figure 5.12: Hand-tracking technology being utilized in the air hockey game.

5.1.6 Database structure and transaction methods

As mentioned in 4.2.5.1, PostgreSQL was utilized for data storage in this application. As the original screening application's database is used, the initial setup was not required. New tables were added for storing VR eye-tracking data and D2 Test results, shown in the left container of the entity-relationship database model depicted in Figure 5.13. Two separate transaction methods were used, and their use cases and implementation details are described in the following sections.

Entity-Relationship Database Model

Are Dieffen | July 25, 2022

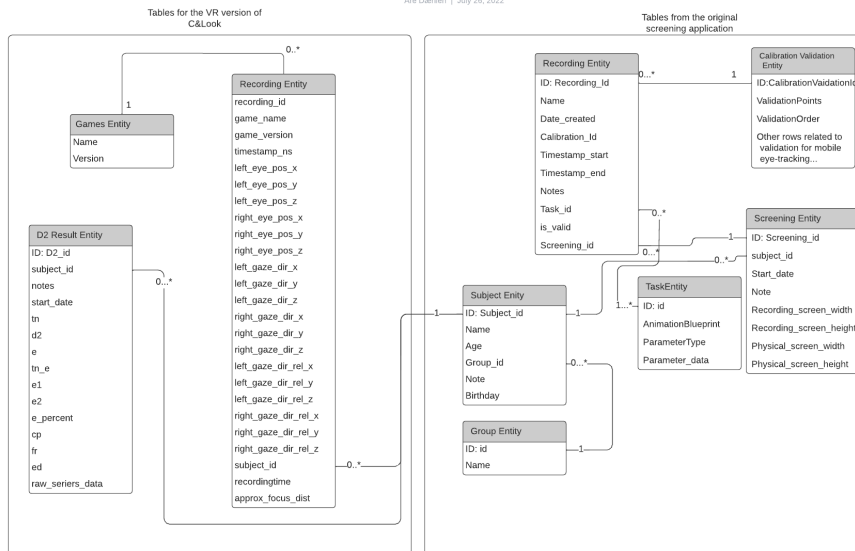


Figure 5.13: Entity Relationship Model of the Database used for the application.

5.1.6.1 Entity Framework Core and the separate visual studio solution

When realizing the complexity of the gaze data structures, it became apparent that an object-relational mapper would be needed to store the data. Entity Framework Core is a tool used in a lot of modern visual studio solutions and provides an object-relational mapper which the developer was familiar with. From attempting to add this framework to the Unity project, it became apparent that Unity does not integrate well with NuGet package management and the ways of modern visual studio project layouts. To get these automated tools working, a workaround solution was implemented. A new Visual Studio solution separate from the one that Unity manages was developed, allowing the use of modern NuGet features and setting up the project in a way that works with Entity Framework Core. However, it was essential to be working on the same DB.cs file containing the same models in both projects, and a hard link between both DB.cs files was made. A hard link means that the same file appears at two different locations in the filesystem. Since the underlying file is the same, edits affect both versions of the file. As a final touch to the workaround, the Stubs.cs file in the visual studio solution declares signatures from the Unity project that are used in DB.cs. This is needed for the solution to compile successfully.

Gaze data storage in the application is done through constructing database sessions via the `DbContext` class. An instance of this object is used to represent a session with the database, allowing for querying and saving data [21]. By defining the use of `Npgsql2` as the active transaction method in the options builder

²Npgsql allows for .NET access to PostgreSQL

with the input of database access information, transactions can be made. The `GameRecorder` class handles the recording of all gaze data for a task's runtime, and once a task has finished, the `GameRecorder` object which contains gaze data, name, version, and timestamp is committed to the database as a new row of the recordings table. Once this process is finished the session is disposed of. When retrieving gaze data for replays, the relevant row from the recording table is fetched based on `game_name` and `timestamp` input using a `DbContext` instance. The `GameRecorder` class can be found under `Assets\Util\GameRecorder.cs`.

5.1.6.2 Unity Web Requests and WAMP

As mentioned in 4.2.5.3, a virtual server hosting environment was used for querying and saving new users in this application. The motivation behind this was to save development time, as the necessary code could be transferred from the Focus 3 version of the D2 Test. The database interaction implementation is partially based on an implementation described in a YouTube video series by Board to Bits Games [5]. This involves defining coroutines that send a web request to the server, expecting a result. Callbacks for each type of request are instantiated on scene startup and called once results from the request are received. Each request targets a specific web page hosted on the local server, and a filtered version of the HTML is sent back as the response in form of a string. Each of these web pages has its own PHP script, which performs the database query returning a JSON response, and displays the result on the web page. The returned strings are serialized from JSON to relevant objects in the callback. The rest of the callback includes method calls to parts of the application that require the fetched objects. This implementation ensures that parts of the application that require information from the database will never starve, as they can only be called when a request successfully receives a response. If the application is to be developed further this should ideally be changed to rely on Entity Framework Core instead. Modifying this would eliminate the need for running the WAMP server in the background while the screening application is being used.

5.1.7 Changes made based on results from the first test

The prototype version of the application used for the evaluation test with a vision expert did not contain all of the features detailed above. For instance, this version included only a very basic environment for the tasks to take place. This was later changed to each scene having a more detailed environment, represented as rooms in a house. The login, main menu, and replay selection scene takes place in a lounge, designed to look calm. In these parts of the application, users should not feel like they need to rush, and there are pictures on the wall as well as other minor details to make players want to look around. The tasks themselves take place in a garage-style room, to give a more industrial feel however not enough to be off-putting. The less comforting room strives to invoke a sense of urgency, making the player want to focus on the task so that they can return to the more comfortable setting. There are fewer details here, as there should not be any distractions available when users perform tasks. All assets such as 3D models and textures used for this project are available for free on the Unity Asset Store, and a list of all assets used can be found in Appendix B.

Other features that were not available during the first iteration of the application were the subject and group registration, as well as replays for the fixation and smooth pursuit tasks. The visual design of menu elements was also changed to make them stand out more, which was requested by the vision expert during the first test. Player positioning, text fonts, and task lengths were tweaked to give a better user experience when engaging with core elements of the application.

5.2 A Virtual Reality implementation of the D2 Test of Attention

To examine how the focus of attention can be measured in VR, a 3D implementation of the D2 Test of Attention was developed for this study. This VR version is based on the attention test application described in 2.2, which is designed to run in a web browser. This section explains the implementation of the three main parts of the test, as well as the differences between the VR and browser version. User registration and relevant database transaction methods are not described in this chapter, as they are equivalent to what was described in 5.1.6.2 and 5.1.1. Originally, a separate application of the D2 Test was developed for the Vive Focus 3 as a result of controller pairing issues with the Varjo. This version was later deemed obsolete, as the availability of user interaction via controllers in VR C&Look allowed for the D2 Test to be part of the same application. It is worth noting that a Focus 3 implementation still exists. Minimal changes were made to the Varjo version, as the only necessary change was to link user selection and registration to the VR C&Look login page. With more available development time it would have been ideal to change all database interactions in the Varjo version to utilize Entity Framework Core instead of WAMP and web requests. This would eliminate the need for running the local server in the background. The scenes and scripts related to the VR version of the D2 Test can be found at: `Assets\Scenes\CandLookHomologues\D2TestScenes`.

5.2.1 Tutorial implementation

The tutorial section introduces users to the different elements and rules of the D2 test. This is done through three different steps. The first is a group of messages which explain the basic concepts of the D2 Test, such as what elements are supposed to be clicked during proper testing. This step contains text elements that fade in and out and a sample D2 row. Different messages are displayed for different amounts of time, based on their length and complexity, and there are a total of 10 different messages. In the code, tutorial steps are part of a `switch` statement, with a total of 13 different cases. The first 10 cases handle displaying the different messages, while the next case initiates an assisted practice round.

Moving on to the assisted practice round makes the D2 row intractable while highlighting the letters which should be marked. If the user makes any errors, those elements are also highlighted. Figure 5.14 shows assisted practice in Virtual Reality. The tutorial will not proceed until no errors are present and all D2s are marked. As the row is randomly generated, each Game Object representing an interactable letter has an attached `ButtonValue` component. This component includes a boolean variable `error` which is set for each button upon

generation. If a letter is a D2, the variable is set to true, otherwise, it is set to false. Once a user marks a D2 letter, its error value is set to false. By reading this value from a letters attached component we can find the errors present in the current row.

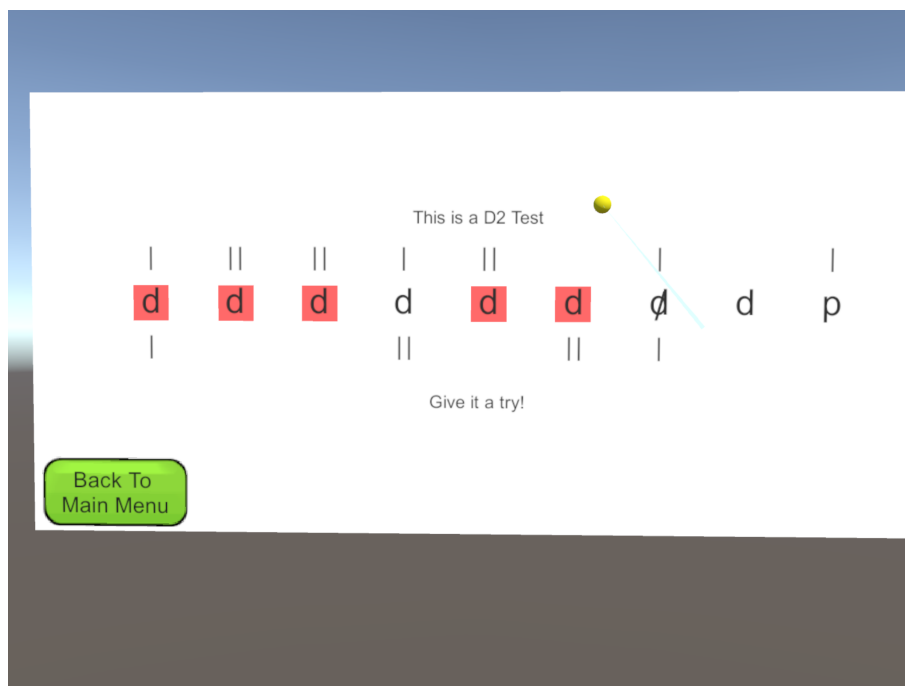


Figure 5.14: The assisted practice tutorial step of the D2 Test in Virtual Reality.

Once the user has successfully marked all highlighted elements, a short message appears stating that a practice round is about to start. The user is again tasked with marking the correct D2 available, however, errors are no longer displayed. The initial number of rows needed to be completed here is one, but if any mistakes are made another row is added. Once all rows have been completed, the user moves on to the main D2 Test. If a total of seven rows are added to the list, the user is sent back to the main menu. This amount of errors indicate a lack of understanding of the rules, and the tutorial should be restarted from the beginning if they wish to perform the real test.

5.2.2 The D2 Test

The main D2 test consists of 12 series containing 14 rows each, with each row containing 9 letters. A series of rows is generated when the test starts, and subsequent series are generated once the previous is finished. Each row in a series is generated according to Merten's specification [42], with the first to the fourth row containing 3 to 5 D2s. The fifth and sixth row has two and four targets, and the seventh row contains 5. Row 8 to 11 and 12 to 14 repeat the same pattern. The position of D2s is random under these restrictions, including

the positioning of dots/markers.

Each series has a time limit of 30 seconds, and it is not expected for users to be able to complete a series within the 30-second window. Limiting the duration of the series ensures that the test takes no longer than 6 minutes, and rows that were not viewed have no impact on scoring.

5.2.3 Scoring and recording of metrics

Figure 5.15 displays the score result page of the Virtual Reality (VR) D2 Test application. Final scores of the D2 Test are measured using 10 different metrics. More detailed descriptions of what each of these metrics represents can be found in 2.2. Their methods of calculation are as follows:

- **TN**: This is the total number of letters seen while performing the test. Whenever a series ends, the current row number is multiplied by 9 and added to this value.
- **D2**: Total number of D2 letters seen. Whenever the user proceeds to the next row or a series ends, the number of D2s in the viewed row is added to this value. To identify if a letter is a D2, a hex value is assigned to each letter upon row generation, encoded as 0x(marked)(ntop)(nbot)(char). Char is 1 if the letter is a d, and 0 if it's a p. Ntop and nbot describe how many dots are visible above and below the letter. The encoding strategy comes from the browser implementation, and marked is not used for the VR version. If the value of char is 1 and the combined value of ntop and nbot is 2, the letter is a D2.
- **E**: The total number of errors. When the next button is clicked or when a series ends, the current row's errors are added to this value. Errors are recognized in the same way as described in 5.2.1.
- **TN-E**: Total number of correct letters. This does not only include correctly marked D2, but also unmarked non-D2 letters. This value is calculated at the end by subtracting E from TN.
- **E1**: Number of D2 not marked. Calculated in the same way as D2, but only added if the D2 was not marked when proceeding.
- **E2**: Number of non-D2 marked. E1 is subtracted from E to find this value.
- **E%**: E/TN as a percentage.
- **CP**: This stands for concentration performance. It is represented by the total number of correctly marked D2 minus E2. The total number of D2 marked can be found by subtracting E1 from D2.
- **FR**: Stands for fluctuation rate. Fluctuation rate is the maximum number of letters seen in a series minus the minimum number of letters seen in a series.
- **ED**: Error Density. It is the average errors in the last four series minus the average number of errors in the first four series.

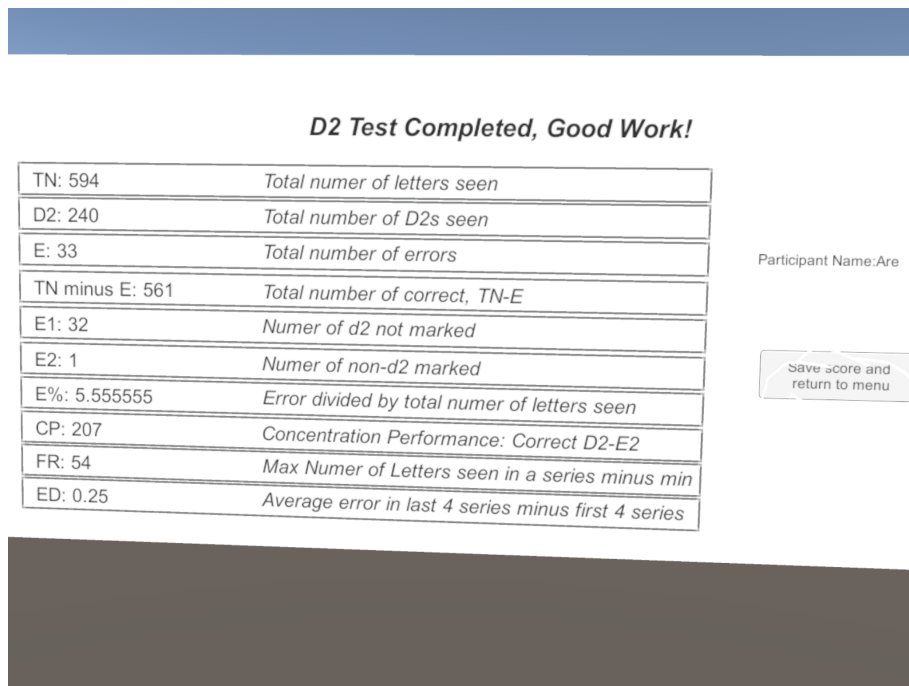


Figure 5.15: Overview of results from the D2 Test in VR.

5.2.4 Differences between the VR and browser versions

The two-dimensional application had a total of 9 rows per series with 14 letters each. It is not entirely clear why this was the case in the original application, as the specifications provided by Merten specifically state the use of 14 rows per series. The other notable difference is the interaction method. In a browser, users mark D2s with a computer mouse, while in VR this is done by using virtual reality controllers. Selecting options with these controllers can be difficult, and users will most likely have more experience with using a mouse. This can affect the final score when performing the test, as there is a time limit per series.

Chapter 6

Evaluation

This chapter presents a comprehensive description of the evaluation methodology and testing steps performed for this thesis. The evaluation focuses on identifying how the existing two-dimensional C&Look screening application can be extended using VR to provide a more general application for screening. It also includes steps for evaluating how the D2 Test of Attention can help extend the current vision screening battery by including estimations for the focus of attention. Investigating the existing programs, technologies and stakeholders needs, a new evaluation methodology using a new battery for information and data collection (designed Haldal, see Appendix C) was defined. While the evaluation is based on existing presence, user experiences, and usability evaluation methods, these were extended and contextualized. A final version is described in Appendix D. While trying out technologies and transferring the programs written on laptops to VR incorporated several tests with developers (technology and software, incorporating studies e.g. [1] and [37]), two main tests were performed collecting data from stakeholders during this project. The tests were:

- Test 1: Evaluating extensions of the current screening application. This includes testing an implementation of the D2 Test of Attention and a prototype of the VR version of C&Look on a vision expert.
- Test 2: Comparing user experience and system usability of C&Look in VR and on Laptop. By testing both applications on 7 participants with a focus on comparison, we can get an evaluation of the current state of the VR application.

Test 1 was performed significantly earlier than test 2, and changes were made to C&Look VR as a result of the first test. This may make the application flow described in section 6.1.4 seem disconnected from what is presented in Chapter 5, as it describes the implementation of the final version of the application which was used during test 2.

6.1 Test 1: Evaluating extensions of the current screening application

To evaluate the proposed extensions of the current screening application, a vision expert was tasked with testing the prototype of the VR application in conjunction with the attention test. The purpose of this test was to get an expert’s opinion on the feasibility of making an attention test a part of the vision screening process, in addition to receiving feedback and suggested changes for the VR C&Look application. This is also an opportunity to receive suggestions for how VR could help extend the original application, as the vision expert that was utilized for the experiment has personal experience using the two-dimensional version of C&Look. The sections below provide a detailed description of each testing step. For a brief overview of the tests, see section 3.3.1. Collected results and experiences are described in section 7.1.

6.1.1 Testing the D2 Test of Attention

This section describes the application flow of the D2 Test of Attention on the laptop used for testing. It is recommended to read section 2.2 first, which explains the different elements and structure of the test. Figure 6.1 describes the flow of actions and events in the application from the user’s perspective.

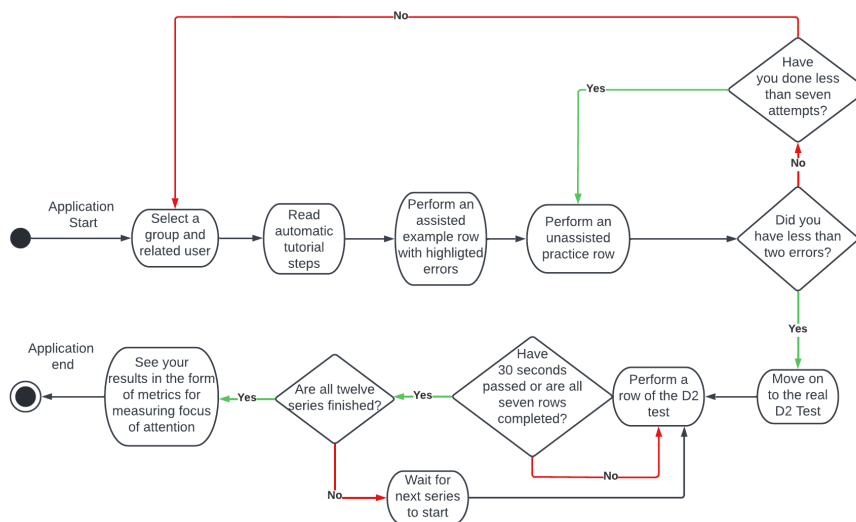


Figure 6.1: User Experience Flowchart for the D2 Test of Attention.

6.1.1.1 User Selection

The application flow of the D2 Test of Attention starts with selecting which user is performing the test. Firstly, a group must be selected. From there, any user within that group can be selected to perform the test. Both groups and users available for the D2 test are connected to the original screening application’s database, meaning a group and user must first be created through

that application. The current implementation offers no user or group creation feature.

6.1.1.2 The D2 Test Tutorial

After a user has been selected, an interactive tutorial starts. This helps to introduce the user to the D2 test and explains how it is meant to be completed. First, a row of D2 letters is displayed. Text elements describing the basic concepts of the D2 test are faded in and out of the page, showing examples of which letters are correct to mark.

Upon having received all the necessary information regarding the test, an assisted practice round begins. Here each letter that should be marked by the user is highlighted, and any mistakes made are shown directly. Instructions for what letters should be marked are also described at the bottom of the page. Once all correct letters are marked, the next step of the tutorial begins.

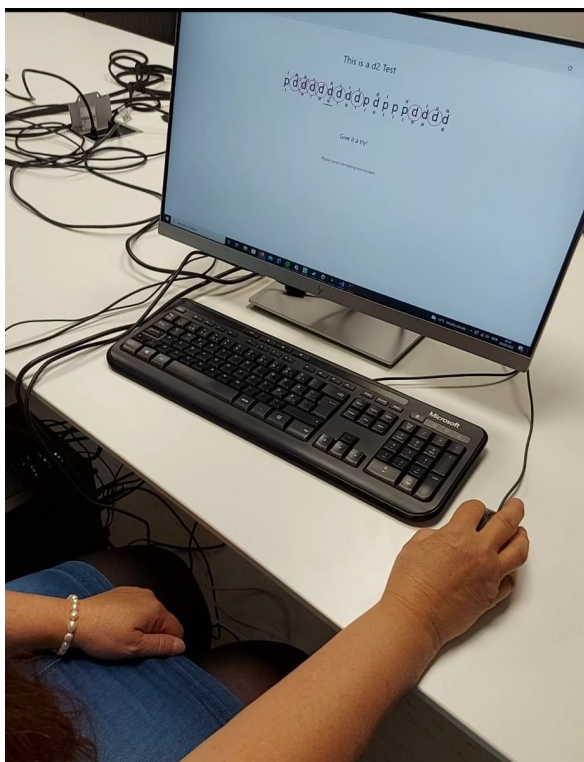


Figure 6.2: The vision teacher performing the assisted tutorial step.

The final step of the tutorial is a practice round without assistance. The user is tasked with performing one row of the D2 Test. If successful, the user moves on to the real D2 test. If two or more errors are made during the first row, a second row will need to be completed. If any subsequent mistakes are made, an additional row will be added to the number of rows to complete. Once all rows have been completed, the user is taken to the real test. If a user makes

seven or more mistakes without completing all rows, they are sent back to the login screen. A large number of mistakes indicate a lack of understanding of the rules, and the user should run through the tutorial again from the beginning.

6.1.1.3 The D2 test and Scoring Page

Once the tutorial is finished, the user is taken to the real D2 Test. Here the number of mistakes and correctly marked letters are recorded, as well as how many rows and series were completed in time. The test originally consists of twelve series, with seven rows each. Each series has a time limit of thirty seconds, and users are not expected to be able to complete a series within its time limit. This version of the test takes approximately six minutes. To reduce the total amount of time spent performing the D2 test during evaluation, the total number of series was reduced to four, making the test duration about two minutes.

Upon completing the test, the user is taken to the scoring page where metrics produced based on their performance are displayed. This page also describes what each metric measures, giving users a better understanding of how they performed. Once results have been reviewed, they can choose to either try again or return to the login screen.

For more implementation details on the D2 test, see section 5.2. Extensive detail on the two-dimensional version's implementation is not described, as the author did not develop this application. However, the VR version of the D2 test is based on this implementation and carries many similarities.

6.1.2 Questions about the D2 Test

Once the initial evaluation step of the D2 Test application was finished, a semi-structured interview was held between the vision expert and this thesis' author. The questions used during the interview were designed around how the D2 test could fit into the vision screening process. Some questions regarding usability and user experience were also included, as vision experts would be possible users if utilized to test a patient. Prepared questions for the interview can be seen found in Appendix C.1.

6.1.3 Demonstration of the VR Equipment

After both steps regarding the D2 Test of Attention were completed, the test moved on to the topic of VR. To give the vision expert an introduction to the VR equipment, a short demonstration of how to use the hardware was given. This included a brief showcase of how to put on the headset and use the controllers by the developer, as well as letting the vision expert experiment with the equipment in Varjo Base while being assisted(see section 2.4.1 for more details on Varjo Base).

6.1.4 Testing the C&Look VR Prototype

When the vision expert was comfortable using the VR equipment, testing of the C&Look VR prototype began. This section describes the application flow of the

first iteration of C&Look VR used for initial testing. An overview of interaction and events as seen from the user’s perspective is shown in Figure 6.3. For a full description of implementation, go to section 5.1.

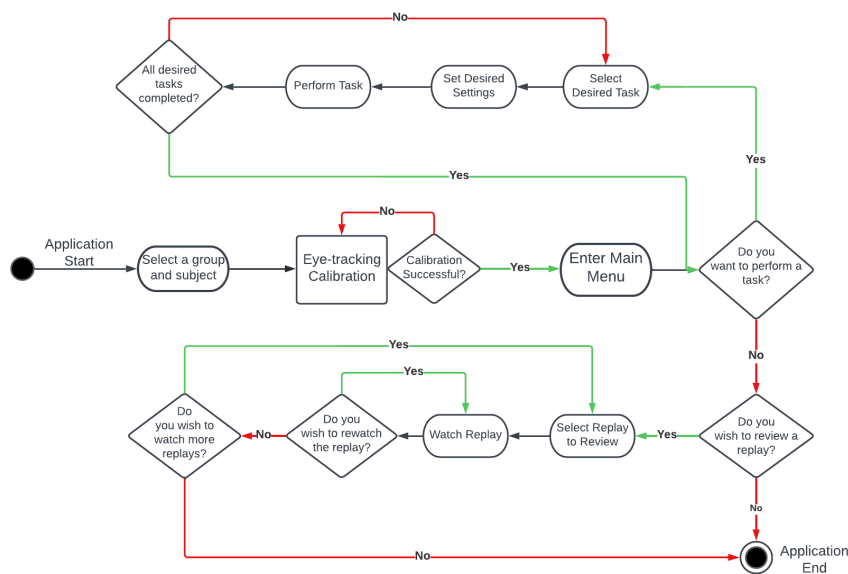


Figure 6.3: User Experience Flowchart for the prototype version of C&Look in VR.

6.1.4.1 User Selection and the Main Menu

To begin the test, a group and attached user are selected. This is done similarly to the D2 Test application, with available users and groups being connected to the original screening application’s database. The user selection allows for practice with the controllers, making future navigation easier. Once a group and user have been selected, a continue button should be pressed. See section 5.1.1 for implementation details.

Once the continue button has been pressed, the user is moved to the main menu. From here a variety of tasks can be selected, as well as an option to calibrate eye-tracking and view recorded replays. Calibration of eye-tracking is automatically started upon entering this scene, however, in the case of calibration failure, the calibrate eye-tracking button should be pressed manually by the user. All tasks in the application rely on the collection of eye-tracking data, thus the user must successfully be calibrated before moving on to any task. After eye-tracking has been calibrated, a task should be chosen from the available options. For testing purposes, the vision expert was asked to perform the tasks from top to bottom, starting with the fixation task. Figure 6.5 shows the main menu of the application while testing on a vision expert. Implementation details for this scene can be found in section 5.1.2.

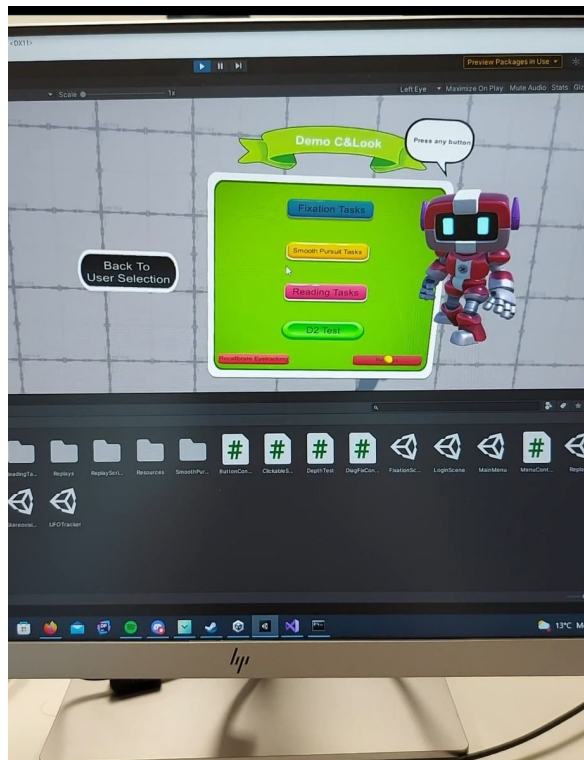


Figure 6.4: The main menu of the prototype application during the test on a vision expert.

6.1.4.2 The Fixation Task

Upon clicking the "Fixation Task" button, the user is moved to that task's respective scene. An introduction message is displayed in the middle of the screen, explaining the goal and structure of the task. Different options can be selected from the settings menu on the right, changing the duration and intensity of the task. During the test, the vision expert was asked to perform all tasks with their base settings, which were two repetitions and five steps per repetition. Once ready, the user may press the "Start Game" button, hiding the settings menu and initiating a timer that counts down from three. Once the timer reaches zero, the ball begins to move diagonally towards the bottom right corner of the orange frame in steps. The goal is to follow the ball with your eyes during its movement. Once the ball hits the bottom right corner of the frame, the same process repeats in the opposite direction. When all repetitions are completed, the task ends. From here, the settings window reappears and the user may perform the task again or return to the main menu. For testing, each task was only performed once by the vision expert. For more information on the implementation of this task, see section 5.1.3.1

6.1.4.3 The Smooth Pursuit Task

Clicking on the "Smooth Pursuit Task" button takes the user to that task's respective scene. The design of this task's scene is identical to the fixation task's scene, except for the movement pattern of the ball. In this task, the ball moves smoothly between the top left corner and the bottom right corner, and the object of the task is to follow it with your eyes. Similar settings to those available in the fixation task are present, except the number of fixation steps is replaced with direction and duration. Direction options for the ball's movement to be vertical, diagonal, and horizontal are available. The duration option signifies how many seconds it will take for the ball to reach its endpoint before starting a new repetition. For testing purposes, the base settings of diagonal movement with a duration of 5 seconds and 2 repetitions were used. Section 5.1.3.2 contains implementation details for this task.

6.1.4.4 The Reading Task

The third and final task available is the reading task. It is accessed by clicking the "Reading Task" button in the main menu, and contains a task where the objective is to simply read the text displayed after pressing "Start Game". This task includes options for changing the language between English and Norwegian and selecting text length of either short, medium, or long. When testing the application on a vision expert, length was set to long and language to English as these are the default settings. Similar to other tasks, an introduction text with instructions is displayed while confirming parameters, and starting the task initiates a three-second count down. Implementation details for the reading task are described in section 5.1.3.3.

6.1.4.5 Replays

After at least one task has been completed, replays for recorded tasks can be found in the replay section of the application. This feature is accessible through the main menu by pressing the "Replays" button in the bottom right corner. Once in the scene, different replays can be found on the left side of the menu, represented with a button. Each replay is named after the task it is connected to and the time in which it was recorded. When the first test of the application was performed, only the reading task had replays enabled. The reasoning for this was that other replays were showing inconsistent results, and more implementation time was required to properly represent the data. When clicking on one of the listed replays, more details for that replay are displayed on the right-hand side. The information varies based on the task, and the details listed are directly linked to the original task's possible settings.

Once a replay has been selected, the user can choose to view that replay. By clicking the "View Replay" button, they are transported to the task scene corresponding to the replay. By pressing the "Start Replay" button, the replay begins, starting from when the count down ended when originally performing the task. During a replay, the given task scene behaves similarly to how it would during regular task performance. The difference is that instead of recording the gaze data, the collected data from when the task was performed is displayed in form of a green and red orb. The red orb represents where the left eye was

looking, while the green orb represents the right eye. Replays of tasks can be paused at any time by pressing the "Pause" button and can be resumed again once paused. After the replay is finished, the option to start the replay or leave the scene returns. For more information on replay implementation, see section 5.1.4.

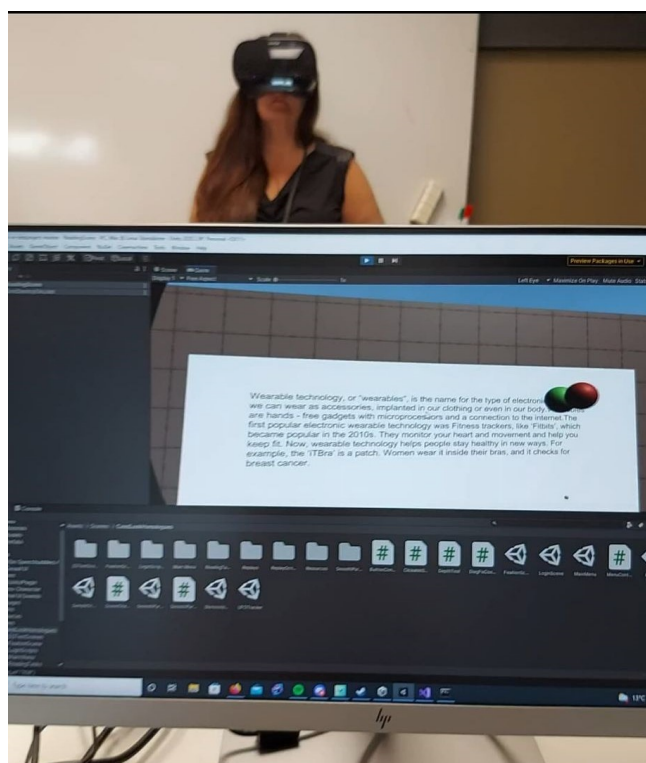


Figure 6.5: The vision expert watching a replay of the reading task during testing.

Having logged in as an existing user, performed each task once, and reviewed a replay, testing of the prototype VR version of C&Look on a vision expert was concluded. For a full overview of implementation details for C&Look VR, see section 5.1.

6.1.4.6 Questions about C&Look in VR

After having tested the VR prototype of C&Look, another semi-structured interview was conducted. Questions for this interview were designed around the feasibility of using VR for vision screening, the advantages and disadvantages of VR for this purpose, and which parts of the vision screening battery VR could cover that a laptop application can not. Some usability and user experience questions were also posed during the interview. Appendix C.2 contains these interview questions. The entire process of testing both applications on a vision expert and conducting an interview lasted approximately two hours. Results regarding this test are located in 7.1

6.2 Test 2: Comparing user experience and system usability of C&Look in VR and on Laptop

If the VR application were to be used in practice, possibly replacing the original screening application as a result of added benefits, information on how it would work on possible end users must first be gathered. This test evaluates the current state of VR C&Look by comparing it to the existing laptop screening application. Information on participants can be found in Section 6.2.2. During testing, subjects filled out a variety of forms containing different questionnaires about usability and user experience. Questionnaires are based on validated methods of data collection, and the data was used to obtain verified measurements of system usability and user experience. Evaluation results containing these measurements are presented in subsection 7.2. All forms used as part of this testing battery can be found in Appendix D.

6.2.1 Improvements made to VR C&Look before the second test

The first evaluation test included some user experience and system usability questions to influence the development of the application towards the second test. Received feedback lead to the implementation of a more detailed and natural virtual environment for the application to take place in. The goal of this was to make it easier for users to understand what elements could be interacted with in any given scene and to make different areas of the application distinguishable. Menu elements, text fonts, and player positioning was also changed for this purpose.

Further development on the application also saw the introduction of user and group registration, removing previous reliance on the original screening application. The default duration of fixation and smooth pursuit tasks were also changed, and visual information of when a task has been completed was added. For a complete overview of improvements made after the first test, see section 5.1.7.

6.2.2 Test Participants

An evaluation was done by testing both applications on a total of seven possible end users, both male and female, ranging from a developer with previous experience in serious games using VR, to a high school student with no experience using HMDs. All participants involved in the comparative evaluation are presented in Table 6.1

Participant	Profession	Use Spectacles	Age
P1	Student	No	26
P2	Student	No	35
P3	Student	No	24
P4	Student	No	23
P5	Student	Yes	25
P6	Student	No	14
P7	Student	Yes	22

Table 6.1: Table of participants

All participants of the study were students, however, P2 is significantly older than the others and a Ph.D. Research Fellow, which serves to give more complicated feedback related to the research value. P7 is also an outlier of the group, being a high school student, providing some insight into how the applications are experienced by a younger audience. The average age of participants was 24. Out of all participants, P4 and P5 had previous experience with VR, and only P5 had experience with Serious Games in combination with VR.

6.2.3 Evaluation Steps

To initiate testing, a brief introduction of the project was given to the subject. This included a verbal explanation and a printed handout with more details which could be read if desired. Introductory steps also involved filling out a consent form, allowing results and pictures from the test to be used as part of this research. Background information regarding the subject’s familiarity with relevant technology, serious games, and vision screening was subsequently collected through a third form.

Once these initial steps were completed, application testing began. To remove any unwanted bias in measurements stemming from the application testing order, the order for each participant was randomly selected before testing began. The next two sections describe the flow of testing of each application separately. Users were assisted by a developer familiar with C&Look during the testing of both applications.

6.2.3.1 Testing the original laptop screening application on a possible end user

Before application testing began, a group of seven different users was registered to a local database on a laptop. This laptop was used for testing all participants, and user selection was done by the assisting developer between tests to expedite the testing process. A task set was also constructed using the tools provided in the application, making all tasks run automatically in a predetermined order without any user intervention. Figure 6.6 shows the application flow used during testing from the user’s perspective.

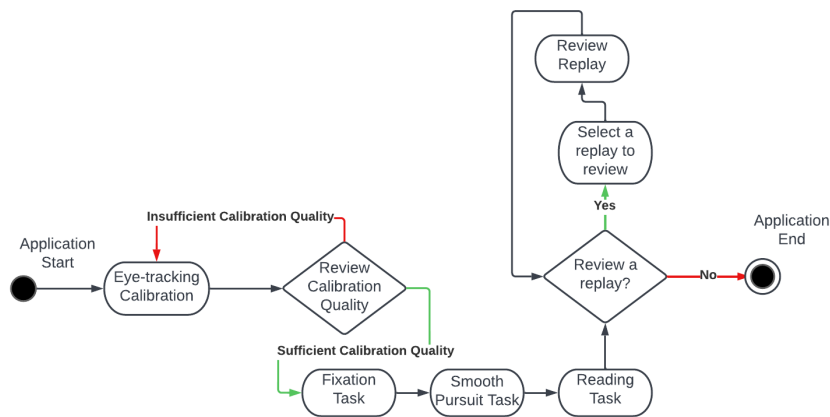


Figure 6.6: User Experience Flowchart for the laptop version of C&Look.

The first action required of the participant was to calibrate eye-tracking. Testing was done using the Tobii 4C eye-tracker, and a custom calibration method developed for this application. Once eye-tracking has been calibrated, some examples of calibration quality are displayed to the user. The assisting developer then informed the user whether recalibration was required or not.

Once calibration quality was sufficient, the user was asked to perform all three tasks in order. This began with a diagonal left to right fixation task using 2 repetitions with 5 steps. In this task, a ball moves in steps diagonally from the top left corner to the bottom right corner of the screen. Two repetitions mean the ball will move from top left to bottom right and back again two times. Five steps indicate the number of short distances the ball will move before reaching the next corner. The second task was a diagonal left to right smooth pursuit task including 2 repetitions with a duration of 5 seconds each. Similar to the previous task, the ball moves diagonally from one corner to the other with two repetitions. During a smooth pursuit task, the ball will move smoothly between its destinations rather than in steps. The duration parameter indicates how many seconds it will take for a repetition to end. The final task was a short reading task in English. Once the user is finished reading, pressing the enter key on the keyboard will end the task.

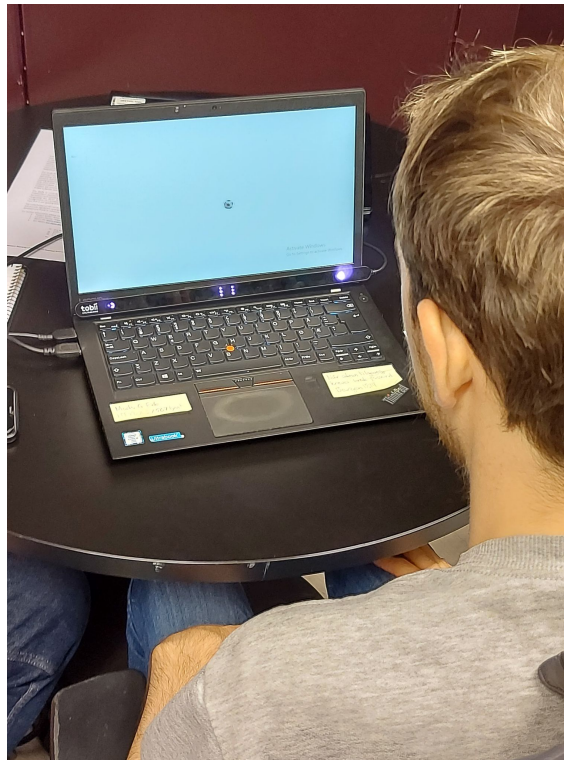


Figure 6.7: A participant performing the diagonal fixation task on the laptop.

Once all tasks were finished, the participant was asked to select a replay to review. The replays in the laptop version of C&Look contain graphs depicting their eye movements, as well as a replay with red and green dots representing their gaze points. A brief explanation of how to interpret results were given to the test subject by the assisting developer, as well as the option to review more replays if desired. Once the user was satisfied with reviewing replays, testing of the original screening application ended.

6.2.3.2 Testing the VR version of C&Look on a possible end user

As mentioned in 6.2.1, some changes and new features were implemented after the first evaluation test. Implementation details of this final version are described in 5.1, and a relevant user experience flowchart can be found here in Figure 5.2.

Similarly to when testing on a vision expert, each participant was given a short demonstration and introduction to the VR equipment. Once they were comfortable with headset positioning and using the controllers, the application was started and they were asked to register themselves as a subject. By clicking on the "Create Subject" button on the login screen, a menu for registering users is displayed. Subjects were asked to select a specific group from the dropdown menu, and enter their name in the "Subject Name" input field. Once the input field has been interacted with, an overlay keyboard is displayed which allowed

participants to write in VR through controller input. The overlay keyboard also gives the user some time to practice interaction in VR before moving on to more essential parts of the application. After a name has been entered, a "Submit" button redirects the user to the main menu.

Upon entering the main menu, eye-tracking calibration initiates. The application flow for testing in the main menu is identical to that of the first test, making each subject recalibrate eye-tracking if it fails and instructing them to do each task in the order they appear in the main menu. Names of tasks were changed for this test, as many regular users will not know what a fixation or a smooth pursuit is.

Just as in the test with the vision expert, subjects were instructed to perform each task with its base settings. Default settings of tasks were changed as discussed in 6.2.1, and the movement of objects/text to read is identical to what is used during the testing of the laptop version. Once a task was finished, the participant was instructed to return to the main menu and start the next task.

After all tasks were finished, the participant navigated to the replay section of the application. A replay was chosen from the list, moving the user to that replays respective scene. The functionality of replays remains mostly the same as described in 6.1.4.5, except for replays now being available for all possible tasks. Once reviewing of replays was finished, application testing of VR C&Look was completed.



Figure 6.8: A participant testing the VR version of C&Look.

6.2.3.3 Forms for data collection

A form related to the tested application was filled out by participants as the next step of evaluation. Unique forms for measuring user experience and usability were designed for each application separately, containing general questions and questionnaires for analysis. The form contains questionnaires designed for user experience analysis according to a benchmark for UX, and questions designed to give insight into system usability. More information on the benchmark for user experience can be found in section 2.8. The more open-ended questions allowed each participant to suggest future directions and current flaws in the application. Once the form was filled out, participants began testing the next application followed by filling out its respective form when testing was done.

After filling out forms and testing both applications, test subjects were asked to fill out a comparison form. This form asks the participant to directly compare the two applications through questions and questionnaires developed to get a better understanding of user experience within the vision screening context. After having filled out the form, a semi-structured interview was conducted where participants could give more in-depth feedback on individual applications and comparisons between them. Testing of each participant lasted approximately one hour and twenty minutes. To see the results of this test, go to section 7.2.

Chapter 7

Results

Results from evaluations described in chapter 6 are presented in this chapter. The evaluation methodology for this thesis includes two tests. The first is a test for evaluating extensions of the current screening application, C&Look on a laptop. The second is a comparative test, testing the laptop screening application against the newly developed VR version. Due to the complexity of the evaluation methodology used for this project, the data collecting methods are unique and are also presented in this chapter. Discussion around the results can be found in chapter 8.

7.1 Results from testing extensions of the current vision screening application

C&Look VR and The D2 Test of Attention provide two unique approaches to extending the screening application, and as such their results from the test are disconnected from each other. This section presents the findings for each application separately based on the interviews held with the vision expert.

7.1.1 Evaluation results: Testing the D2 Test of Attention on a vision expert

The desired outcome of testing the D2 Test on a vision expert was to get a better understanding of how and if an attention test can help separate cases of visual problems from attention problems. If this was the case, an attention test as part of the vision screening battery could help define whether a problem states from issues with attention or endurance of eye musculature. The vision expert used for testing stated that both endurance and attention are tightly connected. This results in the wandering of eye movements leading to a lack of attention, and vice versa.

The vision expert found the D2 test better suited as a searching task for visual scanning therapy. Visual scanning is a core part of visual processing, involving processing information through vision and making decisions based on that information [59]. Scanning therapy is performed when visual scanning is found

lacking, a common problem for stroke patients [14]. One technique used during treatment is visual search tasks, which include placing objects in front of the patients in a strategically organized fashion and having them select defined items. The vision expert found the current implementation of the D2 Test to be a promising design for scanning training using a computer and mentioned this as a possible direction for further development. They also mentioned the possibility of using the D2 Test as a way to quickly identify if a patient has any visual problems since problems distinguishing between formal letters such as "d" and "p" used during the test often indicate problems related to vision. Problems distinguishing between formal letters are not used to identify specific issues, but rather a more general step performed early during testing.

Some usability and user experience questions were also posed, aimed at collecting feedback that may prove useful if the application were to be developed further. The vision expert found tutorial steps to be a little difficult to read, as vision problems often correlate to difficulties with reading and writing. Giving the user more time during each tutorial step to read the text at their own pace would help mitigate this issue. Implementation of an audio-based tutorial is ideal. During testing, the vision teacher did not find the application suitable for younger children. The length and tediousness of the test would have most children lose interest before the test is finished. *"If the test was used as a form of training, such as scanning training, children would be more motivated knowing what they are doing is actively training their eyes. The possibility of running the application on a device with a touchscreen could also be beneficial to catch a child's attention."* the vision expert noted.

7.1.2 Evaluation Results: Testing a VR prototype of C&Look on a vision expert

Background information on the vision teacher's familiarity with HMDs and the original version of C&Look is important to add context behind the given answers during the interview. The vision teacher had never experienced Virtual Reality personally before the test, however, they were aware of its existence and effect on the vision science domain. When it comes to the original version of C&Look, it had not been used recently by the test person as the focus of their work has shifted from screening vision in children to vision therapy for stroke patients. The vision teacher noted that their colleague still utilized the application for screening children, but the tasks available in the application are too difficult for stroke patients to perform.

The goal of testing this early version of the application was to get a better understanding of how VR can extend the current screening capabilities that the laptop version provides. This includes getting a vision expert's perspective on the feasibility of using VR for vision screening and highlighting the possibilities and limitations.

When asked about the possible limitations of using VR, the vision expert answered that a lack of budget restricts the use of VR as a whole. Very little financial support is given to vision screening programs within the educational system, and even commercial-grade VR headsets are out of reach. Limited budget is already the reason for manual screening of vision not being done more

often, and the use of more expensive HMDs with integrated eye-tracking is not a possibility currently. If budgetary constraints were lowered, the benefit of being able to utilize larger virtual environments in small physical spaces would be ideal for screening vision. The vision expert stated that both they and their colleagues believe VR to be the future of vision screening. Another possible limitation mentioned was regarding stereo vision measurements. As the user is, in reality, fixating on the display inside of the headset and not on physical objects at different distances, it is difficult to say whether the perception of "real" depth can be measured correctly.

Regarding the potential of Virtual Reality, the vision expert suggested putting more focus on utilizing peripheral vision. The two-dimensional version is limited in screen size, and using VR to place points of interest in the peripheral could lead to a better understanding of a patient's peripheral vision. Vision problems that are related to deficiencies in this area could be highlighted to gain a better understanding of them. A task designed to test for amblyopia similar to the Eyeport¹ training device was also mentioned as a good fit for VR. The device is expensive but gives good results. Being able to achieve the same form of training within software could make the test available to more patients. The third possibility mentioned by the vision expert was an implementation of the cover test, another test designed around amblyopia. In a physical setting, this test involves covering up one eye, forcing primary usage of the "lazy" eye. By manipulating what is shown in each display on a VR headset, the same effect can be achieved. This would provide a more enjoyable experience for the patient, removing the need to wear an eye patch and not excluding the dominant eye entirely. As a final benefit of using VR, the vision expert mentioned its compatibility with children. They believed children would enjoy using VR and find the challenges it presents motivational during both training and screening. This effect was not believed to be as beneficial for adults, and as the age of the patient rises it could become a limitation when considering the time needed to teach them how to use the equipment.

Results from questions about usability were overall positive for a prototype, however, positioning and visibility of some elements were pointed out as current issues. Visual aid to help users find elements to interact with would be a welcome feature, as well as fixing player positioning². As a final remark, the vision expert mentioned interest in using a more polished version of the application for screening together with the original two-dimensional application. During this test, there was no proper usability and user experience analysis, as the number of participants was limited to one. The reason for posing these usability questions was to influence development towards the second test, where proper analysis on aspects of usability and user experience was made.

¹The Eyeport vision training system is a device designed to give results equivalent to the Brock String method. More information about the Eyeport can be found here: <https://www.bernell.com/product/JLEPV2/Brock-String-Devices>

²Note: For this test, the VR equipment had to be moved to a different location from where it was being developed. The problems with positioning likely stem from having a different room setup and possible problems with floor calculations in this new environment

7.2 Evaluation Results: Comparing user experience and system usability of C&Look in VR and on Laptop

The testing battery for the second part of the evaluation includes three different types of feedback collection, present in multiple forms. The first is questionnaires regarding user experience(UX), second is more general questionnaires about usability. The third and final type is questions with the possibility of giving long answers, as well as a conducted interview at the end of testing. Results from each feedback type are described in the sections below. Filled out forms for each participant can be found in the attached folder *TestParticipantAnswerFiles*.

7.2.1 User experience measurements

Analysis of results from the questionnaires about user experience leads to scores for attractiveness, perspicuity, efficiency, dependability, stimulation, and novelty. These measurements are calculated to be comparable with a benchmark of user experience and are described in 2.8. The questionnaire structure and analysis technique is also explained in this section. Figures 7.1 and 7.2 visualize results for each category, where maximum achievable score is 3 and lowest possible score is -3.

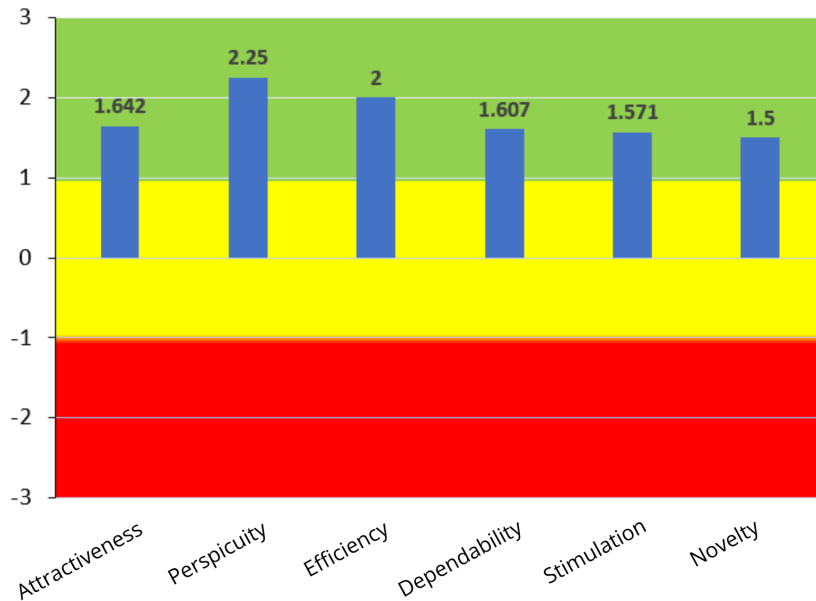


Figure 7.1: Graph of user experience scores for C&Look on Laptop, using a UEQ benchmark.

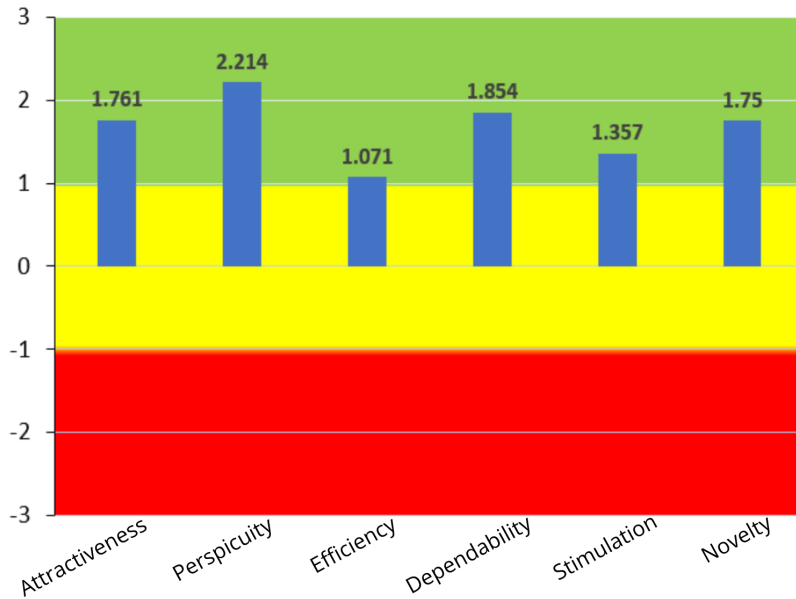


Figure 7.2: Graph of user experience scores for C&Look in VR, using a UEQ benchmark.

These results have then been compared to the benchmark for user experience scores, granting both applications a classification from excellent to bad in each category. Both applications achieve excellent perspicuity and novelty. Efficiency receives a much higher rating on a laptop than in VR, denoting performance issues in the new application. Stimulation also sees better results in the laptop version with excellent classification, although to a lesser extent. The VR version achieved an above-average score with only a difference of 0.214 between them. This signifies possible improvements to user interactivity in VR. Attractiveness and dependability see an increase from good to excellent when going from laptop to VR, meaning a better overall impression and feel of control. Perspicuity for both applications has similar scores, however the VR application scores 0.25 points higher than the original screening application in novelty. Scores and classifications for both applications can be found in Figure 7.1 and 7.2.

Category	Attractiveness	Perspicuity	Efficiency	Dependability	Stimulation	Novelty
Value	1.642	2.25	2	1.607	1.571	1.5
Classification	Good	Excellent	Excellent	Good	Excellent	Excellent

Table 7.1: Category classification results: C&Look on Laptop.

Category	Attractiveness	Perspiciuity	Efficiency	Dependability	Stimulation	Novelty
Value	1.761	2.214	1.071	1.854	1.357	1.75
Classification	Excellent	Excellent	Below average	Excellent	Above average	Excellent

Table 7.2: Category classification results: C&Look in VR.

7.2.2 Calibration quality and comparison with manual screening

Within the comparison form presented in evaluation step two, each participant filled out five questionnaires. The first questionnaire compares the calibration methods of both applications. Possible answers range from 1, difficult, to 7, very easy. The final four questionnaires specifically state that the focus should be on comparing elements of both applications to expectations of manual vision screening. Scores in these questionnaires range from 1 to 7, where 7 stands for evaluations corresponding to situations at a place for testing your eyes by a professional, and 1 is the opposite. Of these four questionnaires, one contained questions about the general user experience. The other three were task-specific, one for each performed task.

7.2.2.1 Calibration Experience

Calibration methods for each application are different. The original laptop version uses a custom-made calibration screen, while the VR version utilizes the Varjo SDK’s legacy calibration method. When asked to compare their experiences using these methods, scores were very similar with the laptop version coming out slightly ahead. The average score for the custom calibration was 6, while the Varjo Legacy calibration achieved an average of 5.85. Scores given by each participant for both applications are visualized in Figure 7.3.

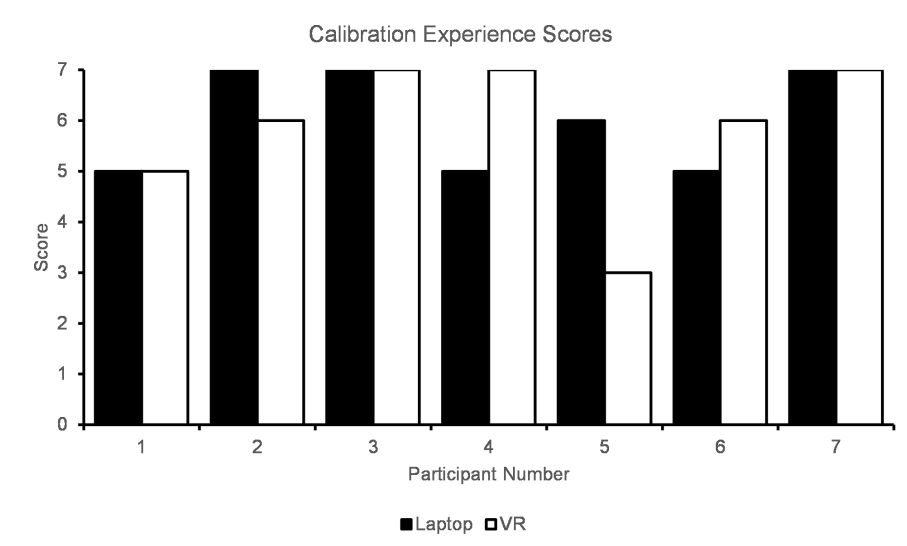


Figure 7.3: Calibration experience scores.

7.2.3 Comparison of experience to expectations for manual vision screening

When asked to compare their overall experience to manual screening techniques, participants found the VR experience to be the most similar. Average scores were higher for the new application in every measured aspect, except for comparison with real memories. Both applications have high averages for all scores, as seen in Figure 7.4

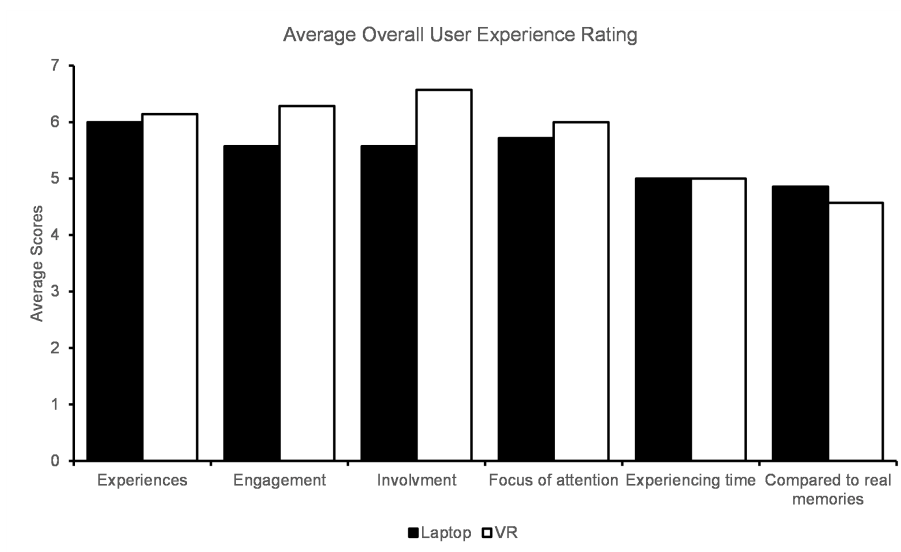


Figure 7.4: Average scores for overall similarity of experience.

7.2.3.1 Similarity of task performance to testing in a professional setting

The final three questionnaires were used to visualize each task's similarity to experiences in a professional vision screening setting. For each task, four measurements were made. "Eye tiredness" measures how tired the participant's eye muscles were compared to manual screening. "Move your eyes" gives an indication of how much freedom the participant felt they had in their eye movements. "Interaction with the environment" describes the feeling of interactivity compared to a real screening, and "Follow instructions" indicates similarity in displayed instruction quality. Tasks in VR have a higher average similarity to real screenings in almost every metric, most notably interaction with the environment in the fixation and smooth pursuit tasks as seen in Figure 7.5 and 7.6. Figure 7.7 shows that participants found the reading tasks most comparable to similar procedures performed at manual screenings.

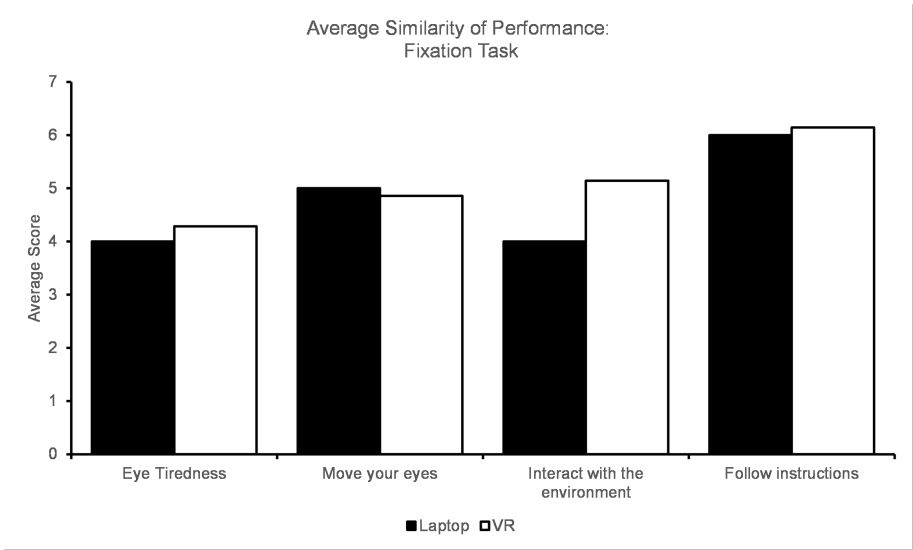


Figure 7.5: Average similarity scores of the fixation tasks.

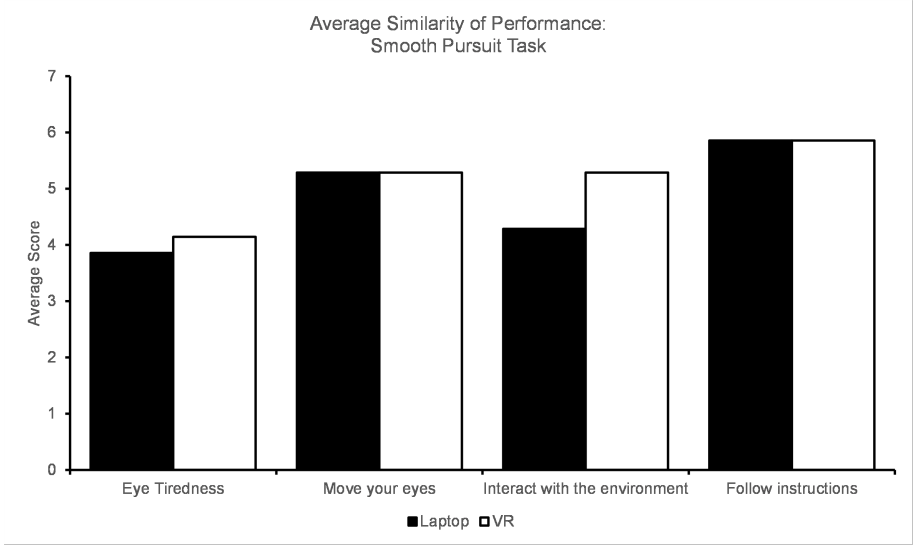


Figure 7.6: Average similarity scores of the smooth pursuit tasks.

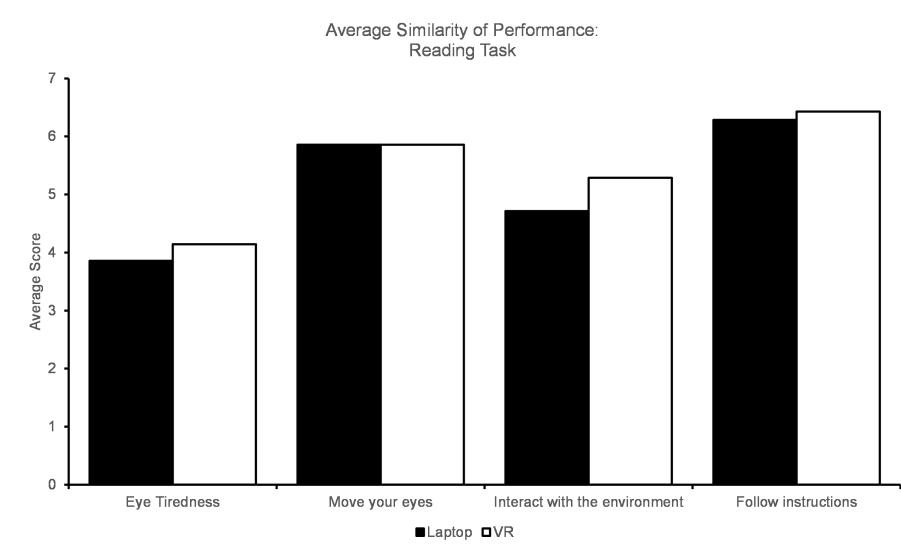


Figure 7.7: Average similarity scores of the reading tasks.

7.2.4 Relevant feedback from interviews and form questions

Answers to open-ended questions and interviews help evaluate elements that are specific to the two examined applications. Participants describe both systems as easy to navigate, and the quality of user interaction sufficient. Suggested changes and specific feedback were given for both, highlighting areas that can be improved.

7.2.4.1 Suggested changes and specific feedback for the laptop application

The laptop version received high praise for its presentation of results and replays. When asked about what aspects they enjoyed the most from each application, one participant said *"I really enjoyed being able to see my results clearly and with a high level of detail in the laptop application."* This expresses an appreciation for the graphs and other elements used to visualize results, suggesting a similar feature would be desirable in VR. The reliability of the laptop application was also described as better than the VR version, with more general confidence in the results. Some participants found the presentation on a laptop to be too "sterile", wishing for a more creative design with more colors. All tasks were well perceived, except for one subject suggesting more interesting text for the reading task. A test subject suggested the implementation of features for regular vision tests, not screening, as younger people may have issues expressing desires to be tested for visual issues.

7.2.4.2 Suggested changes and specific feedback for the VR application

While a lot of positive feedback was given to the presentation and confidence of results in the original screening application, participants found VR more fun and interactive. One participant stated *"On the practical side I prefer desktop, as it is easier and more stable, but for my kid, I would prefer VR as it could be more exciting to use"*. This indicates that children could find it more enjoyable and that some parents would like to use virtual environments to screen their children. The addition of an immersive experience lead to some participants being more focused during testing, as outside distractions were less noticeable. Perception of depth was also well received, increasing the immersive effect of VR, although one participant said they wanted more objects in each scene to highlight this aspect. Regarding negative feedback, most users experienced some performance issues in the smooth pursuit task, indicating a need for optimization of this task. Some also found the objects to focus on too large for fixation and smooth pursuit. Positioning of the player while performing tasks was a divisive topic, as some participants felt they were too close, while others felt they were too far away. The calibration method also got varied feedback, as users that wore glasses had trouble calibrating eye-tracking in VR, while users that did not found calibration in VR easier than on the laptop. A younger participant of the study suggested adding more background environments for tasks to make them stand out and implementing user customization of the objects that are part of the fixation and smooth pursuit tasks.

Chapter 8

Discussion

This chapter contains a discussion of the results detailed in the previous chapter. Consideration of the application itself and its potential improvements are also a focus of this part of the thesis.

8.1 Extending the current screening application

The original version of C&Look is a validated tool that has been utilized by vision experts during screening. As stated in chapter 3, this research aims to extend this application while focusing on the thesis' research questions stated in 1.2.

8.1.1 Separating attention problems and visual problems

As stated in section 7.1.1, the vision expert mentioned that visual endurance and attention are tightly connected. Wandering in eye movements due to visual problems may lead to a lack of attention, and the same is true in the opposite direction. Since these aspects are so tightly connected, measuring them separately seems to be a very difficult task. The vision teacher's response suggests that an additional application or task such as the D2 Test for measuring attention would not be enough. If a test subject receives poor results when testing for the focus of attention, the problem could be with their eyesight and not attention span. This solution would simply move the problem of separating these measurements from one test to another.

A different approach of measuring a user's visual attention instead of their ability to focus for long periods may instead prove a useful extension to the current screening application. This form of test would not separate eye muscle exhaustion from the possibility of focusing for an extended duration, however, testing and training of visual attention are tightly connected to oculomotor readiness [57]. This integrates well with the original C&Look application's goal of screening OMD-related visual problems, and can be an alternative way to identify whether poor results originate from attention or visual problems using a different metric. Quantitative measures of visual attention can be made using

a Usable Field of View test, which is also suitable for training processing speed [12]. This could be considered when deciding on the future direction for research and development.

The results from testing the D2 test application indicate a different use than measuring focus of attention. By changing the focus of this implementation, the test could be turned into a form of scanning training or an initial step for identifying if any visual problems are present. This would include adding support for eye-tracking hardware and gaze data collection within the application. As being able to distinguish between the focus of attention and vision problems through this implementation seems unlikely, utilizing it for a different purpose via minor adjustments seems a better future direction. This extends to the VR version as well, although it would not be possible for the Focus 3 without additional hardware.

8.1.2 Utilizing VR to further assist the current vision screening battery

An apparent limitation of the evaluation with the vision expert was the fact that they did not have recent experience with the laptop version of C&Look. This may have affected the results regarding how VR can help extend this application, as familiarity with a product helps identify its shortcomings. For possible areas where VR could accomplish new tasks, the vision expert put a lot of focus on the ability to better understand a patient's peripheral vision. This could be accomplished by implementing a type of visual field test such as the confrontation test [60]. This test includes a patient fixating on an object directly in front of them, while information is being displayed in the peripheral field of view. Information should then be relayed back, the quality of a patient's peripheral vision being measured by the response. One eye is covered for the duration of the test. Contemporary research [30] shows that this testing method is well suited for VR, resulting in high-quality measurements of visual field defects. An implementation of this test in the VR C&Look application could further assist the current vision screening battery.

Amblyopia testing was also mentioned as a shortcoming of the laptop application, which a VR version has the possibility of overcoming. Two approaches were suggested for this, a similar task to what is provided by the Eyeport vision training system, and a version of the cover test. For a possible implementation of amblyopia testing similar to the Eyeport device, the main advantage would be reducing the cost of performing the test. The Eyeport provides a unique testing method based on the Brock String, and how similar implementation could be to this version introduces licensing and copyright issues. A better approach may be to implement a test based more closely on the original Brock String, as it is a common technique used by vision teachers and not a commercial product such as the Eyeport. For the cover test, its compatibility with VR is well documented [79] [77] [43]. This could be another possible further direction for the VR application to take.

After examining the measuring of hand-eye coordination through experimental development, the current state of hand-tracking technology provided by the Varjo VR2-Pro was deemed unreliable for testing purposes. A study on

utilizing hand-tracking for hand-eye coordination rehabilitation [54] describes this technology being used to great effect with a similar purpose, however, no relevant studies using Varjo’s hand-tracking hardware could be found. If hand-tracking-based hand-eye coordination measurements are to be made within the VR version of C&Look, different hardware with documented validity within the relevant research domain should be considered.

8.2 The state of user experience in the VR application

For evaluating the user experience, a limiting factor of the test was the number of participants available. 20-30 participants are described to provide a stable measurement when using this UX evaluation method [52], but as each test lasted about an hour and 20 minutes this number of participants was not feasible. Gathering that amount of people for testing would already have been a difficult task, and 7 participants were deemed sufficient by the project lead. The UX measurement approach was selected since it provides details on how different aspects of the application compare to other products on the market, and is also suitable for the comparison of specific products. Another limitation of the evaluation is that three of the participants were friends of the developer, constituting about half of the participant pool. These participants were specifically instructed to give honest answers, however, this does not eliminate the possibility of some level of bias. Familiarity may also influence a participant towards giving honest feedback, but how either of these aspects affected results is an unknown factor.

An important advantage of VR is the added sense of presence and depth it can bring to an application. The quality of the entire user experience is important when considering added immersive effects of VR, as low-quality UX can lead to the user being "taken out" of the experience. The results of the user experience analysis presented in section 7.2.1 show that both applications give a high-quality experience, one notable exception being the efficiency of the VR version. This is further echoed by some users stating that they were experiencing performance issues with the smooth pursuit task, making it likely these results are connected. This was not an issue during the original development of the task, and testing after evaluation discovered that this issue originates from the temporary XR plugin provider solution described in 5.1.1.1. No fix to this issue has been implemented and comes from a limitation of the Varjo Unity SDK. A possible solution would be to develop a new overlay keyboard or purchase one from the Unity Asset Store. As the evaluation and development of the application were finished, this fell outside of the scope of this project. Stimulation also received a lower classification than the original application. This indicates more possible user interactions and visual differences could add to the experience, however, the score is very similar to that of the laptop version.

For calibration experiences, results from each user are more varied than any other measurement. Both calibration methods end up with a similar average score, indicating a clear difference in preference for some participants. This is explained by that users with glasses had trouble calibrating in VR, and one user

who specifically mentioned this in the interview gave the VR calibration a score of 3. Some other participants stated that they preferred VR calibration as it was faster than custom calibration on the laptop. Incompatibility of eye-tracking in the headset with users that wear glasses presents a limitation of the Varjo HMD.

Results from comparing the applications to expectations of manual screening described in 7.2.3 show that participants found VR more representative of real-life screening. This highlights the added benefits of immersion that VR brings, with users feeling as if they are in a professional screening setting. One participant mentioned that they were more focused when testing in VR, as outside distractors were less noticeable. By increasing the level of focus during screening, a test person's results may improve. This can offer a better testing experience for participants with attention-related disorders such as ADHD or ADD, and possible future rehabilitation tasks may also benefit from increased focus.

8.3 Current Limitations

Experimentation on measuring stereo acuity levels led to a realization of the necessary complexity required for proper implementation. Representing fine angles down 40 seconds of arc in VR is certainly possible, as demonstrated by VividVision [4], however, the difficulty of implementation made this aspect fall outside the scope of this project. The secondary option became to develop a version of the Titmus Fly test, described in section 2.6.2. This requires a less fine angle of 400 seconds of arc. The problem with such an implementation is that it would require a highly detailed model of a fly, and the limitation that no developer working on this project had extensive experience with 3D modeling made it infeasible. If such a model is acquired in the future, this test should be considered. Hand-tracking technology could be utilized to interact with the fly, as the consistency of interaction would not be as important as when attempting to measure hand-eye coordination.

Many limitations of the Varjo VR2-Pro HMD were discovered throughout the development of the VR C&Look application. Varjo Base would not allow for pairing of multiple types of controllers with the headset, and as a result, new VIVE controllers were purchased as these were specifically mentioned on the compatibility website [68]. The pairing of these controllers was also an issue, confirmed by communicating with another developer in a secondary location using the same hardware. This indicated that the issue lies with Varjo Base and not the setup, requiring direct support from Varjo. This process slowed down the project, with an update to Varjo Base not being available until four months after initial communication.

Another limitation comes from the available documentation for the Varjo Unity SKD. Only a few short web pages containing some documentation and examples are available [66], and as a result of Varjo being a relatively uncommon HMD provider related online resources are sparse. This induced a lot of trial and error during development, with the only content available when debugging of Varjo specific features was sparse comments of vague explanations for method functions and data structures.

Gaze data quality was also a limitation discovered when recording eye movements with this HMD. This data is collected every frame and is stored in the database as objects of Varjo's data structure with queries constructed by a well-known object-relational mapper. The result still ends up with sizable chunks of missing gaze data, and when using Varjo's own live gaze visualization technique this problem can be seen at runtime. These results indicate an issue with the eye-tracking hardware in the headset, however, to be certain of this the application would have to be tested on a different HMD with integrated eye-tracking.

Chapter 9

Conclusion and Future Work

This chapter summarizes the findings of this thesis concerning its research questions and motivations. These conclusions are made based on results from evaluating a Virtual Reality implementation of C&Look and browser-based attention test, and discussion around these results with relevant literature. Description of current limitations and suggestions for future directions are also presented here.

9.1 Conclusion

Motivation for this thesis comes from a desire to better support the detection and rehabilitation of functional vision problems as stated in section 1.1. By using VR and measurements of focus of attention, we hoped to gain a better understanding of how these technologies and techniques can be utilized to aid vision screening. There are still more questions and considerations to be made on this topic, however, some insight has been gained into the possibilities and limitations of these approaches.

The research questions for this thesis were as follows:

- RQ1: How can VR technology be utilized to assist the current vision screening battery?
- RQ2: How can we measure attention to verify that poor results from vision tests are correctly attributed to vision problems?

RQ1 is considered to be partially answered, as experimental development and evaluation have highlighted the advantages and difficulties of this method. Virtual Reality adds a feeling of presence which makes the experience feel more like a professional screening, decreasing the number of outside distinctions which may help users focus on the tasks in front of them. Experimental task development lead to the realization of the difficulties posed by measuring stereo acuity and hand-eye coordination via a Head Mounted Display. Available literature shows that stereo acuity can be measured using VR, however, no proper

task for this could be made for this project and its integration with eye-tracking could not be analyzed. The current stage of hand-tracking technology seems too inconsistent to confidently be used for measuring hand-eye coordination. Consultation with a vision teacher highlights VR's ability to test amblyopia and visual field, providing more coverage of the screening process which a laptop application can not. A comparison of user experience in 2D and 3D screening applications indicates that the developed application for this study is considered usable, although some performance issues should be addressed.

Some insight into RQ2 has been gained, as it has highlighted the limitations of the D2 Test of Attention for measuring the focus of attention together with C&Look. The approach of using both of these applications in conjunction relies on complete separation of measurements for focus and eye-muscle work, however, C&Look does not claim to produce objective eye-muscle measurements. Collecting such accurate measurements through eye-tracking is complex [11], and a different approach of measuring visual attention offers a way to verify whether poor results relate to vision problems or attention[31]. Implementation of a screening task based on researched solutions for screening Visual Attention through a Usable Field of View test [12] could help inform where poor results stem from attention or vision problems. This test is also documented to be tightly connected to oculomotor readiness[57].

In summary, VR technology provides great promise for assisting the current vision screening battery, and the different elements of a laptop-based screening application translate well to a virtual 3D environment. The possibility of measuring some new parts of the vision screening battery looks promising, however, their implementation is complicated and would require a project of a larger scale with more development time. Contemporary research shows that screening and training of stereo acuity using contour tests in VR is possible, with Vedamurthy et al. [71] demonstrating a training technique in VR and VividVision [4] illustrating a screening approach. As stated in section 5.1.5, implementation of one of these researched contour tests requires extensive knowledge in 3D modeling for a detailed fly model, or a more powerful HMD which can smoothly render a complicated mesh of a sphere. A way to separate functional vision problems and loss of focus evaluations to see correlations between these by using the available technologies and measurements has not been discovered in this project, and discussion with a professional within the visual field has only led to skepticism around the possibility of utilizing the D2 Test. At the present stage, finding trustworthy evidence for the correlation is not enough to compare measurements on the effects of lacking focus with the effects of possible OMD problems. Several issues need further investigation, e.g., concrete eye-muscle measurements during eye-movements, reasons for OMD or attention problems, and the effectiveness of a visual attention screening test in C&Look to identify the origin of poor results.

9.2 Future Work

The current VR C&Look application was deemed usable as seen in the results of UX analysis, however, some performance issues are noticeable and should be developed further. Some more technical debt has been accrued from its

reliance on local server hosting and is another area for possible improvement. For future implementation direction, the author of this thesis suggests attempting the development of a visual field screening task, which has been validated to be effective when combined with VR by Mees et al. [40]. This could be followed by an implementation of a new task for visual field training in the form of scanning training which has also seen good results when performed on HMDs [49]. The addition of more interactive elements or tasks would also be ideal for increasing the user's level of stimulation, and other forms of visualization for gaze data results such as the graphs present in the original application could help better convey the quality of results.

This study explored the difference in experience between screening vision on a laptop and in VR. Comparison of results from mobile eye-trackers and HMD integrated eye-trackers, such as eye-tracking sensitivity and specificity of collected measurements, was not explored in this project. This is another important aspect for collecting objective measurements through assisting eye-tracking technologies [28] and should be a focus for future research.

Since several limitations of the project are tightly connected to the used eye-tracking in the HMD, and especially because of eye-tracking hardware in the Varjo VR2-Pro provides low-quality data. For precise eye-movement data measures several technical aspects should be taken into consideration. For example, producing results with a high level of confidence, the quality of gaze data must be high enough to measure minor eye movements. This fact along with other drawbacks of the Varjo HMD described in Chapter 8.3 makes a strong motivation for replacing this VR headset, with options producing quality eye measures available on the market [56].

The D2 Test of Attention does not seem suitable for combination with a vision screening application as a result of the difficulty posed by separating these issues. As stated in 7.1.1, focus of attention is tightly connected to problems with eye musculature, and the D2 Test's reliance on exact data of eye-muscle work. It is suggested in this work to repurpose this test as a form of scanning training instead, which could be done both on a laptop with the original version of the D2 test, or on a HMD by using the newly implemented VR D2 Test. The implementation of a visual attention screening test such as the Usable Field of View test would be better suited for finding the origin of poor results[31]. This test should be rethought in relation to visual attention, validated and integrated as a part of the VR screening application.

Appendix A

Source code

The source code for the VR version of C&Look and D2 Test is available at this URL: <https://github.com/Aredae/candlook-vr-testproject-master>.

A demonstration video of the VR C&Look application can be found here: https://drive.google.com/file/d/1xzLmmCy_eHV4IM-hkN8Id4UpN5hLticx/view?usp=sharing

Appendix B

Assets

Name	Creator	URL
Texture soccer ball	Anton Sokolov	https://www.dreamstime.com/stock-images-texture-soccer-ball-image13533294
Free Arcade Asset Pack	Ferocious Industries	https://assetstore.unity.com/packages/3d/props/free-arcade-asset-pack-123704
2D Atlas Speech bubbles Alphabet Numbers	RAFMANIX	https://assetstore.unity.com/packages/2d/environments/2d-atlas-speech-bubbles-alphabet-numbers-88398
15 low poly models	Rob lu	https://assetstore.unity.com/packages/3d/props/15-low-poly-models-202061
2D Casual UI HD	MiMU STUDIO	https://assetstore.unity.com/packages/2d/gui/icons/2d-casual-ui-hd-82080
Arm Chair	Mario Haberle	https://assetstore.unity.com/packages/3d/props/furniture/arm-chair-80384
Big Furniture Pack	Vertex Studio	https://assetstore.unity.com/packages/3d/props/furniture/big-furniture-pack-7717
Buttons Set	KartInnka	https://assetstore.unity.com/packages/2d/gui/buttons-set-211824
Free HDR Sky	ProAssets	https://assetstore.unity.com/packages/2d/textures-materials/sky/free-hdr-sky-61217
FREE Suburban Structure Kit	Ferocious Industries	https://assetstore.unity.com/packages/3d/props/free-suburban-structure-kit-142401

Jammo Character Mix and Jam	Mix and Jam	https://assetstore.unity.com/packages/3d/characters/jammo-character-mix-and-jam-158456
Minimal UI Sounds	cabled_mess	https://assetstore.unity.com/packages/audio/sound-fx/minimal-ui-sounds-78266
Office Room Furniture	Elcanetay	https://assetstore.unity.com/packages/3d/props/furniture/office-room-furniture-70884
Picture frames with photos	3Dfrk	https://assetstore.unity.com/packages/3d/props/interior/picture-frames-with-photos-106907
Pictures Mini pack	Tatiana Gladkaya	https://assetstore.unity.com/packages/3d/props/furniture/pictures-mini-pack-194762

Table B.1: Free assets used during development

Appendix C

Interview Questions and Topics, Testing on a Vision Expert

C.1 Interview questions regarding the D2 Test

- Q: Did the tutorial presented to you in the beginning of the D2 Test help you complete the test? Why, why not?
- Q: Do you think the D2 Test or another form of testing for focus of attention could help during a vision screening?
- Q: Would you utilize the D2 Test in conjunction with C&Look for vision screening.
- Q: Do you think the D2 Test of Attention could be suitable for testing the attention of children?
- Q: Do you think the D2 Test could help separate cases of visual problems and attention problems?
- Q: Do you think an attention test could help define whether a problem stems from issues with attention or endurance of eye muscles?

C.2 Interview questions regarding C&Look in VR

- Q: Do you know of any other use of VR in the domain of vision screening? Have you ever used or wanted to use any such screening programs?
- Q: How much time do you spend using C&Look when performing vision screenings?
- Q: Would you like to utilize a VR version of C&Look?
- Q: What do you think are some limitations of screening vision in VR?
- Q: What options would you like to have available in a VR version of C&Look? Where do you see the most potential?
- Q: How was the usability of the VR version of C&Look? Anything that should be improved.
- Q: What do you think are some of the advantages of screening in VR?

Appendix D

Files of the Testing Battery Used for the Second Evaluation Test

PDF Studio - PDF Editor for Mac, Windows, Linux. For Evaluation. <https://www.qoppa.com/pdfstudio>

Virtual Reality, Simulations, Serious Games and Eye-Tracking (XR-ET)

How do XR-ET technologies complement today's vision screening and training?

A well-documented problem in vision and eye care is the lack of attention to vision diagnostics for children. Vision specialists (eye-care practitioners) are few and do not have enough resources to screen all school-aged children or help them with continuous training if needed. This screening is time- and resource-demanding and rarely includes the screening of children's functional vision [1]. The resources allocated to train the eyes, if needed, almost do not exist. The last mandatory health control at the age of 4-5 includes vision screening, while in contrast, their sight is still under development when they begin school. 25-30% of school-aged children have vision problems [2], and up to 85% of them were not detected before [3, 4]. Vision impairments can cause later impediments in academic success, education system, public health system, and social well-being [5].

The study XR-ET (hereafter, the Study) "How do XR-ET technologies complement today's vision screening and training?" aims to provide a better understanding of how XR-ETs support vision problems. The initial focus is on identifying and helping specific functional vision disturbances. The first step is to identify state-of-the-art research and development projects to increase knowledge about screening and training school children with existing technologies. The next is to test and develop XR-ET solutions to support the vision. This support cannot only come from technology development but has to be anchored with various groups involved in supporting children's health and education. The robustness, trust, and continuous availability of support for all school-aged children are essential. The long-term goal is to contribute to knowledge about integrating XR-ET technologies usable in health, schools, families, and other environments responsible for eye health.

The Study is cross-disciplinary and addresses the vision problem holistically by tackling the network of stakeholders' responsibility from children's health care (parents, school teachers, school nurses, vision care specialists) and soliciting participation for real-life demonstration of feasibility. Investigating the possibility of integrating the XR-ET technologies into social, institutional, and economic contexts to obtain a working configuration of a scalable person-centric health monitoring solution will contribute to children-centric vision care that is not existing today.

The stakeholders in the current study are *Høgskulen på Vestlandet (HVL, Bergen, Norway)*. The research project will provide significant synergies from collaboration, and we will work on applying for European research and development funds to continue. Initial contacts to build up a consortium have already been made.

For further information please contact:

- Project leader: Ilona Heldal, ilona.heldal@hvl.no
- Carsten Gunnar Helgesen, carsten.helgesen@hvl.no
- Qasim Ali, qasim.ali@hvl.no
- Are Dælen are.daelen@hvl.no

- [1]. Ali Q, Heldal I, Helgesen CG, Krumina G, et. Al. Current Challenges Supporting School-Aged Children with Vision Problems: A Rapid Review. *Applied Sciences*. 2021.
- [2]. EuroSTAT, *Correction of Vision Problems by Sex, Age and Degree of Urbanization*. 2014.
- [3]. Johnson, R., R. Blair, and J. Zaba. *The visual screening of title I reading students*. *J Behav Optom*, 2000. **11**(1).
- [4]. Falkenberg, H.K., T. Langaas, and E. Svarverud, *Vision status of children aged 7–15 years referred from school vision screening in Norway during 2003–2013: A retrospective study*. *BMC ophthalmology*, 2019. **19**(1).
- [5]. Zaba, J.N., *Children's Vision Care in the 21st Century & Its Impact on Education Literacy, Social Issues, & The Workplace: A Call to Action*. *Journal of Behavioral Optometry*, 2011.

Virtual Reality, Simulations, Serious Games and Eye-Tracking (XR-ET)

Approval of participation: How do XR-ETs complement today's vision screening and training?

Høgskulen på Vestlandet (HVL, Bergen, Norway) is conducting a research study on the use of new technologies and computer games in vision screening and training. The name of the study is "How do XR-ETs complement today's vision screening and training?" and hereafter referred to as "the Study."

The aim of this Study is to find requirements for further development and use and identify concrete practices that show under what conditions and how XR-ETs can complement today's vision screening and training. For this, several different tests with different stakeholders are planned. The results will be used for further research.

The Study is conducted in accordance with the rules set out in the Personal Data Act (1998:204). The methods used for data collection are not invasive or harmful to the participant. All personal data will be treated confidentially. Personal data will be stored in a separate file and protected with a password and login, accessible only to the project leaders. Collected results from the tests and observations, including pictures, video, and screenshots, will only be used in related research.

About my participation

I agree that the following conditions apply to my participation in the Study.

1. I have read and understood the information I have received about the Study.
2. I understand that my participation in the Study is voluntary, and I may choose to discontinue it at any time.
3. I accept that I am not entitled to compensation for my participation in the Study.

Yes. I want to participate in the Study.

No. I don't want to participate in the Study.

Phone: _____

Email: _____

Full Name: _____

Signature: _____

Date and location: _____

Figure D.2: Consent Form.

Date: ___/___/___
Participant no:

Background in vision screening, vision training and technology use
Virtual Reality, Simulations, Serious Games and Eye-Tracking (XR-ET)

1. Please write down your: Age Gender Occupation: _____
F-Female, M-Male

2. Have you participated in vision screening earlier (except for the obligatory screening at the age of 4-5)?

If no (mark with X)

If yes, please describe when and how (e.g., 2020 at an optician because you wear glasses/lenses)

.....
.....

If yes, how many screenings have you been on in total (approximate with a number)?

3. Have you participated in vision training (training of your eyes) earlier?

If no (mark with X)

If yes, please describe when and why

.....
.....

4. How often do you play computer games? Please mark the correct one

Every Day Weekly Monthly/Infrequently Never

5. How often do you use any of the following?

Please select one option in each row

	Never	Some time in a year	Few times for month	Sometime weekly	Several times weekly
Games on mobile	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Games on computer	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
XR-ET	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>

XR-ET = Virtual Reality, Simulations, Serious Games and Eye Tracking technologies

A. If you play computer games, please describe your favorite games:

.....

Figure D.3: Background Form Page 1.

Participant no:

Virtual Reality, Simulations, Serious Games and Eye-Tracking (XR-ET)

B. If you have developed computer games before, please indicate the aim(s) or intended use:

.....

C. If you used XR-ET technologies earlier: Please indicate your experiences (e.g., developed, tested, seen before, recreational use)

Virtual Reality

Simulations and Serious Games.....

Eye Tracking

6. Have you ever used XR-ET for screening something? If no, mark with X:

If yes, please indicate the most used ones:

Name (approximately) or the aim of the application (e.g., evaluating measuring some capacity)	Technology (e.g., with a work application)	Approximate how many times you used it? (e.g., 2)

7. Have you ever used XR-ET for personal training (e.g., a health application)? If no, mark with X:

If yes, please indicate the most used ones:

Name (approximately) or the aim of the application (e.g., serious games for fitness)	Technology (e.g., on mobiles)	Approximate how many times you used it (e.g., 5)

8. Do you think XR-ET can be used to screen vision? Please answer and motivate

.....

9. Do you think XR-ET can be used to train eyes? Please answer and motivate

.....

10. Do you see any risks with XR-ET training:

.....

Figure D.4: Background Form Page 2.

Date: __/__/

After C&Look on Laptops: Vision screening, vision training and technology use

Participant no:

Virtual Reality, Simulations, Serious Games and Eye-Tracking (XR-ET)

Usefulness and UX after screening with C&Look on a Laptop

Please answer (by summarizing your opinions):

1. What is your first impression of the used product?

2. What is your first impression of using eye-tracking (ET) technologies?

- About calibration?

- About utilizing ET?

3. What is your first impression of the used games?

4. About the usage in context

4.1. Would you use it to screen your eyes by professionals? Mark with X, if yes

Why or why not?

4.2. Would you use it by yourself? Mark with X, if yes

Why or why not?

5. Please summarize your opinions

5.1. Regarding the *functionality* of the technology (input, output, responsiveness)

5.2. Regarding *design* (colors, sizes, icons used, available information)

5.3. *Interaction* (possibilities to orient, navigate in the application or manipulate objects)

5.4. Other thoughts:

Figure D.5: Laptop User Experience Form Page 1.

The following questionnaire consists of pairs of contrasting attributes that may apply to the product (technology and application).

The circles between the attributes represent gradations between the opposites. You can express your agreement with the attributes by ticking the circle (making a "x") that most closely reflects your impression.

Example:

Attractive	<input type="radio"/>	<input checked="" type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	Unattractive
------------	-----------------------	----------------------------------	-----------------------	-----------------------	-----------------------	-----------------------	-----------------------	--------------

This response would mean that you rate the application as more attractive than unattractive.

Please decide spontaneously.

Don't think too long about your decision to make sure that you convey your original impression. It is your personal opinion that counts. Please remember: there is no wrong or right answer!

Observe! The comments are not ordered from bad to good or vice versa.

6. Please assess your overall experience of the product by ticking one circle per line:

	1	2	3	4	5	6	7		
annoying	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	Enjoyable	1
not understandable	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	Understandable	2
creative	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	Dull	3
easy to learn	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	difficult to learn	4
valuable	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	Inferior	5
boring	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	Exciting	6
not interesting	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	Interesting	7
unpredictable	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	Predictable	8
fast	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	Slow	9
inventive	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	Conventional	10
obstructive	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	Supportive	11
good	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	Bad	12
complicated	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	Easy	13
unlikable	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	Pleasing	14
usual	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	leading edge	15
unpleasant	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	Pleasant	16
secure	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	not secure	17
motivating	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	Demotivating	18
meets expectations	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	does not meet expectations	19
inefficient	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	Efficient	20
clear	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	Confusing	21
impractical	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	Practical	22
organized	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	Cluttered	23
attractive	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	Unattractive	24
friendly	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	Unfriendly	25
conservative	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	Innovative	26

Thank you for your participation!

Figure D.6: Laptop C&Look User Experience Form Page 2.

Date: __/__/

Comparing Laptop and VR: Vision screening, vision training and technology use

Participant no:

Virtual Reality, Simulations, Serious Games and Eye-Tracking (XR-ET)

Presence and performance for C&Look in VR

Please answer (by summarizing your opinions):

1. What is your first impression of the used product?

.....

2. What is your first impression of using eye-tracking (ET) technologies?

- About calibration?

.....

- About utilizing ET?

.....

3. What is your first impression of the used games?

.....

4. What is your first impression of the used VR?

.....

5. About the usage in context

4.1. Would you use it to screen your eyes by professionals? Mark with X, if yes

Why or why not?

4.2. Would you use it by yourself? Mark with X, if yes

Why or why not?

6. About the different games

6.1 Was the visibility for each game sufficient? If not, what was the issue? (e.g., too close, too far, too low, too high, the field of view, other)?

The Soccerball:

.....

The basketball:

.....

Reading:

.....

6.2 Did being in a virtual 3D environment affect your enjoyment while playing the games? How?

.....

Figure D.7: VR C&Look User Experience Form Page 1.

6.4 How did you experience *depth*?

.....

6.5 How did you feel about the *design* of the task when you reading? (text font, text size, text color, background)

.....

6.6 Were you satisfied with the performance of the different games?(Responsiveness, image quality, etc)

1. The soccerball

.....

2. The basketball

.....

3. Reading

.....

6.7 Was the information presented before a game started sufficient to understand what you were supposed to do during the game?

.....

7 About navigation and menus

7.1 How could you get to where you wanted (*navigate*) in the application?

(using button names, interaction in menus, use of controllers)

.....

7.2 How could you *orient* the application? (Login, main menu, specific task)

.....

7.3 How was your experience with logging in to the application? (Type in name, select correct group)

.....

Figure D.8: VR C&Look User Experience Form Page 2.

The following questionnaire consists of pairs of contrasting attributes that may apply to the product (technology and application).

The circles between the attributes represent gradations between the opposites. You can express your agreement with the attributes by ticking the circle (making a "x") that most closely reflects your impression.

Example:

Attractive	<input type="radio"/>	<input checked="" type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	Unattractive
------------	-----------------------	----------------------------------	-----------------------	-----------------------	-----------------------	-----------------------	-----------------------	--------------

This response would mean that you rate the application as more attractive than unattractive.

Please decide spontaneously.

Don't think too long about your decision to make sure that you convey your original impression. It is your personal opinion that counts. Please remember: there is no wrong or right answer!

Observe! The comments are not ordered from bad to good or vice versa.

8. Please assess your overall experience of the product by ticking one circle per line:

	1	2	3	4	5	6	7		
annoying	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	Enjoyable	1
not understandable	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	Understandable	2
creative	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	Dull	3
easy to learn	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	difficult to learn	4
valuable	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	Inferior	5
boring	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	Exciting	6
not interesting	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	Interesting	7
unpredictable	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	Predictable	8
fast	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	Slow	9
inventive	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	Conventional	10
obstructive	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	Supportive	11
good	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	Bad	12
complicated	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	Easy	13
unlikable	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	Pleasing	14
usual	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	leading edge	15
unpleasant	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	Pleasant	16
secure	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	not secure	17
motivating	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	Demotivating	18
meets expectations	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	does not meet expectations	19
inefficient	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	Efficient	20
clear	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	Confusing	21
impractical	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	Practical	22
organized	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	Cluttered	23
attractive	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	Unattractive	24
friendly	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	Unfriendly	25
conservative	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	Innovative	26

Figure D.9: VR C&Look User Experience Form Page 3.

9. Please summarize your opinions

9.1. Regarding the *functionality* of the technology (input, output, responsiveness)

.....
9.2. Regarding *design* (colors, sizes, icons used, available information)

.....
9.3. *Interaction* (possibilities to orient, navigate in the application or manipulate objects)

.....
9.4. Other thoughts:

Thank you for your participation!

Figure D.10: VR C&Look User Experience Form Page 4.

Date: _/ _/ _

Comparing Laptop and VR: Vision screening, vision training and technology use

Participant no:

Virtual Reality, Simulations, Serious Games and Eye-Tracking (XR-ET)

Presence and performance for comparing C&Look on Laptop and in VR

Please think back to performing the tasks on the Laptop and VR.

1. Comparing with experiences while checking your eyes at a physical place, e.g., at an optician or a doctor's office, can you argue why (or why not) you would like to use a similar application on
 - a. Laptop

.....
 b. VR

.....

2. In which application did you find it easier to navigate? Laptop or VR? Why?

.....

3. Compared to performing the tasks on a laptop, did the addition of depth in VR change your enjoyment/immersion? Why or why not?

.....

4. Were there any features from either application you felt were lacking from the other? If so, what?

.....

5. Please rate your overall experiences on calibration in each environment.

	Laptop								VR								
	Difficult							Very Easy			Difficult				Very Easy		
	1	2	3	4	5	6	7	1	2	3	4	5	6	7			
Calibration	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>			

Comments:

.....

6. Rate your **experiences** of using Laptop and VR on a scale of 1 to 7

Figure D.11: Comparison Form Page 1.

7 stands for evaluations corresponding to situations at a place for checking your eyes, being tested by experts and 1 for the opposite, a completely unrealistic situation.

	Laptop								VR						
	Low 1	2	3	4	5	6	High 7		Low 1	2	3	4	5	6	High 7
experiences	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>		<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
engagement	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>		<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
involvement	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>		<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
focus of attention	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>		<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
experiencing time	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>		<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
Compared to real memories	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>		<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>

7. Rate your **performance** for each task for Laptop and VR on a scale of 1 to 7. 7 stands for your evaluations corresponding to a performance at a place for checking your eyes, when being tested by experts. 1 stands for the opposite, a very low performance.

	Laptop								VR						
	Low 1	2	3	4	5	6	High 7		Low 1	2	3	4	5	6	High 7
Soccerball															
Eye tiredness	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>		<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
Move your eyes	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>		<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
Interact with environment	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>		<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
Follow instructions	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>		<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
Basketball															
Eye tiredness	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>		<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
Move your eyes	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>		<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
Interact with environment	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>		<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
Follow instructions	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>		<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
	Laptop								VR						

Figure D.12: Comparison Form Page 2.

Reading									
Eye tiredness	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
Move your eyes	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
Interact with environment	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
Follow instructions	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>

Thank you for your participation!

Figure D.13: Comparison Form Page 3.

Date: __/__/__

Interview: Vision screening, vision training and technology use

Participant no:

Virtual Reality, Simulations, Serious Games and Eye-Tracking (XR-ET)

Interview for comparing C&Look on Laptop and in VR

Please think back to performing the tasks on the Laptop and VR.

1. Please tell us some important things you need we should know about your background regarding XR-ET?

2. Which one of the applications did you enjoy most? Laptop VR
Please argue for the answer

3. What was your preferred method of eye-tracking? Why?

4. What are your opinions regarding using the technology, input/output devices, the tasks, and their functionalities?

Technology and devices

Performing the tasks?

Functionality

Can you comment on experiences with the Laptop application and the surrounded experiences in VR?

Can you comment on experiencing depth?

Can you comment on experiencing the FOV?

Figure D.14: Interview Questions Page 1.

5. What are your opinions regarding the games?

For using games for vision screening?

For further possibilities?

6. Do you have some unpleasant experiences?

7. Do you have some pleasant experiences?

8. Do you have some additional comments?

9. What do you think about the future of this type of application

- In 5 years?

- In 10 years?

Thank you for your participation!

Figure D.15: Interview Questions Page 2.

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