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Article

Technologies Supporting Screening Oculomotor Problems: Challenges for Virtual Reality

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Abstract: Oculomotor Dysfunctions (OMDs) are problems with eye-musculature relating to coordination and accuracy of eye movements. Eye-tracking (ET) technologies show great promise in the identification of OMDs. Current computer technologies for vision screening are specialized devices or laptop based technologies with limited by screen size and the inability to measure depth. In this experimental study, we examine the possibilities of immersive virtual reality (VR) technologies for increased user experiences, presence, immersiveness, and the use of serious games. Further results of an experimental study present increased interest in VR-based screening, its ability to focus better, and aspects motivating for its use, despite the actual limitations of current technologies. These limitations currently include lower performance and confidence in results of the used HMDs. Some users also describe being more focused when screening in VR, free from outside distractions. Using serious games for screening in VR is also estimated to have great potential for developing a more robust vision screening tool, especially for younger children.

Keywords: Eye-tracking; Head Mounted Display; Presence; Immersiveness; Oculomotor Dysfunction

1. Introduction

Several people can have eye disorders and diseases. Many common problems can be identified by visiting clinical experts, e.g., ophthalmologists, orthoptists, or some clinical specialists in vision, and corrected with eyeglasses or surgery. However, vision problems can occur even if the eyes seem normal, and the results from the most usual vision tests (e.g., visual acuity assessment, refraction for eyeglass prescription, or examination of the anterior and posterior segments of the eye) do not show vision disorders [1,2]. Some people may have problems processing visual information, addressed in this paper as Functional Vision Problems (FVPs). These, also known as functional visual disorders or functional vision impairment, refer to disturbances that cannot be explained by structural or physiological abnormalities in the eyes. These conditions are characterized by a mismatch between the actual eye health and the visual symptoms experienced by the individual. These are sight disturbances hindering one from, e.g., correctly estimating distances, reading, or experiencing problems with their balance. FVPs are common, especially in stroke patients [3,4] or in adults suffering from brain injury [5]. Not diagnosing FVPs can have negative consequences, especially for children who cannot necessarily realize and report their problems and are not tested by usual vision testing with the ages of 5-7 [6].

Oculomotor dysfunction (OMD) is an FVP related to problematic coordination between the left and right eye. Approximately 17-30% of children with vision problems have problems related to FVPs such as OMD [7]. These problems can lead to more severe vision disorders if not treated correctly, however, many children do not know that they have OMD, and the impact is it has on their vision [7]. FVPs are a societal problem that cannot be solved with current resources due to the limited number and capacity of vision professionals [6,8].

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Utilizing eye-tracking (ET) technologies shows great promise in the identification of OMD [9]. These ETs are integrated or attached to laptop systems and, based on following a person's basic eye movements during a time, helping professionals approximate if the person has or does not have OMD related vision problems. Due to the limited screen size and the inability to measure depth accurately, essential issues for a complete vision screening, these solutions have inherited limitations. Measuring basic eye movements helps professionals understand how a person can focus on objects (measuring fixations), follow objects with their eyes (measuring smooth pursuits), or jump with their eyes from one object to another. Since the two eye movements can be measured separately, how the eyes are coordinated can also be measured, making this solution highly effective for examining FVPs related to OMD. There are already validated solutions on the market offering ET and laptop-based measures to professionals engaged in screening FVPs [10]. Supporting screening via technology is essential since vision screening should be based on objective measures and take less time. A complete vision screening, including screening for FVPs, takes more than one hour [11], and there are not many professionals who are educated to perform this.

Since VR equipment allows experiencing a larger Field of View (FOV) and depth, the hypothesis behind this work is that VR can add to future vision screening batteries. Until now, we are not aware of research or practice utilizing VR equipment for vision screening. This may be evident due to the main limitations of VR, e.g., handling "binocular disparity is a critical stimulus to vergence, which is a critical depth cue" making those eyes "are always focused on a single depth," which implicate loss of focusing and in accommodation in a current review considering ET in VR. However, this review is positive for utilizing larger FOV, by a foveating view or for specific vision testing, e.g., for contrast sensitivity [12]. Another review, also considering AR technologies argues for many limitations such as including unsatisfactory accuracy, weak validation, and hardware limitations, but promising user experiences [13]. However, not many studies examine how these experiences are, more in detail.

VR is also a technology that allows for vision training [7], which can help, e.g., for training stroke patients [14] or children with OMD [15]. Since many FVPs, and in particular OMDs, can be helped by training [16], to see the effects of the training this should incorporate screening possibilities. According to our knowledge today, there is no VR application for screening OMD and no VR eye training application incorporating the possibilities of screening.

In the background of this paper is an experimental study implementing a laptop-based application to screen FVPs and developing an immersive virtual reality (VR) based prototype and evaluating its usability [17]. This paper takes a step forward and focuses on the importance of VR experiences for OMD screening and the current challenges through experiencing presence. The overall goal is to highlight user opinions on utilizing VR for screening and training of vision problems. This focuses on their experience with ET calibration techniques, feeling of presence, comparison between a laptop and VR-based solution, and feedback from open-ended questions and interviews which provides additional justification to questionnaire answers.

While the value of having OMD, and later FVP screening in VR is clear, the way to achieve it depends on technology, context, application, and users [18].

The structure of the paper is the following. We present related literature from VR-based, and laptop-based screening in Chapter 2. Chapter 3 presents a screening tool (C&Look) showed usable on laptop and imported into VR. Study design including data collection methods, test approach, and a brief introduction to analysis methods are described in Chapter 4. Chapter 5 presents analysis of answers to questionnaires and interviews. The context for these results are discussed in chapter 6, along with presentation of current limitations and future work for the project. Chapter 7 provides a conclusion to this paper, presenting an overview of the findings from this study.

2. Literature Background

VR provides a surrounding experience by simulating a real-world environment with help of technologies and users can be surrounded by 3D projection in a room. For example, in a Head-Mounted Display (HMD), when the user is wearing special glasses allowing them to see 3D projections around themselves [19]. Immersion, as defined in the literature, refers to the characteristics of technology to allow experiencing this 3D environment in space, not only on a 2D surface. Accordingly a HMD is an immersive technology and a laptop is not. Presence refers to experiencing being physically present in a computer-generated application and the interaction in it can be as believable as the interaction in the non-mediated conditions [20].

VR has gained significant attention from researchers due to allowing a larger field of view than a laptop, enabling more natural interaction, for example, with the hand, head, or body tracker with a computer-generated environment and built-in eye tracker for gaze recording. For enabling high presence or distracting the users from a painful or boring situations VR is appreciated in various fields, from experiencing new bridges or buildings, training to fight fire or be prepared for surgery, pain management, anatomical education, or the treatment of psychiatric disorders. In recent years, VR has integrated ET technologies and emerged in the field of vision science, integrating built-in eye trackers into HMDs [12]. Therefore, today VR has the potential to be an effective tool in complementing the treatment of a variety of vision disorders, e.g., treating amblyopia [21], convergence insufficiency [22] or augmented reality for treating strabismus [23].

Laptop technologies, in general, and for a longer time showed promises to complement the treatment of amblyopia, strabismus, binocular vision disorders, and visual field deficits [24,25]. However, developing associated algorithms and analyze gaze measurements from ET data for fixations and saccades are available, more exact measurements are needed for better confidence in the results both for laptops and VR [9]. Experiencing presence in the environments is crucial, as an example, for feeling agency [26], and therefore, our hypothesis is that evaluating user experiences, presence, and the role of serious games can help forward research about these technologies.

VR systems do not aim to reproduce an experience as realistic as in films or fiction, the experience and presence in the environment, and knowing how to react to the events, are important. Working with the technology, where the technology itself is hidden and goes away for the good of the application is significant for increased user engagement, motivation, and enjoyment [19]. Since experiencing presence can be considered an added value for VR technologies, many testing aims to collect measurements about presence. These tests can be done by addressing user opinions, e.g., by observations, questionnaires, or interviews, but also by trying to make sense of users action in the environments, e.g. by sensing technologies, such as ETs or EEGs and find more objective measures for presence.

Given the high prevalence of vision problems in the general population, functional vision screening is important for early detection and timely treatment, which can significantly improve visual outcomes and quality of life [6,27,28]. The literature also showed that using serious games increases motivation for learning or performing tedious, repeated, or painful activities e.g., [29,30].

Despite the growing body of research on the therapeutic applications of VR in vision rehabilitation, to our knowledge, there has been no exploration of how subjects are experiencing presence of VR-based vision screening.

3. The C&Look application

3.1. Developing a laptop-based application

The C&Look program developed at HVL for FVS uses affordable eye-tracking technology to support existing detection methods for OMDs [3]. It utilize eye-tracker technologies that has to be started on a laptop, calibrated and used with a structural,

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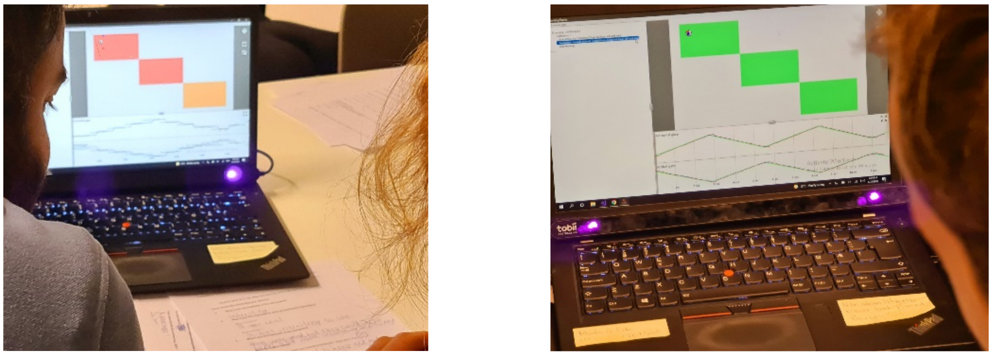
systematically developed application, designed together with vision experts [31]. The use of eye trackers connected to a computer has some limitations such as screen size, for e.g. peripheral vision, and head positioning, for e.g., not allowing larger head movements during the screening. However, it provides new possibilities as the data gathered over time allows for analysis of eye movements, and such difficulties only were possible to examine by ocular examination of vision experts. Further, it has been illustrated the affordability of eye-tracking technologies can assist vision experts in detecting children's oculomotor dysfunction (OMD) and how them can incorporate this technology into their screening procedures [11].

The C&Look program runs on a laptop with ET technologies. Vision experts can choose and adjust a number of tasks and define a task battery for screening, depending on the possible problem of the users and their characteristics (most often age, but also eventual disability, reading competence). After calibration, the screening is performed. After the screening, the performance of each user (how they perform the task and how their eyes, separately the left and right are synchronized, e.g., by fixation, saccade, smooth pursuit) can be analyzed separately. The screening battery includes graphical tasks with measured fixations, saccades, smooth pursuit, and different measurements from reading tasks [3]. Fixation, smooth pursuits, and saccades are major eye movements connected to how people can focus and follow objects. Examining eye movements during reading is considered a good indicator of identifying OMD, a coordination problem between the left and right eyes [11]. Fixation tasks consist of an object moving stepwise across the screen in a predetermined pattern; smooth pursuit tasks follow objects, while saccades are measured for an object jumping from one position to another. Reading tasks display any text to the user, depending on her age and interests, adjusted by the person who sets up the screening. The program records the eye movements while the text is being read. The application also boasts its calibration method and a comprehensive results screen with replays and graphs visualize both eye positions during testing.

The analysis toolkit superimposes the user's eye movements allowing the examination of collected measures, alignments, and together with information about the performance (Figure 1). The analysis can be done for one task or just specific parts which can be associated with special measurements. Current issues with the application include strict user positioning for gaze data collection and the inability to measure aspects of vision related to depth.



(a) (b)

Figure 1. The analysis tool. Both pictures show the examination of the diagonal smooth pursuit eye movements for following a ball from the upper left toward the lower right corner. On the left **(a)**, the pink-red (orange) color indicates bad (medium) eye alignment, contrary to a good alignment on the right picture **(b).**

3.2 Development of a VR-based application

When transforming C&Look to VR, the first step was to convert the same tasks (fixation, smooth pursuit, reading) into a 3D environment. Both the fixation and smooth pursuit tasks follow the same principles when it comes to stimuli movement, although these objects are now 3D and move in a 3D space. The reading task in VR is almost identical, with text being displayed on a plan-screen in the virtual environment. The difference between this task from a laptop and VR comes from the canvas positioning and being able to dynamically adjust the distance between the player and the text. Calibration in VR utilizes the Varjo SDKs built-in calibration method, while results include a live replay with visualization of gaze points. The VR version currently lacks graph visualization of eye positions during testing. Few implementation methods could be reused when developing VR, as the added third dimension changes object movement, gaze point visualization, and necessary calibration techniques. This led to this new application being built from the ground up, except for utilizing the same database.

To transfer C&Look into an immersive VR application using eye behavioral data, and to investigate how to complement manual vision screening and C&Look, the prospects and limitations of using a head-mounted display (HMD) are analyzed. The HMD used is a Varjo VR2-Pro, as it is one of the leading VR headsets with embedded ET together with hand controls (see Fig. 2).

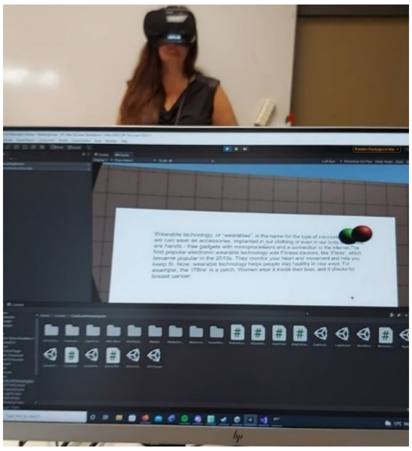


Figure 2. A vision expert testing a prototype of the VR-based screening application.

The sampling rate of integrated ET in the Varjo HMD is 100Hz. Varjo also allows investigating hand and eye coordination. This functionality is useful for recognizing FVPs, since problems with how the eye functions are highly correlated with other functions, e.g., balance or hearing [9].

While the 2-dimensional version of C&Look provides high-quality data when testing for oculomotor problems (OMD) it lacks the possibility of capturing important tasks performed during a special performance that is included in manual vision screenings. The laptop system used for testing the original version of C&Look had a screen size of 14 inches and utilized a Tobii 4C mobile eye-tracker with a sampling rate of 90Hz. The performance of the laptop-based C&Look application was investigated comparatively in a set including two applications for the same tests, one based on higher sampling rates and one with lower [32]. The applications were approximated to be similar and with testing performed by the involved vision teacher (see Figure 2).

4. Study Design

After implementing C&Look in VR the program was tested several times by random students. Each participant tested both C&Look on a laptop and on VR and quantitative data collected from the participants. During this time, a test battery was developed to

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collect data anonymously concerning Norwegian ethical requirements. This test battery (presented in Appendix A) includes:

1. Information about the study (written and oral information)
2. Consent for participation
3. Background information about the participantt's familiarity with vision control and their familiarity with new technologies (ET, VR, and serious games)
4. Questionnaire about experiencing the laptop version of C&Look
5. Questionnaire about experiencing the VR version of C&Look
6. Comparison questionnaire for the laptop- and the VR-application.
    a. Open-ended questions related to the feeling of presence and comparative elements of both applications.
    b. ET calibration experience questionnaire.
    c. Presence questionnaire for the laptop- and the VR-application.
7. 9 interview questions with the possibility to discuss after each about comparatively evaluating their presence and experiencing the technologies and serious games.

This experimental study was tested by 7 subjects, one vision expert (a teacher in special education with competence in vision), and six other voluntary subjects in June 2022. Testing one subject lasted between 60-90 minutes. The first subject was one vision expert critically examining the test battery on the laptop and VR applications; the last one was adjusted after her comments. All participants, except one, had some vision difficulties, but all participants experienced vision testing at a vision specialist earlier.

The test was performed in the following way: Introduction (using questionnaires 1-3), performing a randomly assigned vision screening (laptop or VR), and after each set, the subjects filled in a questionnaire (questionnaire 4 or 5). After the first application's vision screening and data collection was completed, the process was repeated for the remaining untested application. The evaluation of the user experience (UX) of the laptop and VR application was inspired by an overall UX questionnaire [33]. Each participant filled out the comparison questionnaire (6) after having tested and evaluated each application separately. This questionnaire begins with open-ended questions related to the feeling of presence and comparative elements of both applications (6a). During the comparison questionnaire, participants were asked to rate their experience with calibration in each environment (6b). The activities during application testing involved 2 different calibrations on the laptop, one from Tobii and one developed in this environment for more precise calibration. For the VR calibration, Varjo's legacy calibration method was used. These calibration methods were ranked on a scale from 1 to 7, where 1 indicates difficulties with calibration, and 7 relates to an easy calibration experience.- For the comparison questionnaire, a modified overall presence questionnaire (6c) was constructed inspired by earlier work from Slater [34,35].

The testing session ended with semi-structured interviews about the comparative experiences, aligning the experiences to earlier familiarity with vision screening and using VR.

User experience and usability evaluation have been presented in an earlier study, showing similar high quality results for both applications except for a few performance issues in VR [17]. The study also highlights many limitations of the used HMD and the need for interdisciplinary assistance for development with the vision science domain experts when developing a vision screening suit for VR. For this study this experience was based on vision expertise from an earlier study developing C&Look for laptops [3], as well as testing of an early prototype of the VR application on a vision expert to influence further development.

To analyze the data collected through questionnaires and interviews, different analysis methods were used. Calibration experience results have been plotted into a graph for better visualization (section 4.1). Open-ended questions regarding comparative elements and presence were analyzed using code analysis (section 4.2). Presence questionnaire data was averaged separately for both applications, providing a mean sense of presence score for all tasks performed in different environments (section 4.3). Interview answers have been compared to other results for user experience and presence, relating answers to each participant and their previous experience with vision screening/testing (section 4.4).

5. Results

The results presented in this section include different techniques for analyzing user feedback. This includes calibration experience results, code analysis of answers to open-ended questions, task performance similarity results, and analysis of feedback received during interviews.

5.1 Calibration Experience Results

When collecting ET data from users, calibration of ET technologies is a mandatory step to ensure high-quality data collection. The laptop and VR screening applications use different calibration methods, with the laptop version using a custom-made calibration screen proposed by Eide and Watanabe [3], and VR utilizing Varjo's built-in legacy calibration mode. When asked to compare these methods in step 6a of the testing battery, ranking each calibration method on a scale from 1 to 7, feedback from test participants varied greatly. Scores for each calibration method per participant are shown in Figure 3. The average score for calibration on a laptop is 6, while the VR method scores an average of 5.85.

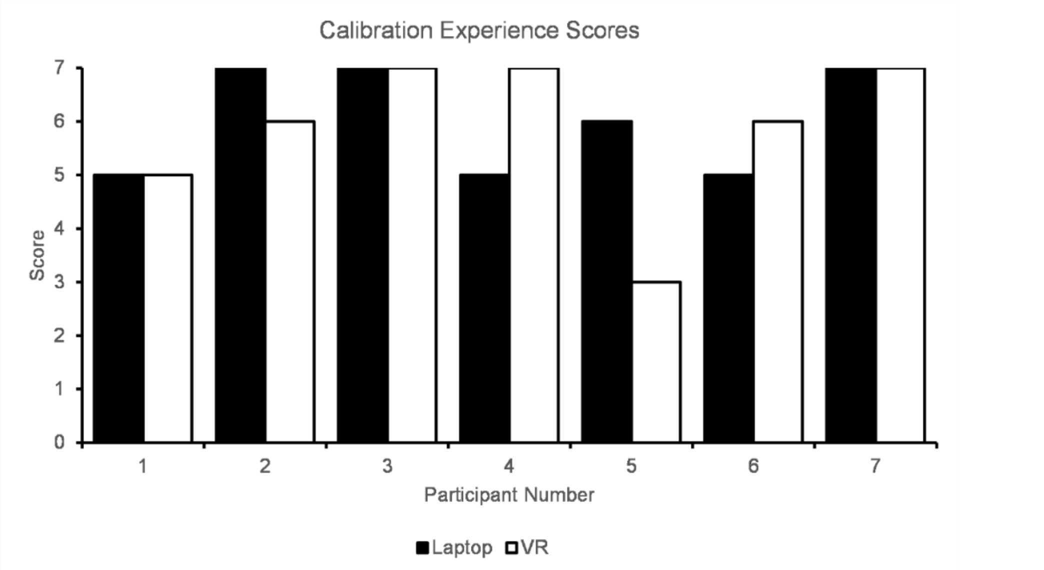

Figure 3. Calibration experience scores for each test participant, ranging from 1 to 7.

Both calibration methods produced similar averages, with the VR version falling slightly behind the laptop version. However, this difference was influenced mainly by Participant 5, who had difficulties calibrating in VR due to wearing glasses. On the other hand, participant 7 also wore glasses but had no issues calibrating in either environment, giving both calibration methods a score of 7 when asked to rate their experience.

5.2 Open-ended Questionnaire Results

Open-ended questionnaires were administered to participants in step 6a of the testing battery to compare different aspects of the two applications. The questionnaires were designed to get qualitative feedback from participants about their experiences with each application. The following are the questions:

- Q: 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?

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   - Laptop:
   - VR:
- Q: In which application did you find it easier to navigate? Laptop or VR? Why?
- Q: Compared to performing the tasks on a laptop, did the addition of depth in VR change your enjoyment/immersion? Why or why not?
- Q: Were there any features from either application you felt were lacking from the other? If so, what?

To analyze participants' responses to the open-ended questions in step 6a, each answer was assigned a "Code" based on its intention. Each response was given only one code, ensuring responses have the same weight. The following codes were used:
- "Laptop is easier to understand/use": indicated that participants found the laptop application easier to use, especially those with limited technological background or prior knowledge of the system.
- "Higher confidence in laptop results": indicated an interest in better data representation and collection for the VR environment, leading to higher confidence in the laptop application's results.
- "VR is more fun/exciting": highlighted the additional immersive elements that VR brings, with an emphasis on enjoyment.
- "VR helps with focus": included mentions of participants finding task performance easier or more motivating with fewer outside disturbances in VR.
- "VR is easier to navigate": and "Laptop is easier to navigate" described preferences for different user interfaces and navigation options.
- "VR performance issues": included responses that mentioned optimization issues in the VR application.
- "No Answer" contained answers that were non-existent or completely unrelated.

Figure 4 shows the number of occurrences for each code based on participant answers to each question. The numerical values in the graph represent the number of times an open-ended question answer was given a specific code. As an example, the "VR helps with focus" code was given to 3 responses.

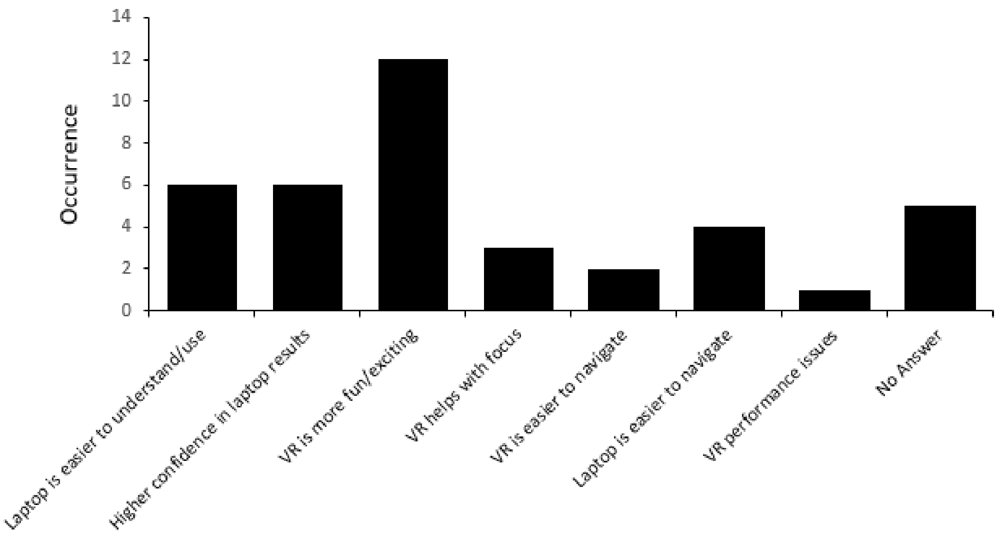

Figure 4. Occurrences of codes from responses to open-ended questionnaires for all participants.

Although most participants (n=6) preferred the reliability and confidence in results from the laptop application, the highest code occurrence was "VR is more fun/exciting" (n=12). Participants reported being more engaged when using the immersive elements of

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VR, which motivated them to perform tasks correctly. Additionally, some participants mentioned having a higher level of focus when performing tasks in VR, as there were fewer outside disturbances.

5.3 Task Performance Similarity

Each participant performed three different tasks in both applications. In step 6b of the testing battery each participant was asked to rank different aspects of tasks on a scale from 1-7. This ranking focuses on the similarity of performing tasks to what it feels like to perform a similar activity at a specialist's office, where 7 stands for evaluations corresponding to situations at a place for checking your eyes, and 1 for the opposite, a completely unrealistic situation. Table 1 shows the average similarity scores given for each question on the laptop application, while Table 2 shows the average scores for the VR application.

Table 1. Similarity of task performance: Laptop

Task	Fixation	Smooth Pursuit	Reading
Eye tiredness	4	3.85	3.86
Move your eyes	5	5.28	5.85
Interact with environment	4	4.28	4.57
Follow instructions	4	5.85	6.28

Table 2. Similarity of task performance: VR

Task	Fixation	Smooth Pursuit	Reading
Eye tiredness	4.28	4.28	4.14
Move your eyes	4.85	5.28	5.85
Interact with environment	5.14	5.28	5.28
Follow instructions	6.14	5.85	6.42

Every question, except for "Move your eyes" on the fixation task, received a higher average user score in the VR application than in the laptop application. This indicates an increased sense of presence in the VR environment. While some of these aspects are not necessarily positive, such as "Eye Tiredness", their higher averages indicate that execution of screening tasks in VR produces a feeling like that of performing homogenous activities at a professional place for testing your eyesight.

4.4 Participant opinions on using serious games for vision screening

This subsection includes the comments from the participants to the question, "What are your opinions regarding the games?", associated with direct comments about the game experience from the interview. Table 3 shows each participant's previous experience with vision screening/testing, as well as opinions about using the developed games in VR and on laptops.

Table 3. Opinions on using the games to screen vision.

P Nr.	Experience with vision screening/testing	Opinions about the used games
1	Has some previous experience with regular vision checkups from school.	"[The VR] worked well for the things we would like to accomplish…Changing the size of the objects was fun." The participant also expressed that she enjoyed the fixation game more in VR for the enjoyment alone. She also mentioned apprechating the the analysis application after

		screening on laptop. She wished to have the possibility to screen the children's eyes alone with a trustable gamified application.
2	Wears spectacles and undergoes eye tests every second year	"A fun way to do screening, I think. I felt that when I am performing an eye test, I focus on the games, which is good. Here the eyes may work normally, as in reality. He explained that his son is 5, and as a parent, he would like to ensure that he has no vision problem. This is an innovative way for vision testing. Although, elderly people may experience this otherwise."
3	Has regular check-ups at least every second year	The games "were well designed. Most important is to see how my vision is moving when I follow objects." "I also believe that the games are not only useful for doctors and opticians, but also for schools, universities, or other workplaces needing to measure the employees' focus or help children to learn better by showing them eventual problems with their eyes."
4	Had vision problems at a younger age, so they have experience with regular vision controls. No longer has any vision problems today.	"It is an entertaining way to test, especially in VR. I liked the easy applications. Maybe to construct an environment with more games and being able, maybe, to change the figures would be fun." If I know the game is trustable and "cost and time effective, I may test my eyes in this way rather than go to the optician. However, I believe this also has several ethical questions behind it."
5	Wears spectacles and undergoes regular controls (frequency not specified).	"I like the idea to tests your eyes with games. I [also liked experiencing] more depth in "games," which should be exploited for more traditional games as well, adding more experience." He also "believes that depth perception can be measured on laptops."
6	Wears spectacles and undergoes regular controls (frequency not specified).	"I prefer ET and games on laptop because it is faster and takes up info better. VR [was] more difficult" While it was "cooler with VR, [it was] more practical on laptops." VR was "a bit more like in reality, but it is moving from a distance. "the reading tasks was better on a laptop." It was "a bit boring to read in VR [..] you should put more interesting text there."
7	Wears spectacles and undergoes eye tests every year.	"Games easy to understand and intuitive, except that the VR had some lagging for basketball … framerate drops. Overall, a nice experience to see and to understand how things [the eyes] are focusing … maybe we can avoid eye specialists."

Although their preference for either laptop or VR changes, participant 1, 2, 4, and 5 expresses increased enjoyment when testing with games and an interest in performing future vision screenings via games. Participants 1, 3, and 7 mentioned appreciating being able to better understand their own eye movements when using the applications. The test subjects mention multiple shortcomings of the VR application, such as Participant 4 wanting more use of depth, participant 6 finding VR more difficult to operate and the reading task boring, and Participant 7 mentioning performance issues during the smooth pursuit task.

6. Discussion, Limitations, and Future Work

The current laptop FVP screening solution is limited by available screen size and the inability to utilize depth. Contemporary research shows that measuring depth perception is possible using HMDs [36,37]. A stereo acuity task attempting to measure depth perception in VR was developed as part of this study, however, implementation proved difficult, as scaling and generation of 3D models to represent extremely shallow angles (200-400 seconds of arc) introduces high computational complexity. This resulted in difficulties in measuring and lagging, observable for users. It was also discovered that small errors from the eye-tracker itself lead to high variance in the gaze vector, resulting in measurements too far from the desired target. These limitations are discussed further in the study's related MSc thesis by Dæhlen [38], which suggests some FVP screening tasks that may be better suited for VR. This includes visual field screening, shown to be compatible with HMDs by Mees et al [39], and amblyopia testing, proven measurable in VR by multiple research teams [40-42].

Task performance in virtual environments has been described to be positively influenced by an additional sense of presence, and we should attempt to take advantage of these unique aspects of HMDs when screening FVPs. Presence questionnaire answers and open-ended question code analysis show an added sense of presence when performing screening tasks in VR when compared to performing similar tasks on a laptop. User experience results indicate worse user experience and less confidence in results in VR [17], which is further supported by code analysis of open ended questions (section 4.2) and answers to interview questions (section 4.4). However, participants still report increased focus and motivation despite the current issues with the application. This can be associated with the hype of VR technology.

Calibration is a necessary step when utilizing ET technologies for data collection, however, the process can reduce the immersion and engagement of users. Calibration in the different environments is reported by users to be similar, however, calibration in VR was inconsistent with those that wore glasses. This was only an issue for one out of two participants with spectacles, where they had to recalibrate multiple times to achieve sufficient gaze data quality. The issue could stem from the strength of their lenses, as gaze data quality of ET technologies in other HMDs yield lower performance for users wearing glasses [43]. Other users report having an easier time calibrating in VR, as the process is both faster and requires less strict head positioning.

A clear limitation of this study is the participant pool, with 5 out of 7 participants being in their mid-20s. As the FVP screening tools are intended to be used on school-age children, both applications should ideally have been tested on their target demographic. This is especially important when attempting to measure the added sense of presence and additional cognitive aspects that VR can bring to the vision screening domain, as participants aged 10 to 20 tend to provide higher scores for immersion and presence [44] for this stage of the prototype. Another limitation comes from the data quality and reliability of the used HMD, further explained in a related publication [17].

A major motivation for this study was to investigate the possibility of screening and rehabilitating vision training for people who need help. As we have argued, both school-age children and people after a stroke or some other brain injury would need such help. Today, there are no professionals who can perform the necessary screening and vision training for all these people. By having supporting technologies, which can complement

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the work of professionals or replace it, these technologies can help many. The road to this is long, but not impossible.

7. Conclusions

Data from both questionnaires and interviews about user experiences and presence exemplify increased interest in VR-based screening, despite the actual limitations of current technologies. Better focus and great motivation for experiences were reported when using VR, despite worse performance and lower confidence in the obtained OMD screening results. Using serious games for screening in VR was also appreciated to have great potential, while their role on the laptop was experienced as simplistic, opinions were certainly affected due to the hype of technology. Some users also describe being more focused when screening in VR, free from outside distractions. This highlights the higher evaluation of the sense of presence for VR in comparison with laptops as presented in section 4.3, with a focus on problem-solving. From the learning perspective, the more comprehensive analysis tool was appreciated, allowing users to replay and examine eye movements with more functionalities than only superimposing the eye positions on the images as we had in VR. Utilizing the possibility to screen eye movements was considered a unique aspect of VR and laptop ET technologies. The participants believed in this opportunity as a future way of screening vision, which can keep users engaged.

Author Contributions:

Conceptualization, Ilona Heldal; Data curation, Are Dæhlen; Investigation, Are Dæhlen and Qasim Ali; Methodology, Ilona Heldal; Software, Are Dæhlen; Supervision, Ilona Heldal; Validation, Qasim Ali; Visualization, Are Dæhlen; Writing – original draft, Are Dæhlen; Writing – review & editing, Ilona Heldal and Qasim Ali. All authors have read and agreed to the published version of the manuscript.

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Research data collected is available in the non-published materials . This data is in the form of filled out questionnaires by test participants.

Acknowledgments:

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Conflicts of Interest:

The authors declare no conflict of interest.

Appendix A: Testing Battery

Figure A1: Study information

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.

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Western Norway University of Applied Sciences (HVL, Bergen, Norway)

Figure A2: Approval of participation

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: ____________

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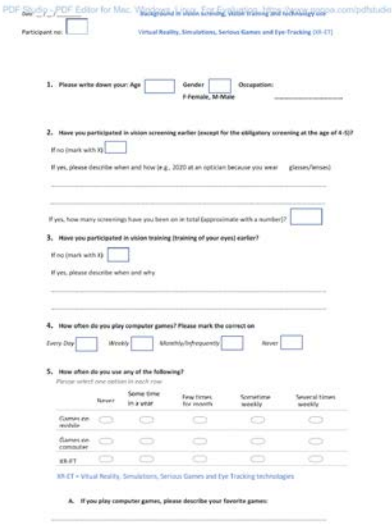
Figure A3: Background Form



Date: __/__/______ Background in vision screening, vision training and technology use

Participant no: Virtual Reality, Simulations, Serious Games and Eye-Tracking (XR-ET)

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

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 on

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	○	○	○	○	○
Games on computer	○	○	○	○	○
XR-ET	○	○	○	○	○

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

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

Page 1

Date: __/__/______ Background in vision screening, vision training and technology use

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)

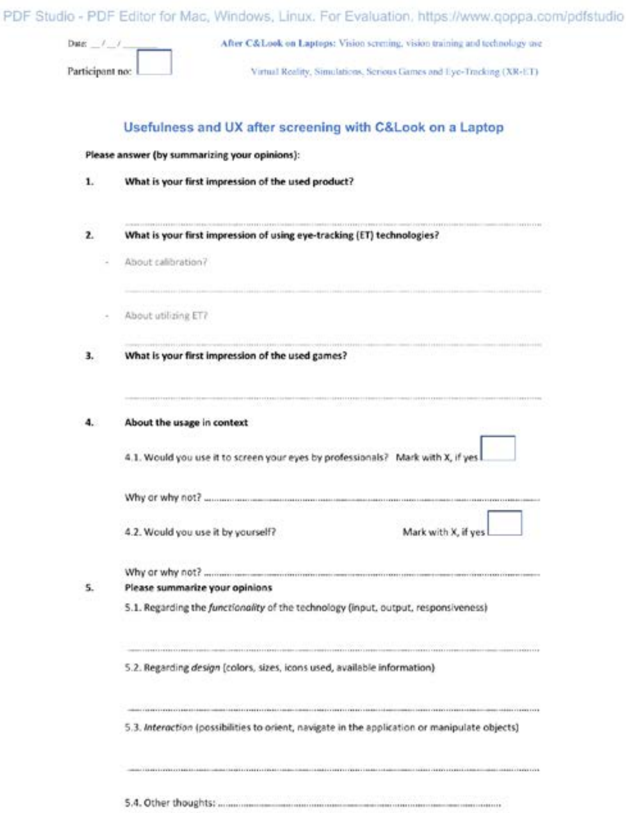
8. Do you think XR-ET can be used to screen vision? Please answer and motivate

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

Page 2

Figure A4: Usefulness and UX after screening with C&Look on a Laptop



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

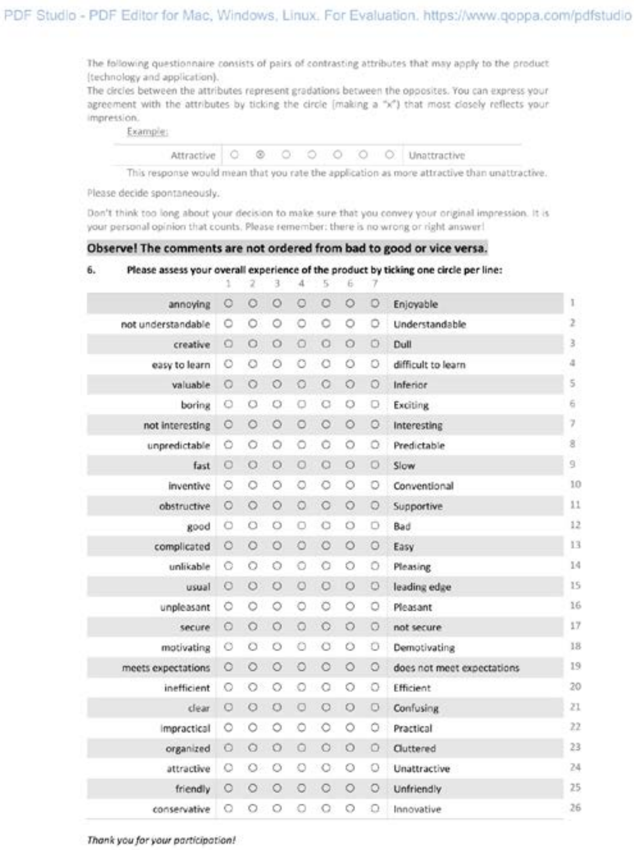
5.1. Regarding the *functionality* of the technology (input, output, responsiveness)

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: ......

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

Thank you for your participation!

Page 2

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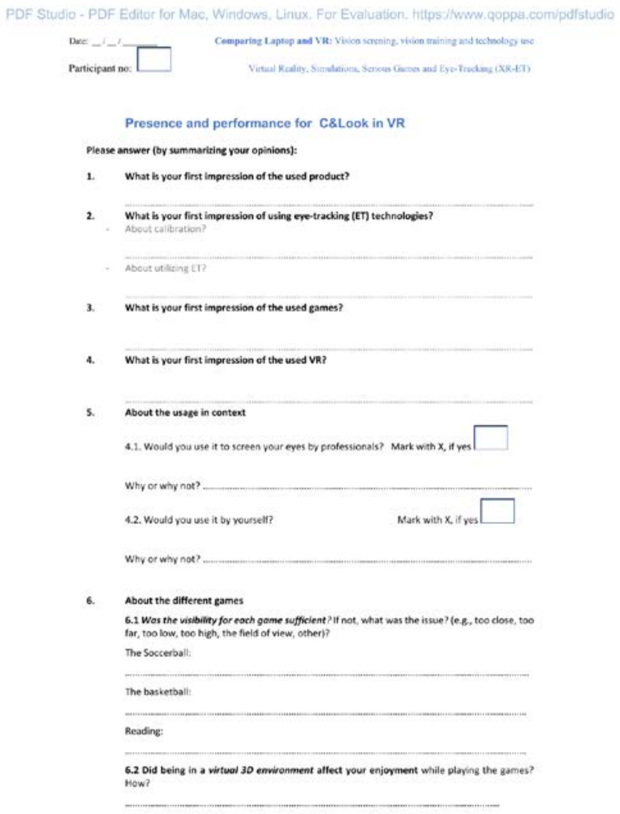
Figure A5: Usefulness and UX after screening with C&Look in VR



Date: __/__/______

Participant no:

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

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)?

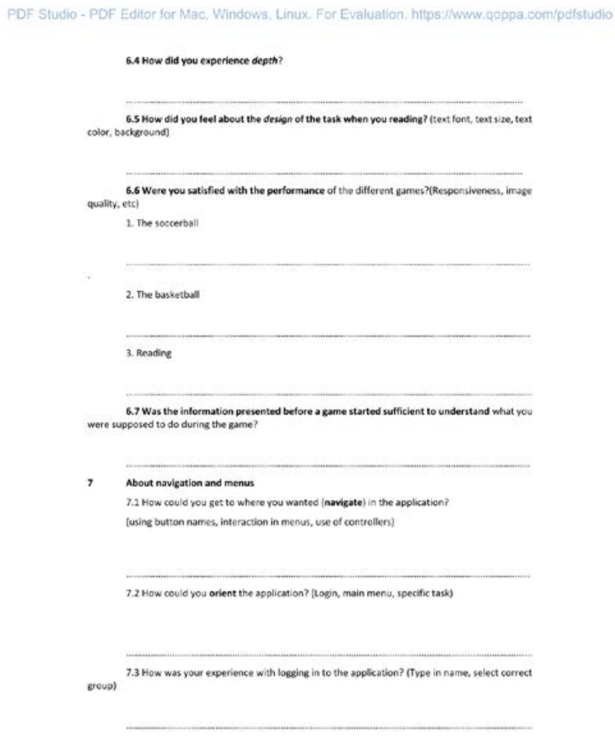
   The Soccerball:

   The basketball:

   Reading:

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

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)

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

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!

Page 3 **Page 4**

Figure A6: Presence and performance for comparing C&Look on Laptop and in VR

Date: __/__/____

Participant no:

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

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: Difficult 1	2	3	4	5	6	Very Easy 7	VR: Difficult 1	2	3	4	5	6	Very Easy 7
Calibration	▯	▯	▯	▯	▯	▯	▯	▯	▯	▯	▯	▯	▯	▯

   Comments:

   ....

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

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: Low 1	2	3	4	5	6	High 7	VR: Low 1	2	3	4	5	6	High 7
experiences	▯	▯	▯	▯	▯	▯	▯	▯	▯	▯	▯	▯	▯	▯
engagement	▯	▯	▯	▯	▯	▯	▯	▯	▯	▯	▯	▯	▯	▯
involvement	▯	▯	▯	▯	▯	▯	▯	▯	▯	▯	▯	▯	▯	▯
focus of attention	▯	▯	▯	▯	▯	▯	▯	▯	▯	▯	▯	▯	▯	▯
experiencing time	▯	▯	▯	▯	▯	▯	▯	▯	▯	▯	▯	▯	▯	▯
Compared to real memories	▯	▯	▯	▯	▯	▯	▯	▯	▯	▯	▯	▯	▯	▯

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: Low 1	2	3	4	5	6	High 7	VR: Low 1	2	3	4	5	6	High 7
Soccerball														
Eye tiredness	▯	▯	▯	▯	▯	▯	▯	▯	▯	▯	▯	▯	▯	▯
Move your eyes	▯	▯	▯	▯	▯	▯	▯	▯	▯	▯	▯	▯	▯	▯
Interact with environment	▯	▯	▯	▯	▯	▯	▯	▯	▯	▯	▯	▯	▯	▯
Follow instructions	▯	▯	▯	▯	▯	▯	▯	▯	▯	▯	▯	▯	▯	▯
Basketball														
Eye tiredness	▯	▯	▯	▯	▯	▯	▯	▯	▯	▯	▯	▯	▯	▯
Move your eyes	▯	▯	▯	▯	▯	▯	▯	▯	▯	▯	▯	▯	▯	▯
Interact with environment	▯	▯	▯	▯	▯	▯	▯	▯	▯	▯	▯	▯	▯	▯
Follow instructions	▯	▯	▯	▯	▯	▯	▯	▯	▯	▯	▯	▯	▯	▯
	Laptop							VR						

Page 1 **Page 2**

Reading														
Eye tiredness	▯	▯	▯	▯	▯	▯	▯	▯	▯	▯	▯	▯	▯	▯
Move your eyes	▯	▯	▯	▯	▯	▯	▯	▯	▯	▯	▯	▯	▯	▯
Interact with environment	▯	▯	▯	▯	▯	▯	▯	▯	▯	▯	▯	▯	▯	▯
Follow instructions	▯	▯	▯	▯	▯	▯	▯	▯	▯	▯	▯	▯	▯	▯

Thank you for your participation!

Page 3

Figure A7: Interview questions for comparing C&Look on Laptop and in VR

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Date: __/__/______

Participant no: ☐

Interview: Vision screning, vision training and technology use

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?

Page 1

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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!

Page 2

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