Augmented Reality Escape Room

To support the Rehabilitation of People with Visual Impairments

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Abstract

Rehabilitation is crucial for individuals with visual impairments, enabling them to enhance their residual vision and achieve greater independence in daily activities. Rehabilitation centers employ personalized training methods using both paper-based and digital exercises. Specialists in these centers welcome new technologies that can aid in rehabilitation and motivate their clients throughout the challenging process. However, the details of low vision rehabilitation training are often poorly documented and unfamiliar to outsiders. In my thesis, I collaborated with an association dedicated to assisting individuals with visual impairments, conducting a formative study to gain valuable insights into low vision rehabilitation. I synthesized these insights into a model for gamifying rehabilitation tasks. Additionally, I explored the application of augmented reality technology in low vision rehabilitation, an area that has seen limited use. As part of this exploration, I developed an augmented reality escape room to explore the usability and accessibility of different interaction methods. The results highlighted the significant impact of interaction modalities on the time required and the number of errors made when solving the escape room. Through my exploratory work, I found that the augmented reality headset used hold great potential, emphasizing the importance of providing customizable apps and experiences to individuals with visual impairments.

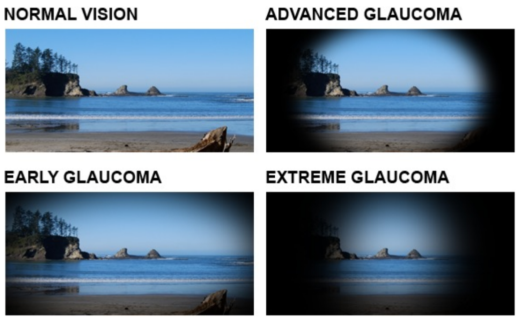
Keywords: augmented reality, people with visual impairment, rehabilitation, escape room, gamification

Contents

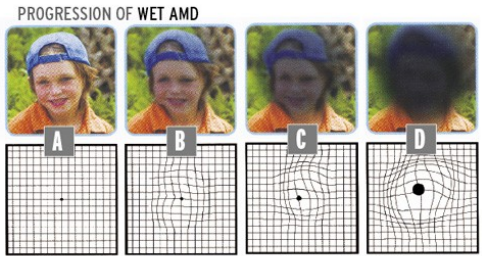
1 Introduction

Rehabilitation plays a vital role for People with Visual Impairments (PVI) to reach their full potential[13]. PVI have ”impairment of visual functioning even after treatment and/or refractive correction” but use or are ”potentially able to use, vision for the planning and/or execution of a task”, as defined by the WHO[7]. The goal of rehabilitation is to optimize the everyday functioning of the PVI by training their residual vision and giving them social, psychological and economic supports[17].

Vision impairment can result from a variety of eye disorders; some of them are depicted in Figure 1. These disorders, along with the resulting requirement for training, may exist from birth, appear suddenly during life, or develop with age. Such training also requires a great amount of focus and commitment. The training may start with straightforward paper exercises that require only eye movements and a fixed head, and it may then progress gradually to more beneficial tasks that are more in line with daily activities.



Glaucoma[1]: peripheral loss vision.



AMD[2]: central vision loss. A=normal vision, D=AMD.

Figure 1: Examples of simulations of eye conditions causing vision impairment.

Vision impairment can be of various severity, and one is Low Vision (LV). LV is when a person has a several visual impairment with a specific visual acuity level (level which varies from definition to definition), and the person has a residual vision. LV experts aim to offer customized and interesting training sessions to aid clients in their arduous journey. To create a playful element, they may use toys such as wooden shape blocks. They may also use smartphone or tablet apps to provide a variety of exercises that are digitalized versions of conventional tasks and may be more captivating.

In the context of Low Vision Rehabilitation (LVR), Head-Mounted Device (HMD)s and smart glasses are being used more recently[5] [3] [21]. These HMDs are most frequently used for orientation and mobility training, as well as supporting tools like magnifiers and contrast enhancers[2]. Only a few HMD apps, like Regal and al.[19]'s low vision rehabilitation software for lazy eye syndrome, leverage gamification to execute training and optimization of residual vision. A technology like an Augmented Reality (AR) HMD, with see-through like the Microsoft HoloLens 2, lets the user be aware of her surroundings at all times and offers the possibility for ambulatory rehabilitation in the context of the client's home, in contrast to virtual reality HMDs that completely immerse the client.

While there is potential for new development overall with these HMDs, accessibility needs to be taken into consideration. On Virtual Reality (VR) and accessibility, some valuable work already exists such as the set of tools for a more accessible VR by Zhao and al.[30]. On Augmented Reality (AR) and accessibility, Herskovitz and al.[9] provides a roadmap for future research on AR applications for mobile. However, little work has been done on accessible solutions employing AR

[1]Source: `https://www.eyecarels.com/wp-content/uploads/2015/02/glc.jpg`, visited 09/15/2022
[2]Source: `https://www.zoomax.com/wp-content/uploads/2019/08/amd.jpg`, visited 09/15/2022

HMDs, according to my literature review.

Since there are few to no resources available in the specific context of AR HMDs used to support the rehabilitation of PVI, I have collaborated with the Fédération suisse des aveugles et malvoyants (FSA) in the form of a formative study throughout my thesis. I looked at some of the traditional Rehabilitation Task (RT)s that might be made more engaging through the use of gamification, and identify the main key features required to design Gamified Rehabilitation Task (GRT)s. Then, in order to better understand accessible design and accessible interaction modalities in AR, I developed an AR escape room with three tasks to solve. As shown in Figure 2, I address two Research Question (RQ)s about the accessibility and gamification in my thesis:

RQ1: Which key features from traditional rehabilitation must be considered for successful gamification in augmented reality?

RQ2: How can we make the design accessible for the PVI?

RQ2a: Which gesture is most suited for the PVI?

Figure 2: This schema gives an overview of my research questions from traditional tasks to gamified tasks with RQ1, and to accessible tasks with RQ2.

I conducted an experiment with sighted people to explore the usability of the system and an experiment with PVI to explore the accessibility of interaction modalities. From the experiments, I have done quantitative and qualitative evaluations. The main qualitative takeaways are that: (1) it is important to offer customizable settings for each PVI, (2) gamification has the potential to offer a valuable motivating support in addition to traditional rehabilitation. The main quantitative takeaways are that: (1) the interaction modalities do impact significantly the duration and the number of errors made during a task, and (2) the type of tasks does not impact the time and error made in a task.

2 Related Work

This section describes the work done at LVR rehabilitation centers, what gamification is and why it is essential generally. This section also presents some technologies related to LVR and gamification, along with their usability and accessibility. I conclude this section with the contribution of my work.

2.1 Rehabilitation

Low Vision Rehabilitation (LVR) has a practical approach to help PVIs in their daily-life and is a complex field with diverse aspects. To help practitioners navigate this field, Fletcher[6] wrote a monograph which provides insights such awareness of common challenges with low vision patients and guidelines for training.

Some of those guidelines are on the effective use of low vision. There, Fletcher provides a set of instructions without devices that include the following *basic visual skills*: fixation (eccentric viewing), scotoma awareness, scanning, tracing, spotting, tracking and visual closure.

In Switzerland, the Swiss National Association of and for the Blind (SNAB[3]), and some of its members[4], offer courses for specialists that are based on the work from Fletcher[6]. From these courses, exercises, often paper-based, have been created to train those skills with some variation to increase the playfulness. However, the engagement of the patients may be difficult to maintain over time as the endeavour to form new habits takes time and some exercises may be seen as repetitive over time. Some of these specific skills will be explained in more details in the section 3 Analysis as part as my collaboration with the FSA, and are illustrated in Figure 3.

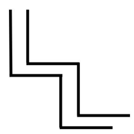


Figure 3: A tracing task used at the FSA where the patient needs to trace a line in-between the two black lines.

The field of LVR is complex and the associations within are doing remarkable work to support their clients. However, there are only very few resources for a comprehensive understanding and exploration of this field.

2.2 Gamification

To uplift motivation in an activity, the use of specific game design elements has specific psychological effects. This has been shown by Sailer et al.[22] through a randomized controlled study by using an online simulation environment. Besides, they have also shown that badges, leaderboards, and performance graphs have a positive impact competence need satisfactions and the perceived meaningfulness of tasks. In addition, their work has shown that avatars, meaningful stories and teammates affect experiences of social relatedness. Also, Deterding et al.[4] defined *gamification* as the use of game design elements in non-game contexts.

There exists various forms of games from which to get inspiration for game design elements and to gamify an experience. One form of games that has grown in popularity in the past few years

[3] SNAB url:`www.snab.ch`
[4] Independents low vision specialists url: `https://www.basse-vision.ch/site-html/Assoc/home.htm`

is the escape room as illustrated by the survey of Nicholson[14]. Essentially, an escape room is a game where players need to solve a series of tasks to win. An escape room offers an experiential experience and a non-traditional game style. To create a better player experience, Nicholson[15] mentions the importance of environmental storytelling and consisent design. A game loop around challenge-solution-reward creates a stronger experience as well as mentioned by Wiemker et al.[25]. The story and the game loop are important game elements to keep in mind. While an escape room may traditionally be without technology, recent examples are changing it with for example Wild et al.[26] who created a poetry escape room in augmented reality.

It is important to note that games and game design are not restricted to the digital category. They can also be non-digital[4], in such a way that a paper-based activity may be gamified as well. Nonetheless, a digitalized application has its advantages. Among other things, it creates the possibility to customize the application to the client's needs and requirements. In addition, the digitalized version has the possibility to track activity automatically for the benefit of both the client and her low vision specialist.

While diverse platforms exists, such as PC, tablets, smartphones, VR, and AR, a critical point is to choose a suitable platform with respect to the aim and requirements of the application or exercise to be developed. This point has been highlighted by Yu et al.[28] in a review of eighty-eight papers on VR, AR and mixed reality game applications in healthcare. Also, customized and tailored product is important for a better appreciation by the client, whether it is on the hardware such has smart glasses[21] or software as illustrated by Kéri et al.[12] in a sighted-student classroom environment with twenty-five teachers in economics.

2.3 Technology

With an increased use of tablets and smartphones which are becoming more user-friendly including for PVIs, there is an interest to incorporate them into the LVR of a client. Especially to overcome the social stigma of more traditional assistive devices. This is highlighted by Irvine et al.[10] whose work explains the accessibility features of tables and smartphones for visually impaired, how to access and use these features: e.g. contrast, zoom, voice command, or text to speech.

While serious games for PVIs do not seem easily searchable as shown in an analysis of ninety-four apps designed for people with disability[24], there are attempts in the literature to exploit tablets and smartphones using gamification. Regal et al.[19] created a scavenger hunt-like location-based game to support orientation and mobility training and tested it with students within their own school building. The mobile platform was preferred, by 10 out 12 students, as it enabled the students to learn in the real world their own school while playing, rather than playing in a virtual world on a PC. Besides, 13 out of 15 students agreed that they would like to play such game in their orientation and mobility training because it is fun and it has an engaging story.

With emerging VR and AR technologies, new devices are used to support PVIs. Yu et al.[28], in their review, pointed out the importance of three aspects for future work: (1) considering consumer-level VR / AR / MR game applications in healthcare, (2) applying personalisation in-game data, multi-user, and data sharing, and (3) explore novel VR / AR / MR game applications in healthcare.

Besides, Zhao et al. 2017[31] have done a study with twenty participants using an optical see-through AR glasses, the Epson Moverio BT-200, and demonstrated that PVIs may benefit from the use of such device and similar AR glasses. Interestingly, the visual acuity on standard physical chart was not necessarily a prediction of the visual acuity of virtual elements, for both sighted users and PVIs because there was occurrences were users had a relative better and worst acuity with virtual elements. While specific to the device used, they conclude their work with guidelines for AR projects such that (1) basic shapes, such as triangle, circle and square, were easier to identify than text, (2) white, yellow and green colors were better than red, and blue could be used to attract the attention of the user, and (3) the size of virtual elements should be greater than one-hundred pixels and a sans-serif font is preferable.

In Zhao et al. 2018[29], an haptic white cane was used with new feedback on physical resistance. The PVIs may transfer their traditional white cane skills into a VR environment. While the study has positive feedback from both participants and experts, this has a focus toward orientation and mobility training. While Yuhang Zhao[5] has an impressive set of projects and publications around VR and AR in the context of low vision, none are on the LVR to train residual vision specifically.

Nowak et al.[16] used the HoloLens device by Microsoft to implement rehabilitation exercises in ambloyopia care, also called lazy-eye syndrome. They tested their application with four adults and four children including one adult and one child with the syndrome. They use the AR technology to overcome the disadvantages of VR in their context and especially toward children whose bodies may be impacted by a full immersion into a virtual world. Besides, traditional method of applying a patch over the healthy eye discards the stereoscopic vision and create an artificial rehabilitation. After a training phase of a few minutes, the participants played successfully and reported that it was more demanding to use an AR game than a VR one. Besides, they reported more comfort by using the AR device. In addition, this AR implementation is expected to offer a more self-reliance training, and to reduce the side effects such as vertigo and eye-exhaustion compared to VR. Finally, by using this AR HMD device, they may offer a tool for home-based treatment-supporting procedures.

While the HoloLens is used in a stationnary way for the ambloyopia by Nowak et al., another use of AR was done by the Fondation Ellen Poidatz [6] for walking rehabilitation for children. While they still train in the same center, the HMD displays gamified instructions and enables them to train by themselves. It results in a more fun, more efficient training, and wearing the HMD helps the children keep a better posture while walking.

"using VR hand controllers (HTC Vive controllers) do not offer realistic movements for wrist and finger (e.g. hand-washing, pouring a drink, or piano activities. Thus, hand tracking controlerless setup is suggested for future use cases." [20]

The benefits of using AR show up through the previous examples. The user remains aware of her real world, the strain on the body is potentially lessen compared to VR, and the use of our own hands is potentially more natural than controllers.

2.4 Usability and Accessibility

There are numerous definitions provided in the literature on usability and accessibility. I take an holistic view to usability and accessibility based on Medina and Thoo's view[11]. I believe it is crucial to take the needs of the broadest population into account at every stage of implementation. I refer to the W3C's definition of usability[8] and to Persson et al.'s concept of accessibility[18]:

- Usability: "is about designing products to be effective, efficient, and satisfying. Usability includes user experience design. This may include general aspects that impact everyone and do not disproportionally impact people with disabilities. Usability practice and research often does not sufficiently address the needs of people with disabilities"[8].
- Accessibility: "the extent to which products, systems, services, environments and facilities are able to be used by a population with the widest range of characteristics and capabilities

[5] Yuhang Zhao's website and projects: https://www.yuhangz.com/projects
[6] Fondation Ellen Poidatz video: https://www.youtube.com/watch?v=aNdIkUt7O1Q&ab_channel=FEHAP

(e.g. physical, cognitive, financial, social and cultural, etc.), to achieve a specified goal in a specified context.” [18]

On the emerging VR and AR technology, Zhao et al. [30] created a set of tools to make VR more accessible to PVIs based on a formative study with PVIs. The tools range from magnification lens to recoloring as illustrated in Figure 4.

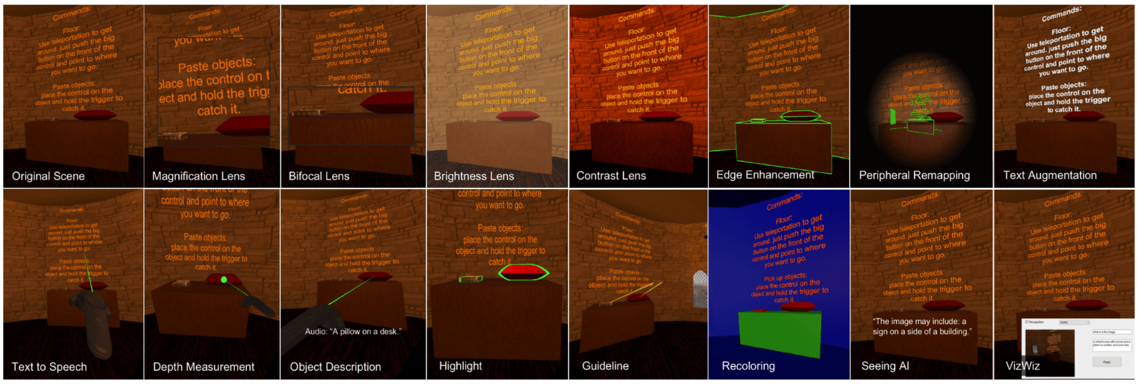


Figure 4: Illustration of the tools from Zhao et al.[30]

interaction mid-air or on surface? Cheng et al.[1] make use of a physical table while using VR to lower the physical fatigue on the body. They found that physical table with VR improves comfort, agency, and tasks performance, and decreases physical exertion and strain on the neck, shoulder, elbow, and wrist.

Herskovitz et al.[9] analyzed existing mobile AR app on iOS and provided a taxonomy of common AR tasks with the goal to provide a path to make mobile AR accessible. They created several prototypes which demonstrated that visual AR is potentially accessible. However, they did not consider animated virtual content or game mechanisms. In addition, they encourage for a participatory approach in developing AR with PVIs because having an application that is not only accessible but also usable and desirable is challenging.

2.5 Contribution of my work

As mentioned in Subsection 2.1, LVR is a complex field with little resources overall. I conducted a formative study in collaboration with low vision experts to bring valuable insights on the traditional rehabilitation tasks. Subsection 2.3 mentions the little use of the emerging AR technology, and both my formative study and my implementation of an AR escape room contribute with valuable lessons.

3 Analysis

PVI have to go through a lengthy rehabilitation process to train their residual vision with traditional tasks. With limited information available on the process of rehabilitation, it is difficult for an outsider to comprehend the process and its essential elements. To understand these and the challenges faced by the PVI in their rehabilitation, I conducted a formative study with the Fédération suisse des aveugles et malvoyants (FSA). The first subsection describes the technology used, AR HMD, notably resuming potential strengths, limitations and constraints of the technology that shall be taken into account for the design of the experience. In the second subsection, I present the formative study in extended details to share valuable information on training process and the points of interests of the low vision specialists and their clients. In the third subsection, I present the traditional tasks which are often paper-based. I relate these tasks to visual skills that clients need to train. In the last subsection, I condense the information of the previous subsections into a concept to gamify rehabilitation tasks. The objective of this concept is to offer a structured set of information to support the design and development of rehabilitation tasks using AR HMD.

3.1 Technology and Device

The choice of the AR technology and an AR HMD is supported by the related work section. The specific device use in my work is a Microsoft HoloLens 2[7]. While a comprehensive comparison of AR HMD devices is out of the scope of my work, the choice of this device may be supported by its positive reviews and use in a wide range of industries. It is a head-mounted device used for augmented reality, giving the ability to the user to remain aware of her surrounding while having virtual elements added in her field of vision. For a better appreciation of the device, I present its characteristics and limitations hereafter.

Its ergonomics offers comfort with adjustable headstraps, a lightweight device, and the possibility to wear the corrective glasses. Its technology can track both eyes and hands, and recognize voice. The eye tracking requires a calibration for each user and ensuring that it is suitable for PVI is out of the scope of my work. Therefore, a basic gesture based on eye tracking, gaze, is excluded from my work. According to the official documentation[8], the device offers other basic gestures that use the hand tracking: touch, hand ray, air tap, and air tap and hold. These basic gestures and the voice recognition are discussed again in the Section 4 Conception. Its technology can also recognize the real world environment. It uses the spatial mapping[9] technology to create a 3D map of the real environment. This offers a more realistic blending of the real and the virtual worlds. As such, there is an interest to explore the possibility to use an AR HMD in an ambulatory context to let the PVI client train at home.

Its limitations may be with respect of the sensitivity to bright light and its limited field of vision. The sensitivity to bright light may make the hand tracking less accurate and the virtual objects less visible. This may limit the rehabilitation with an AR HMD to an indoor training. Testing for outdoor training is out of the scope of my work and I will focus on the concept of indoor training. The limited field of vision may make the virtual world only partially visible and the user will have to move her head more. On one side, this may limit some training exercises that requires to look in the periphery of the vision. On the other side, this may incite the user to make regular head and body movements. I will consider this limitation during my formative study and conception of tasks.

[7]Official website: `https://www.microsoft.com/en-us/hololens/hardware`, visited 17.05.2023.
[8]Microsoft documentation on gestures: `https://learn.microsoft.com/en-us/dynamics365/mixed-reality/guides/authoring-gestures-hl2`.
[9]Microsoft documentation on spatial mapping: `https://learn.microsoft.com/en-us/windows/mixed-reality/design/spatial-mapping`.

(a) Using **spatial mapping**, developers may produce a believable mixed reality experience by accurately representing real-world surfaces in the area around the HoloLens

(b) **Basic gestures** available to engage with Microsoft HoloLens 2: (left to right) touch, air tap, hand ray, gaze and voice

Figure 5: Technical features of Microsoft HoloLens 2: (a) spatial mapping to recognize real world and (b) basic gestures to engage with virtual objects

3.2 Formative Study

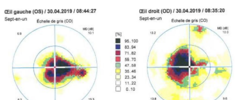
The formative study is built upon a series of around fifteen meetings in collaboration with the Fédération suisse des aveugles et malvoyants (FSA) over eight months from October 2022 to May 2023. These meetings were full of valuable information about the process of rehabilitation, the needs of the PVI clients and the low vision specialists. I regroup and summarized these meetings under themes in Table 1: introduction, training process, training day, prototypes presentation, pretests with specialists, and debriefs. Other extra meetings, giving valuable insights to understand the holistic approach taken by specialists to care for their clients, are listed as *side sessions* at the bottom of Table 1.

Table 1: Summary of collaborative meetings with FSA, including their goals and outcomes.

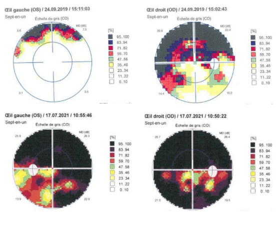
Theme	**Goal**	**Outcome**
Introduction	Present to FSA the concept of an AR escape room to support PVIs' rehabilitation	The use of a new technology is warmly welcomed
Training process	Retrieve information about rehabilitation and tasks	Received information on a concrete plan of actions
Training day	Play the role of a client by accomplishing a typical rehabilitation session	Gained insights into what clients go through
Prototypes presentation	Present GRTs' prototypes and early AR implementation with an AR HMD	Obtained valuable feedback to iterate on ideas and early implementation
Pretests with specialists	Pretest early versions of the implementation in an iterative approach	Got valuable feedback on what to optimize in the implementation
Debrief on pretests	Discuss further on the pretests' feedback	Clarified what is important in building gamified rehabilitation tasks
Debrief on final experiment with PVIs	Ask detailed questions on low vision specialist commentaries	Understood what is of importance from the specialist's eyes
Side session: diagnostic	Shadow optometrist on a diagnostic session	Gained social insights into rehabilitation
Side session: rehabilitation with AR	Assist a LVR session where a HoloLens 2 is used	Strong appreciation of the device emerged
Side session: low-vision IT specialist	Open discussion with the specialist	Importance to customize and let the client customize its tools

Introduction. The collaboration with the FSA started with a presentation of my research questions and an early prototype and implementation to two low vision specialists. The enhancement possibilities from the AR technology was well received, especially the possibility to train in an ambulatory context.

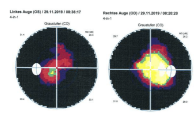
Training process. Low vision specialists begin with an anamnesis and an assessment of the client's needs. They evaluate visual alterations and residual visual potential. Ideally, they would consult information provided by *ophthalmologists*, such as the field of visions, illustrated in Figure 6, but information is not always shared. Fletcher et al.[6] have already highlighted the need of teamwork between the different professionals involved in the low vision rehabilitation of a client. Current practice seems to show that this collaboration may still be lacking.



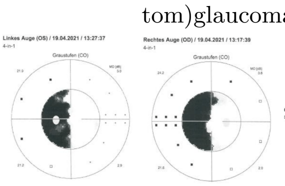
(a) Central: Stargardt disease



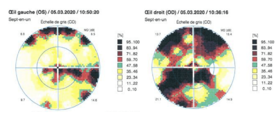
(b) Peripheric: (top) glaucoma incipient, (bottom)glaucoma severe



(c) Peripheric: tunnel vision



(d) Sectoral: hemianopsia



(e) Sparse: retinopathia

Figure 6: Examples of field of visions, left and right eyes in each examples: central, peripheral, sectoral, and sparse impairments

As such, low vision specialists may perform their own assessment of the client based on various types of paper-based exercises. The subsection 3.3 shows a detailed list of these exercises. Typically, the specialist begins using an exercise with a cross in the middle of four squares such as the one illustrated in Figure 7. Such exercise helps the specialist understand what the client may perceive, and it increase the awareness of scotoma for the client. Be aware of the residual vision creates a solid foundation for the next stages of the rehabilitation process.

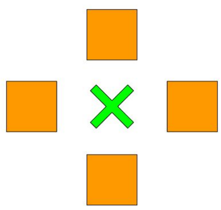
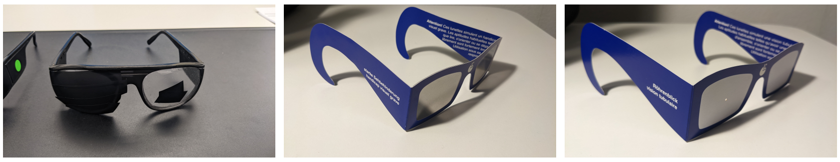


Figure 7: Example of assessment from the FSA to increase awareness of scotoma.

After the assessment of the residual vision, the low vision specialist and the client work together to find and build new habits to use this residual vision. Generally speaking, to retrieve information visually, any person needs to fixate a desired target so that its image is placed on the best area of vision in the retina. In the specific case of a client with visual impairments such as scotomas, there is a desire to use *eccentric vision*. This is a technique to look around a blind spot and view the desired target using the peripheral vision. The client will also try to find a new area of fixation closer to the fovea for better acuity and sharper image. This new area is called the Preferred Retinal

Locus (PRL). Some clients will find their coping mechanisms automatically, some will struggle to train for *eccentric vision*, others will have give up from the start. Therefore, a meaningful training may be of added value for motivation. As such, the ability to train in context, in the living room or kitchen of the client, and with relevant exercises is of greatest interest to keep motivation on the long term training. From the discussions and the technical characteristics of an AR HMD, the use of AR has some potential.

Training day. To add to the overview of the entire process, I took the role of the client using special glasses to mimic some visual impairments such as Age-related Macular Degeneration (AMD), as in Figure 8. Although these are only simulation glasses, the difficulties to train for new habits were well understood and the training day is a valuable step in a user-centered system design.



(a) AMD: scotoma left (b) Blur (c) Tunnel vision

Figure 8: Sensibilization glasses: diverse diseases and more general blur which may impact other diseases as well.

Prototypes presentation. With a thorough understanding of what low vision rehabilitation exercises encompasses, the work on my initial prototypes begins. Among other catalysts, the various designs evolved through brainstorming sessions with a low vision specialist from the FSA. This iterative process is detailed in the section 4 Conception. During prototypes presentation, the low vision specialist shared their opinions on the most important elements to consider:

- Context and goal of the task
- Data: history to keep a trend of the performance of the client, and information on where the client is looking at
- Interaction: interacting with a slider may already train the hand-eye coordination by itself. Even without haptic feedback, the user will need to use her hand to accomplish the different phases to interact with the virtual slider
- Background: both the real and virtual backgrounds are crucial. Each must be as plain and blank as possible, with little to no objects to avoid a cognitive overload by the client.
- Experiment room: the experiment room needs to be prepared with care. The real background should not interfere with the virtual task at hand.

Pretests with specialists. Going from prototypes to testable implementations, I pretested it with two specialists. Their feedback were insightful on contrast, customization, sizes of the objects, and difficulties regarding shapes used and randomness of the task at hands. The conception process and outcome are detailed in the sections 4.1 Technology discovery, 4.2 Exploration, and 4.3 Adaptation.

Debrief on pretests. The pretests lead to a few meetings with one low-vision specialist to debate and discuss important points such as the differentiation between low vision and locomotion. In other words, when is a rehabilitation task aimed for low vision training or for locomotion training. Elements that help design a task for one or the other training may be: the size of the virtual elements, their relative positions and their relative distance to each others.

A main point of discussion is around moving only the eyes, or moving a combination of head and body with eyes movements to solve a task in AR. The debrief leads to think that when only the eyes move, the training is strongly focused on improving *eccentric vision*. This should be for small tasks and as an initial stage in the training process. If we add more head and or body movements, then we move onto a more functional training for the daily-life activities. This does make sense, especially for a gradual training to move toward functional training at a later stage - this is supported by the online article of Spielmann [23]. The distinction of movements is important to know if the client should be in low vision training or in locomotion training, because there might be the need for another specialist.

The FSA's specialist asked advices to other specialists in Switzerland[10] and arrived to the following findings. There exists a continuity between low vision rehabilitation and locomotion training. If the client is in movement, then it is rather a locomotion training and the global strategy is to have a mix of eye and head movements. For a focus on low vision rehabilitation, the client shall remain immobile with her head. The most challenging part is to transition from low vision and locomotion training: the later will be in a setting with more external audio and visual stimuli, require physical effort to stand. In some rehabilitation center[11], short throw projector is used to increase the size of the picture to explore and foster transition to locomotion.

This leads to crucial advantages of using an AR HMD. With such device, a client can either stand or sit. The task can be small enough to be a low vision task or increased to train for locomotion. To illustrate, we may move from an hologram of a size similar to A4 paper format, small enough to be in the field of vision, to something much larger that requires movement of the head or the body or both. Note that defining the exact sizes of holograms required to aim for either low vision or locomotion training is beyond the scope of my work.

Debrief on final experiments. While a low vision specialist accompanied me during the final experiments with the PVIs, handful of notes were taken from the perspective of the low vision specialist. This lead to a few other meetings to gather extra information on the medical points of the client.

[10]specialists from other institutions: one in locomotion (anonym) and Fatima Anaflous from the Jules-Gonin Ophthalmic Hospital in Lausanne, Switzerland.

[11]Jules-Gonin Ophthalmic Hospital

Points of interest for clients and specialists

- Ambulatory context
- Eye tracking to provide more information to specialists on where clients look at
- Technical knowledge on clients come from third party
- Data trend over time provides how the client is improving and is more valuable than single training session
- Training in-context may increase motivation to train
- Tunnel vision (also called tubular vision, peripheral vision loss PVL) may benefit more from AR than, say, tablets due to the possibility to have actual depth in an AR task
- Some interaction modality may be a rehabilitation task in itself
- A minimalist background, both real and virtual, may help the client progress in the task with less confusions.
- Smaller size of holograms that remain within the field of vision, say A4 format, may target more low vision rehabilitation. Larger holograms and tasks may target locomotion training.

Side sessions. During the first session, I shadowed three diagnostic sessions during which the optometrist was providing the client with potential Irlen [12] filters for reasons such as work condition, brightness during sport, or help with color-blindness. For a user-centered approach to my work, this was a valuable experience increasing my awareness of social and psychological aspects surrounding the rehabilitation with PVI.

During the second session, I assisted a rehabilitation session which consisted in a preliminary test for a AR rehabilitation task developed by my supervisor, Y.J. Thoo. The task has also been implemented on a Microsoft Hololens 2 and consists in catching moving virtual animals in the surrounding environment. After a few attempts to understand how to perform the correct gesture, the client was enjoying the serious game more than some rehabilitation software on a computer. The client has mentioned a preference for traditional paper-based exercises that help directly on daily tasks such as writing her own name. With enthusiasm, she suggested to play with her kid while doing her rehabilitation, through for example a collaborative escape room.

During the third session, I had an open discussion with a low-vision IT specialist. This led to another illustration of the importance of customizing the tools used by the PVIs. The IT specialist will have the task to find a proper computer setup for the client to give her the tools necessary to assist her in her job. Software exist but not all of them give an easy access to customization once the IT specialist is not there to help anymore. Hence, the need for a careful selection to provide the client with the most appropriate tool.

[12] Irlen filter url: `https://irlen.com/colored-filters/`, visited 10/05/2023.

Takeaways from side sessions

- Caring for the whole person is key for rehabilitation
- PVIs may have a great ability and willingness to adapt and continue their favorite activities, such as volleyball or climbing, despite severe visual impairments and socioeconomic situations. However, they may still welcome support to persevere through their rehabilitation.
- PVIs and rehabilitation centers' staffs welcome warmly any attempt that provide support and consideration toward them, including uses of new technologies and ideas from universities.

3.3 Paper-based Tasks

Fletcher et al.[6] advises to start the training by teaching visual skills because working on them may maximize visual ability and the use of devices and assistive devices. As shown in the formative study of the previous subsection, FSA and UCBA (`www.ucba.ch`) low vision specialists use exercises that train for specific visual skills. In an attempt to clarify what are those skills, I list and categorize them in Table 2. I categorized stability, saccade and scanning skills as fundamental because they do not have other components in themselves. However, their exist more complex skills that are a composite of fundamental skills: spotting, tracing, tracking and hand-eye coordination. At rehabilitation centers, mainly paper-based exercises to train these visual skills are used. I detailed them below to have a strong foundation before moving to the conception of AR tasks.

Table 2: Listing of visual skills with their category and component, if any

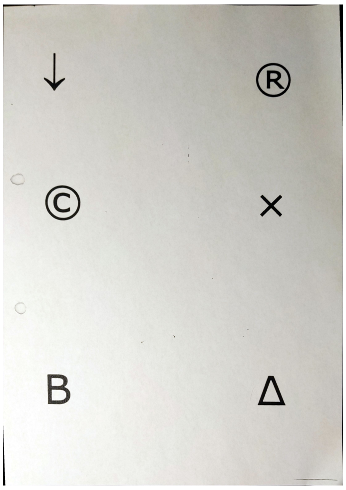
Visual Skills	**Category**	**Component**
stability	fundamental	n.a.
saccade	fundamental	n.a.
scanning	fundamental	n.a.
spotting	composite	scanning and stability
tracing	composite	scanning and stability
tracking	composite	scanning and stability
hand-eye coordination	composite	any fundamental skills

Fundamental. I define a fundamental visual skill as one skill that can be combined into a composite skill. In the fundamental category, I have classified the notions of stability, saccade and scanning.

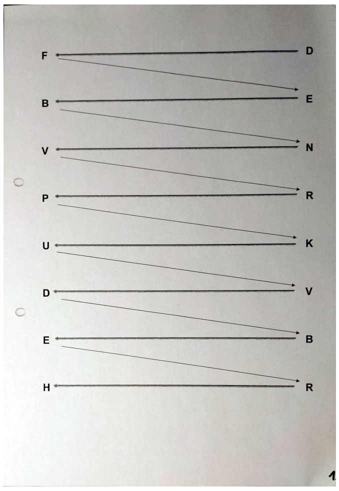
The notion of stability corresponds to fixing a desired target. A client performs an exercise of stability to train to fixate a target. The Figure 9a illustrates an exercise in which is when the client focuses on a designated target as long as possible. At the same time, the specialist will look into the eyes of the client to understand when the fixation on the target is lost.

The notion of saccade corresponds to moving quickly from one target to another. To move from one point of interest to another, the eye performs a little jump called a saccade. This is useful in reading to move from one word to another, or one line to another, as in Figure 9b.

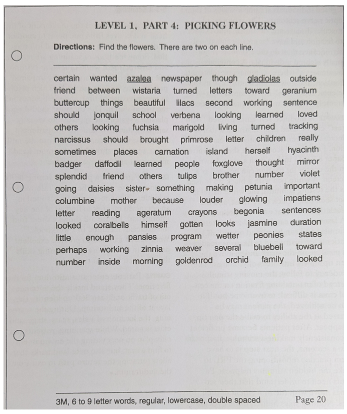
The notion of scanning correspond to exploring a desired area. To gather information across a wider area, one may search randomly and it may leads to inefficient use of vision. A better alternative is to train for systematic approach and this is what scanning exercises aim for, see Figure 9c. On scanning, while both head and eye movements are possible, Fletcher et al.[6] is in favor of more head movements for eccentric viewing.



(a) **Stability** training's example: The goal of this exercise is to fix a designated target as long as possible.



(b) **Saccade** training's example: the goal of this exercise is to move from one side of the sheet to another in one jump ideally or by using the horizontal line as little as possible.

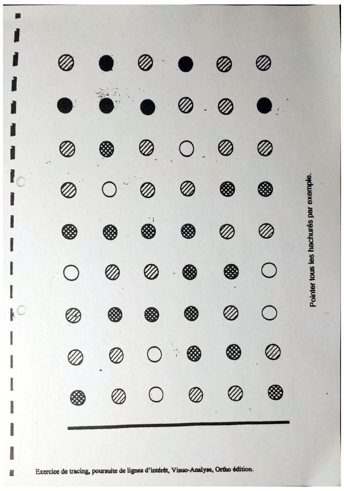


(c) **Scanning** training's example (from Fletcher et al.[6]): the goal of this exercise is to find the flowers names on each line. This is a kind of word-search game.

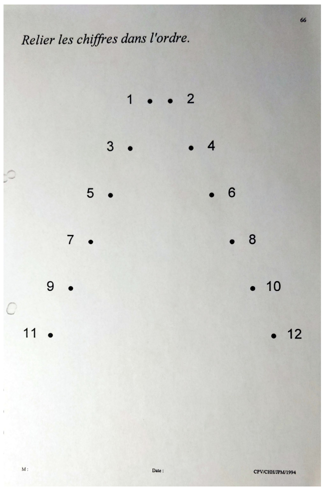
Figure 9: Examples of exercises to train the three fundamental visual skills: (a) stability, (b) saccade, and (c) scanning.

Composite. I define a composite visual skill as one that is a combination of others. In the composite category, I have classified the notions of spotting, tracing, tracking, and hand-eye coordination.

The notion of spotting corresponds to scanning an area to identify a target. The client starts by scanning a specific area to find a designated target. As such, the client finishes her saccade on this target and stabilizes on this target long enough to identify it. The Figure 10a illustrates a sheet of paper with rounds of different patterns. Low vision specialists use this sheet as an exercise to spot all the rounds of a designated type of pattern, for example the empty-white dots. The Figure 10b illustrates a sheet of paper with numbers from 1 to 12 places in a pyramid-like shape. Low vision specialists use this sheet as an exercise to spot the numbers and be able to connect them in order.



(a) **Spotting** training's example: the goal of this exercise is to spot all the rounds of a designated type of pattern.

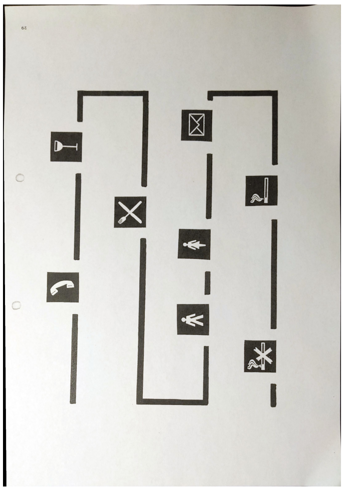


(b) **Spotting** training's example: the goal of this exercise is to spot the numbers and connect them in order.

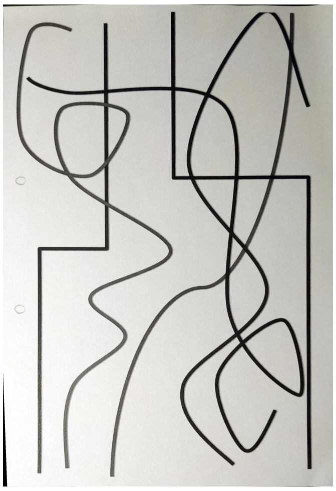
Figure 10: Examples of exercises to train the spotting visual skill (a skill from the composite category): (a) spotting training's example with rounds, (b) spotting training's example with numbers.

The notion of tracing corresponds to scanning an area to identify an immobile target and to stabilize on it to trace it. The client starts by scanning a specific area to identify an immobile target such as a line. Once identified, the client can stabilize on it and trace on to it either with her finger or with a pen. The Figure 11a illustrates a sheet of paper with a black line and icons along it. Low vision specialists use this sheet as an exercise to follow along the black line and stop at each icon to describe them aloud. The Figure 11b illustrates a sheet of paper with intertwined black lines and curves. The lines and curves may also be of different colors. Low vision specialists use this sheet as an exercise to follow one of several immobile target in a more complex environment than with a single line. The Figure 11c illustrates a sheet of paper with two similar dashed-border shapes and a different direction arrow in each of them. Low vision specialists use this sheet as an exercise to trace around the shape in a clockwise or counterclockwise direction.

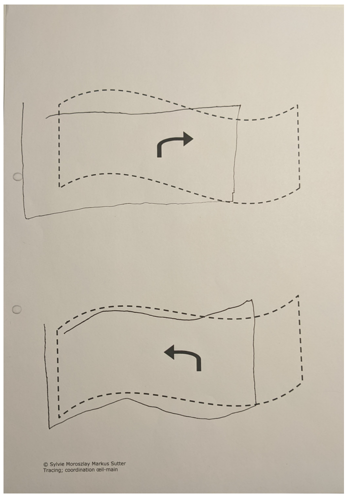
The notion of tracking corresponds to following a mobile target with movements of the eyes, the head, or both while the body is in movement or not. The client starts by scanning the environment in front of her to identify a mobile target. Once identified, the client can stabilize on it. The Figure 12 illustrates a red spatula used as a mobile target. Low vision specialists use this red spatula as an exercise to track it as a mobile target.



(a) **Tracing** training's example: the goal of this exercise is to trace on to the black line and describe aloud each icon along the line.



(b) **Tracing** training's example: the goal of this exercise is to trace on to one of the designated line or curve.

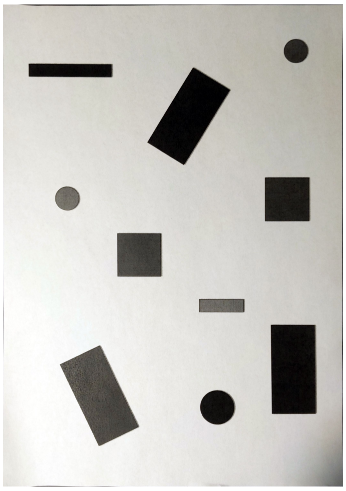


(c) **Tracing** training's example: the goal of this exercise is to trace on to the border of a shape in a given direction.

Figure 11: Examples of exercises to train the tracing visual skill (a skill from the composite category): (a) tracing training's example with one line and icons, (b) tracing training's example with intertwined lines and curves, (c) tracing training's example with dashed-border shapes.

Figure 12: Example of exercise to train the tracking visual skill (a skill from the composite category): tracking training's example with a red spatula used as a mobile target. Example from `www.lalumiere.be`, visited 13.05.2023.

The notion of hand-eye coordination corresponds to performing a designated task with the hands in coordination with the vision. The client starts by scanning a specific area to identify a desired target. The clients uses her hand to interact with the target to perform a specific task. The Figure 13a illustrates a sheet of paper with different shapes. Low vision specialists use this sheet as an exercise to identify wooden shape blocks with the vision and coordinate with the hand to move them onto the adequate shape on the sheet of paper. The Figure 13b illustrates a magnetic stick with tokens. Low vision specialists use this magnetic stick as an exercise to identify tokens of a specific color with the vision and coordinate with the hand to collect them.



(a) **Hand-eye coordination** training's example: the goal of this exercise is to identify wooden shape blocks with the vision and coordinate with the hand to move them onto the adequate shape on the sheet of paper.

(b) **Hand-eye coordination** training's example: the goal of this exercise is to identify tokens of a specific color with the vision and coordinate with the hand to collect them.

Figure 13: Examples of exercises to train the hand-eye coordination visual skill (a skill from the composite category): (a) hand-eye coordination training's example with different shapes, (b) hand-eye coordination training's example with a magnetic stick and tokens.

3.4 Gamified Rehabilitation Task Model

In the last two subsections, I presented in length the learning outcomes from my collaboration with the FSA. Due to the lack of information on the rehabilitation process and the difficulty for an outsider to understand the process and its critical components, this was an important first step. As a second step, I conceptualized a high-level model to gamify a traditional task using AR on a HMD. Such gamified task will be called a Gamified Rehabilitation Task (GRT) and the concept developed here the GRT model. The outcome of this subsection will remain a concept and will not be evaluated in my work.

This model should highlight important elements to consider in the design, prototype and implementation of a GRT. This model is based on two elements represented by two tables. They represent complementary aspects and should be used together:

- **Visual skills to train**: Table 3 shows the visual skills with their key features, training goal and technical elements. Each line is a different visual skill (first column). The second column explain its key features. The third column explains the training goal for a specific visual skill. The last two columns are related to the design and mechanism elements to consider for an AR HMD implementation.

  The low vision specialist will want her client to train some of the visual skills specifically. As such, the key features and training goal give a sound understanding of the visual skill for any outsider. To gamify a task, the technical aesthetic and mechanics elements to consider are listed and should be a starting point.

- **Rehabilitation step at which the client is:** visual skills can be trained even when the client has been in rehabilitation for a little while. In a sens, the client goes through different steps in her rehabilitation journey. Indeed, from the collaboration I had with the FSA, a conceptualization of the rehabilitation steps emerged. Those steps are listed in Table 4 in the first column. The second and third columns detail what each step involves. As this is a progressive journey for the client, it may be beneficial to adapt the gamified tasks through each or some of the step and this is what the last columns of Table 4 explain in terms of technical elements such as aesthetic and mechanics.

This GRT model will remain a concept. Nonetheless, it should be highlighted that this model has encouraged the FSA to recognize the necessity of formalizing a training procedure and work on an improved version of Table 4.

Table 3: Visual skills with their key features, training goal and technical elements. Each line is a different visual skill (first column). The second column explain its key features. The third column explains the training goal for a specific visual skill. The last two columns are related to the design and mechanism elements to consider for an AR HMD implementation

Visual Skills	**Key Features**	**Training Goal**	**Aesthetic**	**Mechanics**
Stability (VS1)	stabilize eye gaze on a point of interest	Fix a point of interest as long as possible	Shape should be simple enough, appropriate size, contrast and colors	Use of eyes mainly (c.f. VS7 for hands)
Saccade (VS2)	jump from one point of interest to another	Be precise and quick	Start with simple shapes within field of vision, not too wide apart	Use of eyes mainly (c.f. VS7 for hands)
Scanning (VS3)	move the head or eyes over an area of interest to collect information	Use systematic and efficient methods	Add a variety of shapes, colors and patterns	Use of eyes mainly (c.f. VS7 for hands)
Spotting (VS4)	scan (VS3) to collect information, jump (VS2) to target of interest and fix (VS1) it for identification	Combine fundamental skills for identification	Add a variety of shapes, colors and patterns	Use of eyes mainly (c.f. VS7 for hands)
Tracing (VS5)	scan (VS3) an area and fix (VS1) the line of interest, then maintain stability to follow on the line	Be stable along a line	Line, curve, outline, with different colors and contrasts	The use of eyes should be sufficient to perform the main task
Tracking (VS6)	maintain the stability (VS1) on a moving target	Use VS1 in motion	Keep the motion smooth and clear to follow	Use of eyes mainly (c.f. VS7 for hands)
Hand-Eye Coordination (VS7)	scan (VS3) and use the hand to interact with a given target	Combine other skills (VS1 to VS6) with the use of the hand(s)	More freedom to be creative	Add an object to manipulate or interaction with the hands

Table 4: Steps of low vision rehabilitation and its implications on a gamified implementation

Step	**Actions**	**Outcome**	**Aesthetic**	**Mechanics**
Introduction	Explain what involves training and why it is beneficial	Client has a better understanding of why rehabilitation can help	Printed examples may be a better format to start with	Not relevant
Preliminary	Stability, Saccade, Scanning	Get used to train elementary skills in *eccentric vision*	The tasks should remain small, such as A4 format, to keep the area of interest within the field of vision	Natural interaction might ease understand why this task is useful. "Fun" modalities might offer distraction from real-life.
Intermediary	Spotting, tracing, tracking	Combine fundamental skills to train the composite skills	The tasks can start to be a little bit bigger in size, to train movement of head potentially	Can be similar to preliminary step
Final	Hand-eye coordination, reading and writing	Gradual move to functional training	with potentially a favor for hand-eye coordination considering AR HMD	Add hand(s) and fingers recognition
Long term	maintain or move the training to locomotion	Ensure continuity in the rehabilitation of the client	The tasks may involve moving the body and moving around in a room	Maintain current mechanics, or may consider additional devices/modalities to extend the rehabilitation

4 Conception

With the knowledge acquired through the formative study, I designed and prototyped Gamified Rehabilitation Task (GRT)s using Augmented Reality (AR). I used a HoloLens 2 device by Microsoft for the AR and I prototyped in the game engine Unity[13] The GRTs will be prototyped within the theme of an escape room, a choice based upon the increasing interest in escape room concepts as described in Section 2 Related Work. The ultimate objective is to use a AR HMD in an ambulatory setting where the client trains with virtual elements added to her real environment such as their own kitchen. In ambulatory setting, data about the client's performance can be recorded to present the progress and trends to both client and low vision specialist. With GRTs to train with, the goal is to increase the motivation and engagement of the client in doing her rehabilitation. An implementation of GRTs using AR should offer a diversity of tasks and customization to both the client and the low vision specialists. It is important to note that my work is the first step toward this ultimate objective of an AR ambulatory rehabilitation program supporting the traditional low vision rehabilitation.

[13] my code is available, upon request, on the Git repository: https://github.com/SeriousAR-for-LowVisionRehab/ar-lv-game. Unity version 2021.3.8f1, https://unity.com/, packages used from their Mixed Reality Tool Kit (MRTK) 2 (https://learn.microsoft.com/en-us/windows/mixed-reality/mrtk-unity/mrtk2/?view=mrtkunity-2022-05, visited 17.05.2023): Mixed Reality Toolkit Foundation, version 2.8.2, Mixed Reality Toolkit Standard Assets, version 2.8.2, and Mixed Reality OpenXR Plugin, version 1.4.4. The project is coded in C# using Microsoft Visual Studio 2022, version 17.3.2, https://visualstudio.microsoft.com/, visited 17.05.2023.

The first subsection presents the technology discovery. I sketched a first individual task and prototyped it using AR on a HMD. I presented the first prototype and conducted a pretest with a low vision specialist from the FSA. It is important to have a common understanding of the possibilities and constraints of using AR on a HMD before going further.

The second subsection presents the exploration of ideas to sketch GRTs and to prototype some mechanics within the concept of an escape room. This iteration marks the transition from traditional task to a gamified version. When working on a new GRT, it is crucial to maintain the key features of the visual skills that we want to train through this GRT. Also, it is helpful to start exploring the possible mechanics of the escape room to ensure a proper experience within an GRT and between the GRTs.

The third subsection presents the adaptation of the prototyped GRTs within the concept of an escape room with respect to feedback from low vision specialists. At this iteration, I conducted a formal pretest with the prototyped escape room and explanation to pretest participants. This helped understand the entire flow from GRT to GRT, and the comprehension of the GRTs themselves by the participants.

The fourth subsection presents the finalization of the GRTs ready to be integrated into the final escape room. I did a few minor changes and clean up before having a final version of the escape room that is presented in the next Section 5 Implementation.

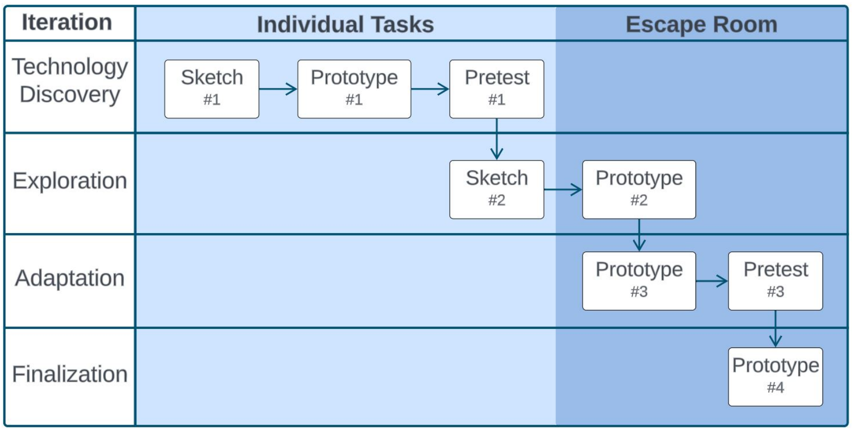


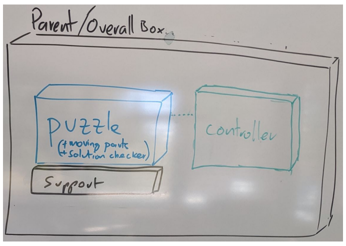
Figure 14: Roadmap of the conception in four iterations (one per row) from individual tasks (light blue second column) to integration as an escape room (dark blue third column). The first row is about **Technology Discovery** with the first sketch, prototype and pretest. The second row is about **Exploration** of ideas to sketch GRTs and to prototype some mechanics within the concept of an escape room. The third row is about **Adaptation** of the designed GRTs with respect to feedback from low vision specialists and conducting formal pretest of the prototyped escape room. The last row is about **Finalization** of the prototyped GRTs as an escape room with respect to the pretests feedback. This finalized version forms the escape room presented in the Section 5 Implementation.

4.1 Technology discovery

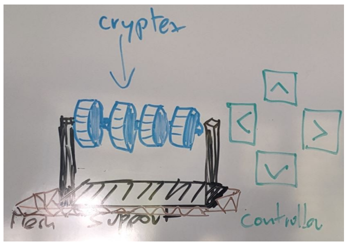
In this section, I discover the technology used by sketching a first individual task and prototyping it using AR on a HMD. I presented the first prototype and conducted a pretest with a low vision specialist from the FSA. This was an important step because it helps to have a common understanding of the possibilities and constraints of using AR on a HMD before going further.

Sketch #1. I started by developing a generic GRT that can be used for different type of task and visual skill to train. This generic GRT has three components. I consider the *core* component, which is the actual task to solve, the *support* on which the core sits, and the *controller* to manipulate the core component. Figure 15a illustrates these three components. Because the GRT will be a virtual object included within the real world, a support component may help to position the virtual object with convenience. The controller component may help to keep uniform implementation and customization for user.

For an initial task within the theme of an escape room, I sketched the idea of a vault with a hidden secret message to unlock. This satisfies the game loop of challenge-solution-reward that a escape room puzzle uses, according to Wiemker et al.[25]: (1) the challenge is the locked vault, (2) the solution is the combination of the lock, and (3) the reward is the secret message. The Figure 15b illustrates this vault called a cryptex[14]. The core component is made up of four cylinders, each having potential symbols to align to unlock the vault. The controller could be a set of buttons. In term of visual skills to train, it is possible to consider spotting to identify the correct symbols and to identify the desired controller. With the controller, hand-eye coordination may be considered.



(a) Sketch of a generic GRT's components: (1) the core component which is the actual task to solve, (2) the support on which the core sits, and (3) the controller which represents a gesture to manipulate the core component.



(b) Sketch of a cryptex GRT's components: (1) the four cylinders that need to be aligned to solve the task, (2) the support in black under the cylinders, and (3) the four arrow buttons as the controller.

Figure 15: Sketches #1 illustrated with (a) a generic GRT and its three components and (b) a concrete example of a cryptex GRT.

Prototype #1. My next step is to prototype the sketches of Figure 15 in the game engine Unity. For the controller component, I need to choose a gesture to control the core component. As seen in the subsection 3.1, the chosen AR HMD offers voice recognition and four basic gestures related to hand tracking:

- touch: this gesture gives the possibility to touch a virtual object to interact with it. An example is to press on a virtual button with the index finger.
- hand ray: this gesture gives the possibility to control virtual objects at a distance.
- air tap: this gesture gives the possibility to briefly grab something between the index finger

[14] Definition on Wikipedia: `https://en.wikipedia.org/wiki/Cryptex,visited17.05.2023`

and the thumb. The finger is released as soon as the object is grabbed. An example is to put out a virtual candle by pinching briefly the flame.

- air tap and hold: this gesture gives the possibility to perform an air tap and keep the finger down to hold a virtual object. An example is to pinch a slider and hold it.

Besides the default gestures, I could consider the development of a custom gesture recognition to recognize, say, the grab with the entire hand. An example would be to grab the handle of a virtual door. This may offer a more realistic experience to the user. However, the freedom of a custom gesture recognition comes with the challenge to have an easily testable gesture and a gesture easily understood by the user. In addition, the grab points may not be well recognized by the headset. Potentially, the user may need to repeat the gesture again, and this might be more frustrating than with a simpler gesture like press a button or pinch a slider. But this would need to be tested in further studies.

The discussions with the low vision specialist lead to a preference for an interaction modality that is easily understood and realistic. A clear modality offers a well-defined and reassuring rehabilitation environment. A clear modality helps restrict the experience and what is tested, even if there is a cost of missing on more realistic gesture. In addition, a default gesture already implemented by the chosen device requires less fine-tuning of how the virtual elements work. This offers more stability in the experience and in the test.

With these considerations, I want to start prototyping with the idea to press on a button, like pressing on a light switch. I also want to start prototyping with the idea to pinch a slider. This may not be as natural as grabbing an object with the entire hand. But it offers an additional challenge to the user while being clear and restricted enough to be tested. Figure 16 illustrates a cryptex GRT. The prototype has four cylinders as its core component, black and brown cylinders as its support and three variations of controller component. Each cylinder has four letters. The goal is to align a combination of letters by selecting each cylinder one by one and rotating them to form the desired alignment. The idea for rehabilitation is to train the spotting visual skill to identify the cylinders and their symbols. Figure 16a depicts the version with four buttons: the cylinder is selected with the left and right buttons, the desired letter is chosen with the up and down buttons. Figure 16b depicts the version with two sliders: the cylinder is selected with the horizontal slider, the desired letter is chosen with the vertical slider. Figure 16c depicts the version with radio buttons and normal buttons: the cylinder is selected with the horizontal radio buttons, the desired letter is chosen with the vertical buttons.

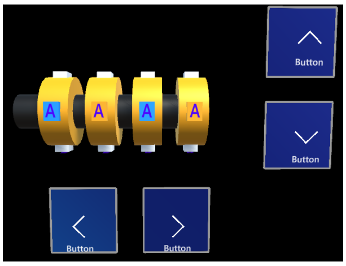
The radio buttons were a default example and is more suitable for on and off choice, or discrete selection. As such, there may be some limitation in their use for gamification within rehabilitation. The classical buttons seemed to have more potential. It can easily take different shape and offer the possibility for repetition of movements which may help remember gestures through the rehabilitation - compared to a one time choice with the radio button. The slider, while more complex, seemed to have great potential in selecting objects, moving objects an axe or rotating them.

Other designs emerged, based on tracing and hand-eye coordination paper-based tasks, and are illustrated in Figure 17. While they bring added creativity and freedom of movement, this freedom of interaction is more challenging to properly evaluate. There is hand-eye coordination without any constraint, compared to a slider, and as such, this represent a considerable challenge for PVIs. The formative study advises to keep such implementation for a later study. As such, these designs are discarded for my current work.

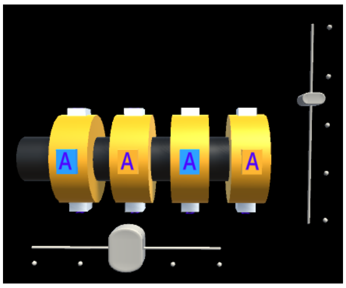
Pretest #1[15]. I pretested the cryptex in its three variations in three different locations:

- At home: Figure 18 shows the cryptex floating (a) near a wall and (b) above a desk. Not an actual pretest because it was simply my own experience. However, this example help to

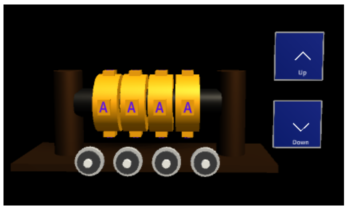
[15] Code source: `https://github.com/SeriousAR-for-LowVisionRehab/ar-lv-game/releases/tag/v0.1.0`



(a) Touch four buttons: the cylinder is selected with the left and right buttons, the desired letter is chosen with the up and down buttons.

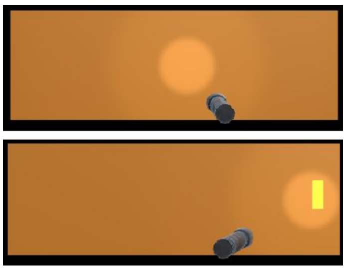


(b) Air tap and hold two sliders: the cylinder is selected with the horizontal slider, the desired letter is chosen with the vertical slider. The user air tap and hold a slider and then slide it to the desired position.

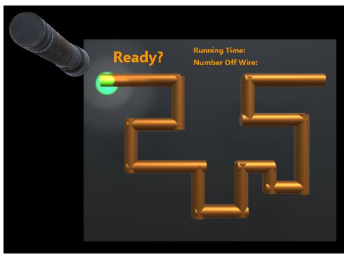


(c) Touch radio buttons and buttons: the cylinder is selected with the horizontal radio buttons, the desired letter is chosen with the vertical buttons.

Figure 16: Prototype #1 of a cryptex GRT to train the spotting visual skill. It is illustrated with three version of its controller component: (a) a variation with buttons only, (b) a variation with sliders only, and (c) a variation with buttons and radio buttons.



(a) Hand-eye coordination: a virtual light torch to reveal hidden objects



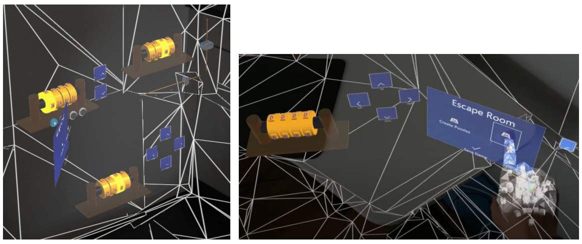
(b) Hand-eye coordination: a virtual light torch to follow a line

Figure 17: Discarded examples with hand-eye coordination using a virtual torch: (a) reveal hidden objects, (b) follow a pipe.

understand how the real background may interfere with the virtual objects. Bright natural light and windows created stability problems and the virtual objects were more difficult to perceive and interact with.

- At university: Figure 19 shows (a) the empty desk and (b) the cryptex above a desk with wireframe. This was a pretest with a student at the university of Fribourg.

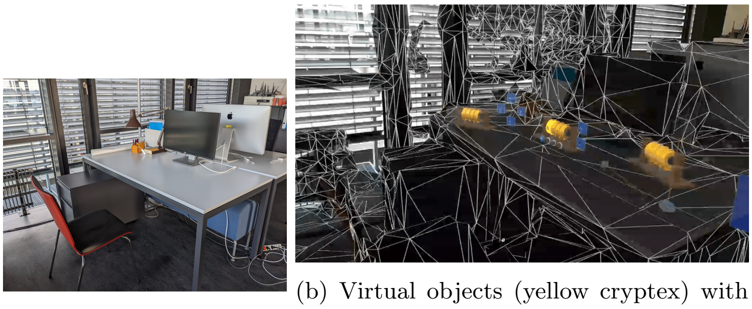
- At rehabilitation center: (no picture) I presented the prototype to the low vision specialist. The first impressions are that buttons are easier to work with, compared to sliders. While discussing the mock-ups, the specialist emphasized that natural interaction might be more beneficial. Even though *hand ray* was not implemented, from the comment of the specialist, this gesture is not a natural way of interacting for a human and will be discarded from my exploratory work. In addition, the specialist shared that the slider may be a rehabilitation task in itself. This is about keeping the focus of the slide along the slider's axis, and can be assimilated to hand-eye coordination on a small scale.



(a) Cryptex at home floating near a wall with wire-frames on.

(b) Cryptex at home floating over a desk with wire-frames on and hand recognized.

Figure 18: Examples of self-made test at home: (a) the cryptex floats near a wall, (b) the cryptex floats above a desk. This is a pretest with an initial use of spatial mapping and debug wire-frames to show what is recognized by the headset.



(a) Desk only

(b) Virtual objects (yellow cryptex) with meshes of recognized world by the device

Figure 19: Pretest #1 of the cryptex with different controllers

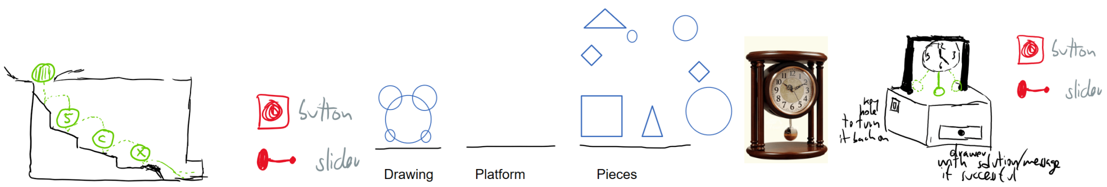
The technology discovery iteration helped to structure the components of a GRT and find the appropriate gestures to consider for an exploratory work in the context of low vision rehabilitation: a touch-based gesture with buttons, and an air-tap and hold based gesture with sliders.

4.2 Exploration

This subsection is about the exploration of ideas to design GRTs sketches and to prototype some mechanics of an escape room.

Sketch #2. At this moment in my work, I have decided to use both a touch-based gesture with buttons, and an air-tap and hold based gesture with sliders. Any task should have a controller for each type of gestures. For a clearer nomenclature, I will use from now own the term **button modality** to designate an interaction based on the touch-based gesture with buttons, and the term **slider modality** to designate an interaction based on an air-tap and hold based gesture with sliders. These two interaction modalities are discussed in greater details later in Section 5.1 Interaction modalities.

After an initial iteration over sketch, prototype pretest, further sketches were attempted with the knowledge acquired from the early formative study's part. They are illustrated in Figure 20. The non optimized use of the slider modality in the task in Figure 20a make it not adapted. The unnatural use of button or slider modalities versus use of hands in the drawing copy task in Figure 20b. Due to potential cognitive overload in the task in Figure 20c, having a moving target to practice the tracking visual skill might be too complex for an introduction to AR HMD device for PVIs.



(a) Bouncy ball sketch: click on the bouncing ball at the right moment. Downside: unease with bouncing virtual object, unnatural use of slider modality.

(b) Drawing copy sketch: use pieces on the right to copy the drawing illustrated on the left. Downside: unnatural use of button and slider modalities.

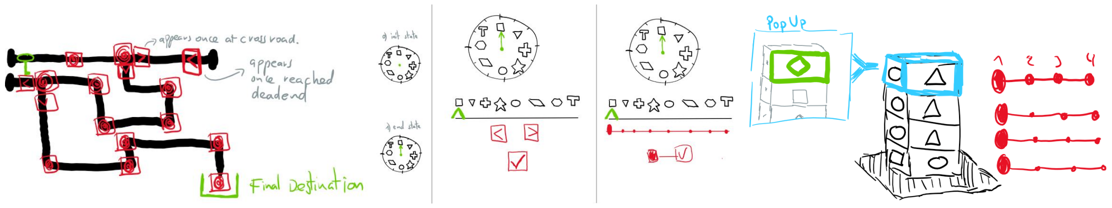
(c) Pendulum sketch: click on the swinging pendulum at the right moment. Downside: unease with swinging virtual object, unnatural use of slider modality.

Figure 20: Discarded sketches due to complexity and non-optimal use of interaction modalities: (a) bouncy ball, (b) drawing copy, (c) pendulum.

The ability to combine knowledge and discussions' feedback did lead to three successful sketches that will be kept for the final escape room. Figure 21a represents the pipes task which is based on tracing visual skill, and the user presses on buttons or pinches & slides on slider to make a key move out of the pipes. The use of pipes come from the similarities to lines and curves used in traditional tracing exercises. In Figure 21b, the training of spotting visual skill is required to select in the middle the correct shape indicated by the clock at the top. The user needs to select and confirm her choice. In traditional exercises, the use of familiar shapes help the client to train in a reassuring environment. As such, the idea of a clock and basic shapes seemed an appropriate start. The third task, Figure 21c, is a tower where spotting visual skill is trained again. A each level of the tower, a hint is given to the user and the user needs to select the same shape by rotating the current level using the controller. The choice of a tower is to train spotting information along a taller or longer object that may be of use in daily life activities.

The escape room emerged from the combination of three GRTs which are based on the sketches illustrated in Figure 21. The three type of tasks are: **pipes**, **clock**, and **tower**. To have a captivating escape room experience, a narrative needs to be present. In the context of my work, a minimal story is build around solving the three tasks in a successive order: get the key out of the pipes task, then the key automatically starts the clock task which the user needs to solve to obtain hints, use the hints to solve the tower task and discover a treasure.

Each task went through four iterations, each having their own code release on my repository: prototypes #2 v0.2.0, prototypes #3 v0.3.0, v0.4.0 with pretest #2, and v1.0.0 being the final version for the implementation. The implementation of the escape room is detailed in the next section. Each GRT will have a controller for the button modality and one for the slider modality.



(a) Pipes sketch: train tracing visual skill.

(b) Clock sketch: train saccade and spotting visual skills.

(c) Tower sketch: train saccade and spotting visual skills.

Figure 21: Chosen three sketches for the GRTs of the escape room: (a) pipes to train tracing, (b) a clock to train saccade and spotting visual skills, and (c) tower to train saccade and spotting visual skills.

For clarification, Figure 22 has the top line, (a) to (d) with button modality, and the bottom line, (e) to (h), for slider modality. Each column is for a different version: 1st (a) and (e) for v0.2.0, 2nd (b) and (f) for v0.3.0, 3rd (c) and (g) for v0.4.0, and 4th (d) and (h) for v1.0.0. Start buttons are only shown when they change for simplification in the pictures. Figure 22f should be displaying similar sliders as the other versions.

Prototype #2[16]. The first task, **pipes**, in Figure 22, is based on the tracing visual skills. There is an attempt to add identification at the intersection with the buttons, Figure 22a, but this is not used for the pinch&slide.

4.3 Adaptation

The third row is about **Adaptation** of the designed GRTs with respect to feedback from low vision specialists and conducting formal pretest of the prototyped escape room.

Prototype #3[17]. For **pipes**, the identification at the intersection is dropped. The discussions with experts point to a possibly overloaded environment for the PVIs and a need to explore the new technology step by step is recommended. For **clock**, the selection is clarified with a <> shaped middle-point added on the selection line. The contrast of the round background of the clock is changed to have a stronger contrast with the four yellow shapes. For **tower**, a dark blue background for the tower elements is used. The window with hints and the controller are regrouped on the right of the tower. Regrouping the elements on one side will require less saccade, and less fatigue for the PVIs. While this is the third and last task in the escape room, it might still be better to lessen the burden on the visual training for now. Overall for each GRTs, the *start* button has not changed and is not showed in the 2nd column. For each GRTs, the user-interface has a text for *Turns left*, *Time*, and *Points*.

Pretest #2[18]. The 3rd column is an iteration used for the first formal pretest conducted in a formal setting with proper protocol as presented in Section 6 Experimental Design. **pipes** has a new set of icons with the distinctive meaning of a lock. From discussions with low vision specialists, the length of the pipes are increased such that the task is not contained in its entirety in the field of the vision of the PVIs. Otherwise, there might not be any training to discover what lies in the task, and eccentric vision might not be trained sufficiently. **clock** has again a new contrast for the round. Similar to the **pipes**' buttons, the buttons for the **clock** and the **tower** are now harmonized with clearer icons: red arrows for left and right selection, and a green check for the validation. Similarly, the slider version has a red slider for selection, and a green one for the validation. Each GRTs has now the same *start* button and slider for the respective versions.

[16]Code source: `https://github.com/SeriousAR-for-LowVisionRehab/ar-lv-game/releases/tag/v0.2.0`
[17]Code source: `https://github.com/SeriousAR-for-LowVisionRehab/ar-lv-game/releases/tag/v0.3.0`
[18]Code source: `https://github.com/SeriousAR-for-LowVisionRehab/ar-lv-game/releases/tag/v0.4.0`

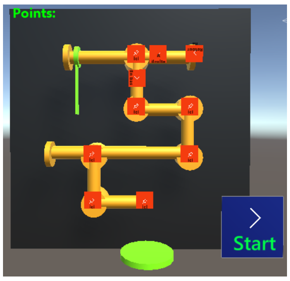
Their user-interface's text elements are now aligned horizontally on each task.

4.4 Finalization

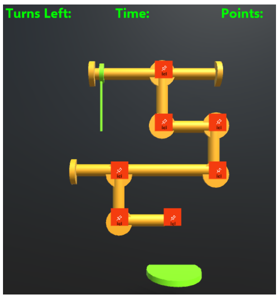
The last row is about **Finalization** of the prototyped GRTs as an escape room with respect to the pretests feedback. This finalized version forms the escape room presented in the Section 5 Implementation.

Final[19]. Finally, the last columns of Figures 22, Figures 23, and Figures 24 are the GRTs for the implementation of the final escape room, which is discussed and presented in the next section. Only the **clock** sees a modification, again in terms of contrast of the round of the clock. The challenges around the contrasts between multiple colors will be discussed in more details in the Section 9 Limitations and Future Work.

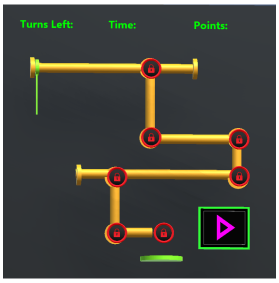
[19]Code source: `https://github.com/SeriousAR-for-LowVisionRehab/ar-lv-game/releases/tag/v1.0.0`



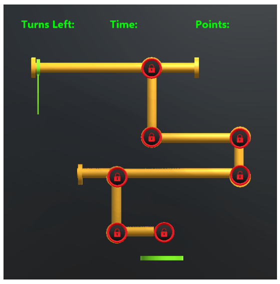
(a) Buttons: the user needs to identify where to go at each intersection.



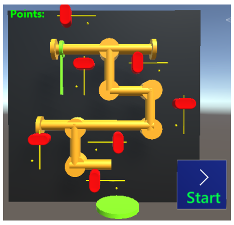
(b) Buttons: the user has only one possible path to follow. The UI shows turn left, time and points.



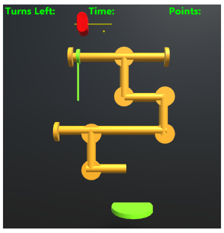
(c) Buttons: the user follows longer pipes to increase the use of eccentric vision. Button start has a new contrasted icon.



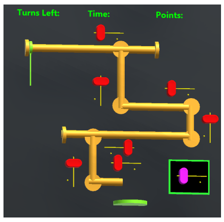
(d) Buttons: the pipes task is finalized.



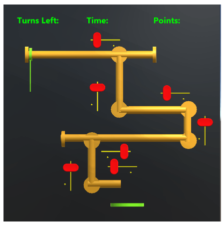
(e) Sliders: the user has only one possible path to follow.



(f) Sliders: the illustration shows the state of the task at the beginning when the user sees only one slider. The UI shows turn left, time and points.

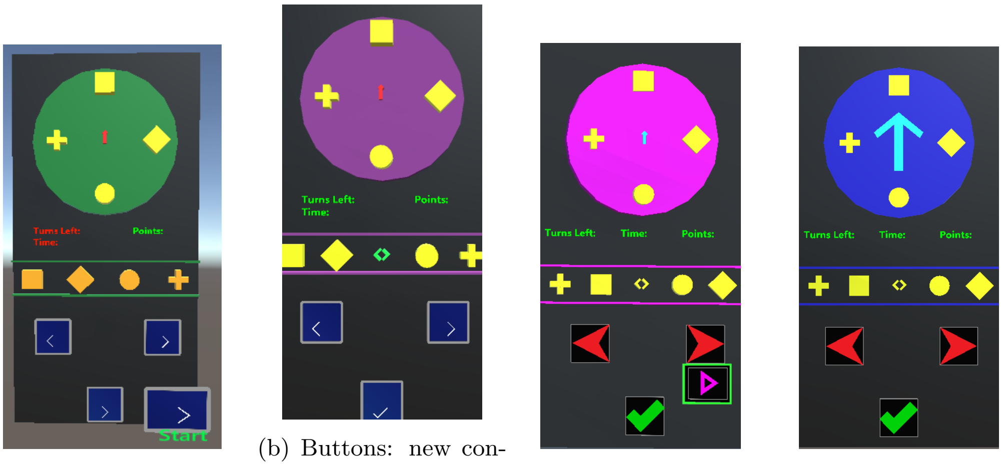


(g) Sliders: Button start has a new contrasted icon.

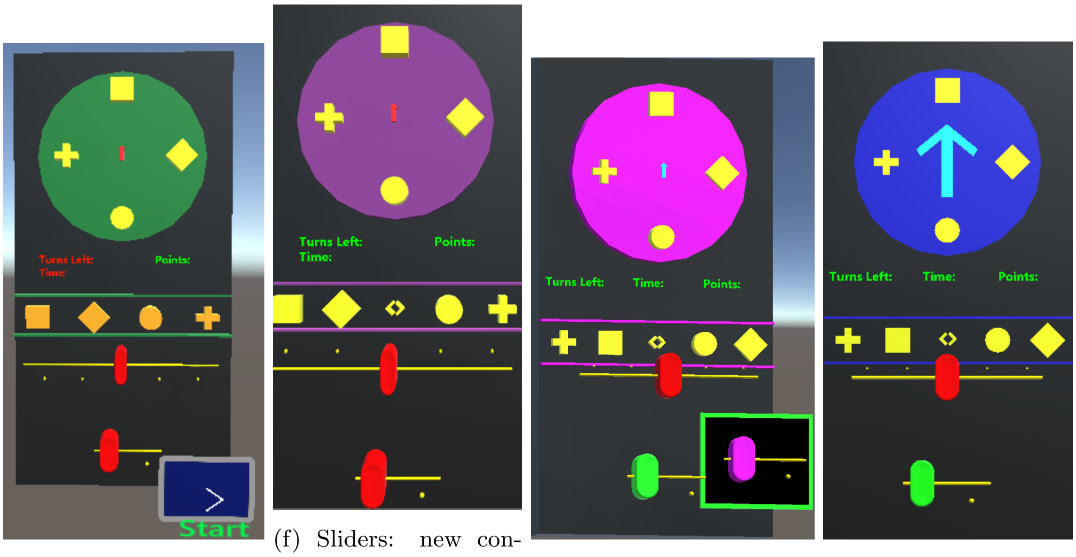


(h) Sliders: the pipes task is finalized.

Figure 22: **Pipes** evolution with the button modality on the top line and the slider modality on the bottom line: (a, e: v0.2.0) attempt to use identification at intersection with buttons, (b, f: v0.3.0) simplified to only one track of pipes (button start not shown for simplicity), (c, g: v0.4.0) harmonized start button and slider, increased length of some pipes, and new icons for pipes' buttons, and (d, h:: v1.0.0) final version used for evaluations.

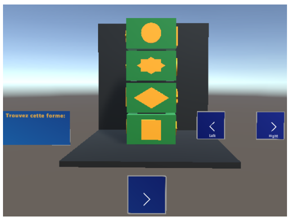


(a) Buttons: initial prototype (b) Buttons: new contrasts and middle selector (c) Buttons: new icons for buttons (d) Buttons: New contrast

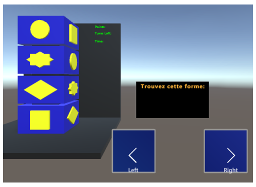


(e) Sliders: initial prototype (f) Sliders: new contrasts and middle selector (g) Sliders: new color for sliders (h) Sliders: New contrast

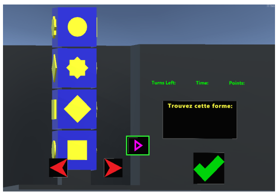
Figure 23: **Clock** evolution with the button modality on the top line and the slider modality on the bottom line: (a, e: v0.2.0) initial prototypes, (b, f: v0.3.0) new contrasts and middle selector (button start not shown for simplicity), (c, g: v0.4.0) harmonized start buttons, new buttons icons and sliders colors, and new contrast, and (d, h:: v1.0.0) final version with new contrast used for evaluations.



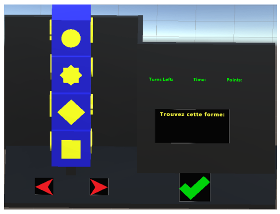
(a) Buttons: tip window and controller on each side



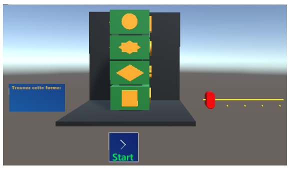
(b) Buttons: new contrast, regroup tip window and controller on the right



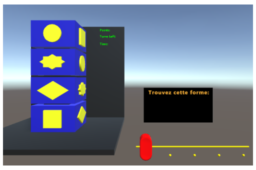
(c) Buttons: harmonized buttons



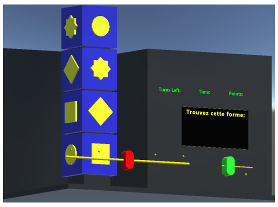
(d) Buttons: final version



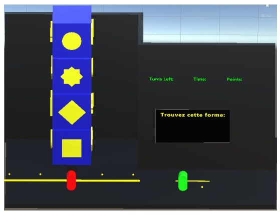
(e) Sliders: tip window and controller on each side



(f) Sliders: new contrast, regroup tip window and controller on the right



(g) Sliders: harmonized sliders



(h) Sliders: final version

Figure 24: **Tower** evolution with the button modality on the top line and the slider modality on the bottom line: (a, e: v0.2.0) tip window and controller on each side of the tower, (b, f: v0.3.0) new contrast, regroup tip window and controller on the right, (c, g: v0.4.0) harmonized buttons and sliders, added background, harmonized UI texts, and (d, h:: v1.0.0) final version used for evaluations.

5 Implementation

The previous section discussed the progress from sketches to actual GRTs. This section presents how the three selected GRTs, **pipes**, **clock** and **tower**, come together to form the final AR escape room[20]. In other words, the developed escape room is constituted of three GRTs: one pipes, one **clock** and one **tower** task. An escape room can be solved by using a press gesture, Figure 29a or a pinch & slide gestures, Figure 29b. The former interaction modality uses buttons and the latter uses sliders. The person creating the escape room, e.g. a low vision specialist, decides which interaction modality to use.

The Figure 25 shows a real example and use of the developed escape room.

(a) Overview of the room setup: one desk on the right with laptop for protocol and consent form, three desks and chairs on the left for the GRTs, windows with closed blinds, two lamps for optimal lights.

(b) Example of the developed escape room viewed from the device

(c) User in action from an external point-of-view

Figure 25: The developed AR escape room illustrated in three pictures: (a) room overview, (b) an example of the escape room viewed from the device, and (c) a user in action from an external point-of-view.

The Figure 26 shows a schema overview of the developed escape room, the three tasks it contains, the transition time required to the first task and between the others, and the interactions required to perform each tasks. A technical schema is given in Figure 30.

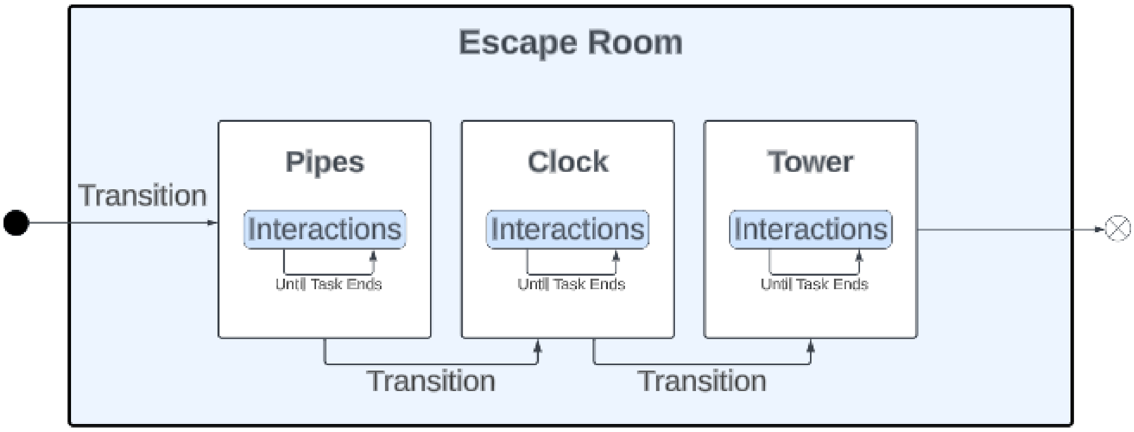


Figure 26: The developed escape room contains three tasks. There is transition times to the first task and between each tasks. For each task, the user has to do certain interactions to complete the task.

I use specific terms to consider data collected and these terms are explained in the Table 5. The terms related to interaction modalities are illustrated in the next sub-section.

[20]Final code source: `https://github.com/SeriousAR-for-LowVisionRehab/ar-lv-game/releases/tag/v1.0.0`.

Table 5: Terms used in the analysis of the experiment with an explanation.

Term (with abbreviation used)	Explanation
Task duration (Task)	Time spent to complete a given task
Escape room duration (ER)	Sum of time spent on the 3 tasks and of time to move from task to task
Hover	The move on the slider or button without actually touching it
Start interaction (Start I.)	To actually air tap the slider or press the button without releasing it
Success interaction (Success I.)	An interaction that creates the required result
Errors Hover	Number of hover performed without a successful interaction
Errors Interaction (Errors I.)	Number of start interactions performed without a successful interaction
Minimum successful interaction (Min. I.)	for each of the 3 tasks, there exists a minimum of interaction required to finish the task

5.1 Interaction modalities

Button modality. To interact with a button, the user does a press gesture. The Figure 27 illustrates the required phases of the modality.

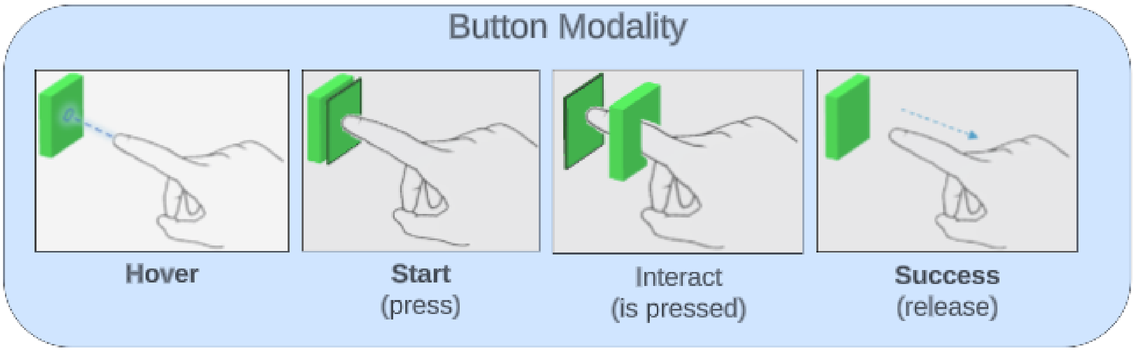


Figure 27: The button modality contains 4 phases: (1) hover, (2) start interaction, (3) actually interact, and (4) success interaction. These phases happen has the user approach her index toward the button, through the front plate to the back plate, and finally release the pressure on the black plate.

Slider modality. To interact with a slider, the user does a pinch & slide gesture. The Figure 28 illustrates the required phases of the modality.

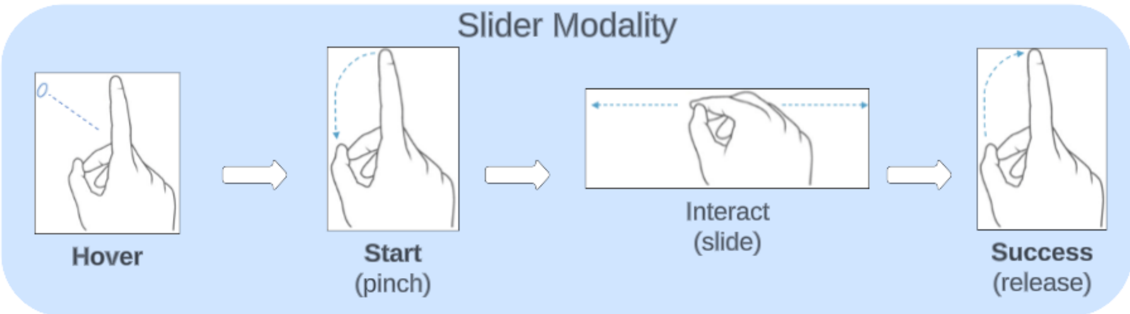
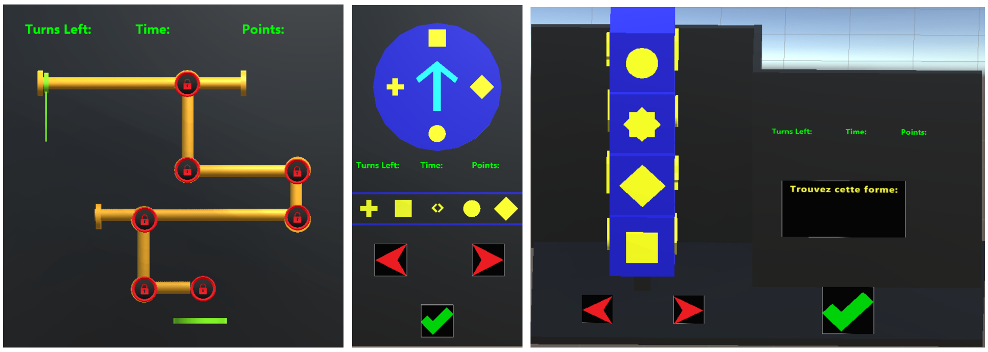


Figure 28: The slider modality contains 4 phases: (1) hover, (2) start interaction, (3) actually interact, and (4) success interaction. These phases happen has the user approach her index toward the cursor of the slider, pinch the cursor, slide it to the desired position and release the pressure on the cursor.

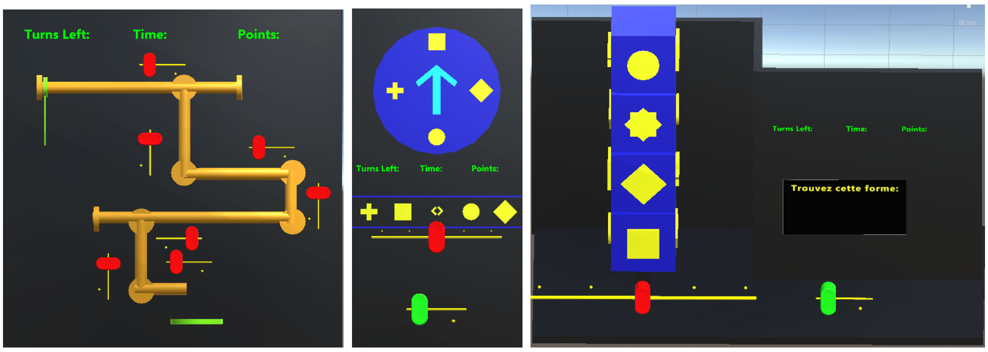
5.2 Creating the escape room

Game preparation. To start the game, it is assumed that a specialist or any person accompanying the PVI will be responsible to launch the application on the HoloLens 2 device and set up the escape room. This set up is done by clicking the creation button in the home menu, Figure 31a, and accessing the creation menu, Figure 31b. The main part is to place three markers, one for each task (blue for pipes, green for clock, and red for tower), in the desired place in the real environment[21]. The positions of the markers can be loaded from a JSON file for reproducible tests. Once the markers in place, one click on "Place Tasks On Settings' Markers" will place the tasks; the buttons pipes and sliders pipes will be at the same location, and similarly for clock and

[21] In my code development, I had difficulties in using spatial mapping (`https://learn.microsoft.com/en-us/windows/mixed-reality/design/spatial-mapping`) to place the tasks at chosen locations. For now, the virtual objects representing the tasks are placed manually.



(a) Press GRTs: (left to right) pipes, clock, and tower



(b) Pinch&Slide GRTs: (left to right) pipes, clock, and tower

Figure 29: Escape room with (a) press, and (b) pinch&slide gestures

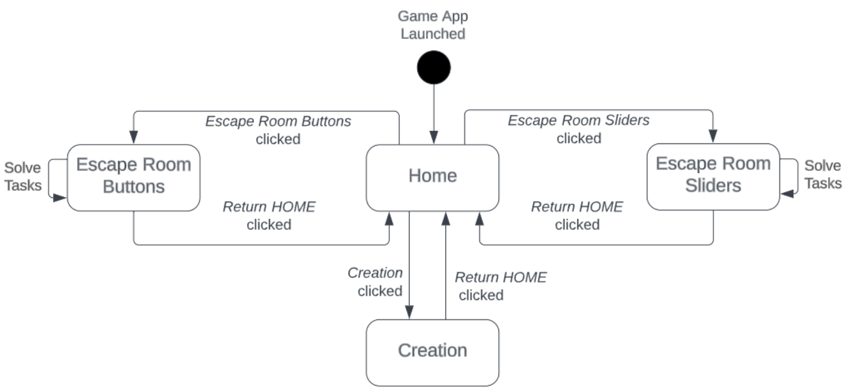
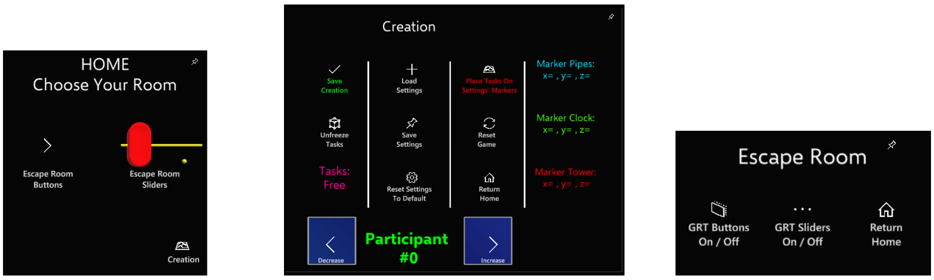


Figure 30: Technical schema of the implemented menus: the user arrives on the Home menu at the launch of the app and can create an escape room with Creation button. Once created, a user can enter either escape room and solve the three tasks to complete the escape room.

tower. One click on ”Save Creation” will freeze the tasks in place and mark the escape rooms as ready to play. The next step is to go back to home menu and select one of either escape room, by a press or a pinch & slide gesture. Once into the desired escape room, the first task, pipes, will appear. At this moment, the headset can be given to the PVI. Once an escape room is solved, the escape room menu, Figure 31c, can be used to return to the home menu and select the other escape room there. The escape room menu is used to hide the previous tasks, e.g. the GRT buttons if the first escape room was the escape room buttons and is now the escape room sliders.



(a) Home menu (b) Creation menu (c) Escape Room menu

Figure 31: Menus in the game

5.3 Playing the escape room

Headset. With the headset on herself, the user can go in front of the first task and position herself as comfortably as possible either sited or standing. The first task is always the **pipes**. Once the button or slider start activated, the task's time limit is activated: there is a time limit during which points can be accumulated, and after which no point is given but the task can still be finished. The **pipes** is solved once each buttons or sliders have been activated and the key is metaphorically out of the pipes. Then, a green box will cover the task and a finish sound will be heard. The second task, always the **clock**, will appear. Once started, the user will face four rounds of thirty seconds each. One round consists of looking at the top clock and recognize which shape is highlighted. Then, select the same shape with either left and right arrow buttons or the red slider. Finally, validate the choice with a check button or a green slider. For each correct validation, a point is given and a positive sound is activated. For each incorrect validation, the selection is reset without sound and the user needs to try again within the given thirty seconds. Once the fourth round ended, the task is covered with a green box and the **tower** task is showed. There, the user faces again four rounds of thirty seconds each with the goal to identify a given shape on the right in a window. The task starts with the lowest level, the cube at the bottom, highlighted. The user rotates the cube on the right or left with either arrow buttons or a slider. Once the same shape is in front of the user, she validates her choice with the check button or green slider on the right. A correct validation gives a sound and the cube one level above is highlighted. An incorrect choice will reset the current level and the user needs to try again within the thirty seconds. At the end of the fourth and top level, the escape room ends.

Currently, the menus, especially the creation menu, were implemented for practical purposes for myself to ease the preparations and obtain reproducible tests where the location of each tasks will be the same, given that the application is started at the same real location each time. This limitation is discussed later on.

Tutorial. At the application's start, there is a button and a slider placed automatically in front of the user at a fixed position. This enables the user to practice both gestures as illustrated in Figure 32.

The initial format of the tutorial had text and videos. However, based on the formative study, they were removed as reading is considered a difficult task for PVIs and might not be appropriate for an initial exploration of a new technology for their rehabilitation. The video explanations were replaced by verbal explanations and printed documents.

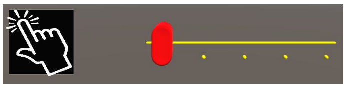


Figure 32: Tutorial for the button modality (left) and the slider modality (right). To complete the tutorial: the button needs to be pressed 5 times, and the slider needs to be pinched & slide to each yellow mark on the horizontal axis.

5.4 Data collection and limitation

Data collection. There are an automatic recording of data into a JSON file. This records the number and time per click and slide on each task of each escape room. The goal is to illustrate the type of data and the ease to record them, for both the low vision specialist, and for the client herself. However, creating a dashboard of the data collected is out of the scope of my work.

Limitations. The virtual tasks need to be placed manually via markers, and to repeat the same setting, the application needs to be launched from the same physical point to have a similar initial position. Ideally, the solution is to use the spatial mapping of the device but this was not achieved in my work. The contrasts of the different tasks and elements can not be changed by the user or low vision specialist. A settings menu with predefined color sets would be ideal. The size of the tasks can not be adjusted in the application but can be changed relatively easily in the game engine. Other limitations will be discussed later in the final sections of my work.

6 Experimental Design

My thesis has two principal objectives. The first one is about identifying key features. The second is about the usability of the system and the accessibility of the interaction modalities. I wanted to assess the accessibility of the solution with respect to the type of gestures used to perform the interaction modalities in the escape room. The two interaction modalities are the button modality and the slider modality. I conducted two within-group experiments. The first experiment was done with a population of 20 sighted individuals and the second experiment was done with a population of 5 PVI. I detail the quantitative and qualitative hypotheses in the next subsection. Then, I give details on the participants, the procedure, and the questionnaires used.

6.1 Hypotheses

I explore the usability of the AR escape room with a quantitative evaluation with 20 sighted individuals. More precisely, I will focus on two interaction modalities: the slider modality, and the button modality.

Both the slider and the button are basic virtual elements in the creation of an AR application. The slider offers an efficient way to chose among a wide selection. A button will be less efficient to go through numerous choices, but it would offer a quick answer to confirm a yes-no choice. In addition, it might be more complicated to interact with a slider in AR than to interact with a button considering the detailed actions required and presented in the previous section. To gamify an experience, it is important to have the appropriate mechanic. As such, I want to explore which of the slider modality and button modality takes more time and creates more errors by interacting with them. For the quantitative evaluation, I consider an hypothesis on time spent on a task, and an hypothesis on the number of errors made to accomplish that task:

1. **Quantitative - Time:** $H_0 : \mu_{\text{duration with slider modality}} \geq \mu_{\text{duration with button modality}}$
2. **Quantitative - Error:** $H_0 : \mu_{\text{number of errors with slider modality}} \geq \mu_{\text{number of errors with button modality}}$

I explore qualitatively the accessibility of the AR escape room with 5 PVI with different visual impairments through semi-structured interviews. I am interested in exploring if the slider modality is less intuitive than the button modality.

3. **Qualitative:** the slider modality is less intuitive than the button modality

6.2 Participants

There are two populations considered for the experiment: population A with sighted individuals, and population B with PVI.

For **population A**, I recruited 20 participants by personal message invitations through my personal network. Only *Participant0* has visual impairment (spatial neglect) and is excluded from the quantitative analysis. To keep a balanced number of participants between the order of the two conditions, I have removed the last participant by simplicity and because no clear outlier could easily identified in the data. I am left with 18 sighted participants (44% (8) female, 56% (10) male; age median (56%) in 25-34 age bracket, min. in 18-24 (17%), max. in ¿65 (6%)). These participants did not participate in any of my pretests.

For **population B**, The FSA recruited 5 participants (40% (2) female, 60% male; age median (60%) in 35-44 age bracket, and the rest (40%) in 25-34) with visual impairments from their client-base. To participate in my exploratory work, any type of visual impairments is welcome, and both central and peripheral vision losses are welcome to participate. Table 6 shows some demographic information and the Table 27 in the Appendix shows the full and detailed information available. These participants did not participate in any of my pretests. Two of the participants (PVI0 and PVI1) are currently doing rehabilitation, and three (PVI2, PVI3 and PVI4) have only received information but not started. 4 have scotoma and central vision impairment (PVI0, PVI2, PVI3 and PVI4). One has has peripheral vision loss (PVI1).

Table 6: Demographic information of the 5 PVI participants. Information collected from questionnaire and FSA documents, and WHO's notation (www.who.int). Detailed information available in the annex. CVL = Central Vision Loss, PVL = Peripheral Vision Loss.

Alias	Age/Sex	Rehabilitation Stage	Diagnosis	WHO impairment
PVI0	35-44 / F	Intermediate	CVL	moderate
PVI1	25-34 / M	None	PVL	severe
PVI2	35-44 / F	Just started	CVL	moderate
PVI3	35-44 / H	Informative	PVL	blindness
PVI4	25-34 / F	Informative	CVL	moderate

6.3 Procedure

I consider a within-group experiment with two dependent variables and one independent variable with two conditions. The dependent variables are the duration to complete a task of the escape room and the number of errors done during a task. The independent variable is the interaction modality and has two conditions: slider modality and button modality. The experiment is done once with population A and once with population B. Because it is a within-group experiment, each participants perform the experiment under both conditions: they complete the escape room once with the slider modality and once with the button modality.

The experiment lasted between 30 min and 90 min with an average of about 45 min, in a room at the university of Fribourg. The sighted participants arrived directly at the room by themselves. A low vision specialist from the FSA accompanied each of the 5 PVI individually and stayed for the entire session. The blinds of the room were closed and lights were turned on. The Figure 33 illustrates the layout of the room. The low vision specialist judged that the setup was ideal with a darkened room, direct and indirect floor lamp with possibility to turn off and adjust intensity, tasks were in front of a real white walls, and overall minimization of external real information and noises.

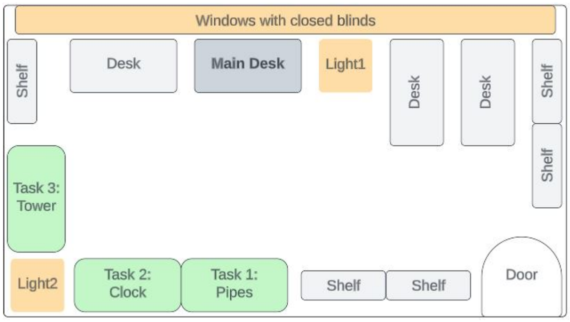


Figure 33: Sketch plan of the room where the experiment took place. The setup was confirmed to be ideal by low vision specialist. Main Desk (dark grey) was used to read protocol, sign consent form and answer questionnaire. Blinds were closed, Light1 was always turned on, and Light2 was on by default but turned off for PVI1, PVI3 and PVI4 participants.

The Figure 34 illustrates the 8-step process that each participant went through:

1. **Protocol and consent form.** I read the protocol of the experiment to each each participants. In addition, I read the consent form aloud to the 5 PVI participants of population B and to *Participant0* of population A. The other participants read the consent form themselves. All participants signed the form.
2. **Introduction questions and tutorial.** Each participant answered the introduction questions of the questionnaire. After, each participant wore the headset and performed the tutorial: five press gesture on a button, and five pinch & slide gesture on a slider.
3. **Escape room with 1^{st} modality.** Then, each participant started the escape room with either the slider modality or the button modality. I balanced the experiment.
4. **Questions for 1^{st} modality.** Once the escape room finished, each participant answered the part of the questionnaire related to the interaction modality they used.
5. **Escape room with 2^{nd} modality.** Then, each participant started the same escape room with the other gesture.
6. **Questions for 2^{nd} modality.** Once the second escape room finished, each participant answered the part 2 of the questionnaire which relate to the escape room done.
7. **Final questions.** Each participant answered the final questions of the questionnaire to compare the two modalities.
8. **Final interview.** I concluded the experiment with a final interview. I conducted an open discussion with population A. To retrieve the maximum information on precise topics, I conducted a semi-structured interview with each PVI participants of population B.

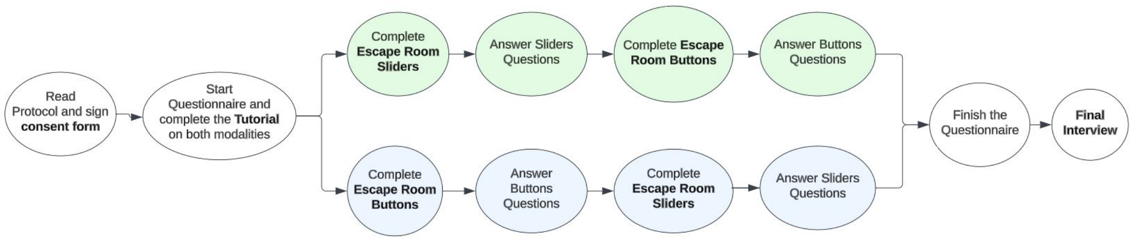


Figure 34: Schematic overview of the procedure. After being welcomed and informed about the experimental protocol, the participants were performing the escape room experiment. Each participants performed the escape room in both conditions: the slider modality and the button modality. The order of the conditions were balanced between the participants. A questionnaire follows the participant along the experiment. A final interview concludes the experiment.

6.4 Questionnaire and semi-structured interview

My questionnaire is based upon the spatial interaction evaluation (SPINE) questionnaire[27]. The SPINE questionnaire has six main sections:

1. system control (SC) is about general usability of the system and overall control of the app
2. navigation (NG) measures movement through space
3. manipulation (MP) measures clarity of directions from the app, selection

4. (SL) measures important elements and actions within the app, input modalities
5. (IM) such as gaze, gesture and voice, and last section is output modalities
6. (OM) such as audio, text, holograms and spatial arrangement

In addition, I inspired myself from the questionnaires developed by my supervisor Yong Joon Thoo. These questionnaires are particularly tailored to experiments with PVI and offer pertinent aspects with respect to their visual impairments. My questionnaire was given for both populations and was available in either French or English. The questionnaire has 4 parts: (1) demographic and past experiences, (2) escape room with first interaction modality, (3) escape room with second interaction modality, and (4) overall preference for the interaction modality. An example is available in the Appendix B.2.

For the population A (sighted participants), the experiment was concluded with an unstructured interview. For the population B (PVI), the experiment was concluded with a semi-structured interview to ensure maximum and relevant information on critical points: the rehabilitation phase, potential to rehabilitate with AR GRTs, motivational aspect, and potential to train at home.

7 Results

This section is split in two subsections: one to present the results on the usability of the system, and one to present the results on the accessibility of the interaction modalities. Each subsection presents results from: (1) the experiment itself, (2) the questionnaire, and (3) the final interview. Additional quantitative data are available in the Appendix C.

in the Section 5 Implementation, the Table 5 explains terms that are important in the implementation. I use some of these terms to present the results. The Table 7 lists the abbreviations of these terms used in the tables' headers in this section.

Table 7: Terms used in the results and their abbreviation.

Term	Abbreviation
Escape room duration	ER
Task duration	Task
Hover duration/count	Hover (depends on table's name)
Start interaction	Start I.
Success interaction	Success I.
Minimum successful interaction	Min. I.
Errors Interactions	Errors I.

7.1 Usability of the system

I performed pretests before reaching the final version of the developed escape room. It was important for user experience design consideration. For the final version, it is also important to ensure an effective and satisfying experience. As such, exploring the usability of the system is an important aspect. This subsection has 4 parts. First, it gives an overview of the data from the experiment. Then, it presents the results on the experiment, the questionnaire and the final interview are presented in separated parts below.

7.1.1 Data overview of population A's experiment

The data collected during the experiment of population A is presented from three different perspective to give an overview and to understand if any trend emerges in the data. Table 8 presents the data per escape room order: A if the participant started her first escape room with slider modality, and B if the participant started with the button modality. Table 9 presents the data per interaction modality: slider and button. Table 10 presents the data per type of task: pipes, clock and tower. The data is presented with means and standard deviations. Each table has a sub-table (left) for duration data and a sub-table (right) for counts data. The duration data is the time spent in an escape room, time spent on a task, and time for the phases of an interaction. The count data is the number of attempts for each phases of an interaction, and for a relative reference, the minimum interaction required to complete a given task.

Escape room order. The Table 8 presents in two sub-tables the duration (left) and count (right) data per escape room order. The first line is when participants start the experiment with the slider modality. The second line is when participants start the experiment with the button modality. The third line is the p-value for difference in means between the escape room order A and B. The first column of the left sub-table shows that participants starting the experience with the Slider modality spent a significantly higher average time in their escape room than the participants whom started the experience in an escape room with buttons. These participants with escape room order A also made significantly more hover attempts when there first escape room is with sliders.

Table 8: Population A: For each escape room order (A = slider modality, B = button modality), the mean and standard deviation of the duration (left, in seconds) and count (right) of the phase of an action: hover, start interaction, success interaction and the minimum successful interaction. ER = escape room's order, I. = interaction, Mod. = Modality, Min. = minimum. The last row shows significance of the mean differences with p-value: *p < 0.1, **p < 0.05, ***p < 0.01.(N=18)

ER	ER	Task	Hover	Start I.
A	338.08	56.33	24.71	11.29
	(279.49)	(72.53)	(32.67)	(9.92)
B	259.25	43.08	16.74	10.48
	(100.52)	(27.54)	(14.16)	(10.37)
p	*			

ER	Hover	Start I.	Success I.	Min. I.	Errors I.	Errors Hover
A	25.17	9.78	9.43	9	0.35	15.74
	(35.46)	(3.32)	(3.41)	(1.43)	(0.73)	(36.35)
B	14.91	10.06	9.56	9	0.5	5.35
	(8.02)	(3.38)	(3.23)	(1.43)	(1.18)	(7.79)
p	**					

Interaction modality. The Table 9 presents in two sub-tables the duration (left) and count (right) data per interaction modality. The first line is for the slider modality. The second line is for the button modality. The third line is the p-value for difference in means between the slider and the button modalities. The takeaway is that the slider modality has a significantly higher duration on each measured variable (escape room, average per task, hover, start interaction) and significantly higher number of interaction and hover errors. The button modality has significantly higher number of success interaction than the slider modality.

Type of task. The Table 10 presents in two sub-tables the duration (left) and count (right) data per type of task. The first line is for the pipes task. The second line is for the clock task. The third line is for the tower task. The last three lines are p-value for difference in means between: (p:c) the pipes and the clock tasks, (p:t) the pipes and the tower tasks, and (c:t) the clock and the tower tasks. The type of task does not seem to create any significant difference in time spent per task or in any of the phases of an interaction. The only significant difference in start and success interaction can be explain by the minimum number of interactions required to complete each task: 7 for the pipes, and 10 for both the clock and the tower.

Table 9: Population A: For each interaction modality, the mean and standard deviation of the duration and count of the phase of an action: hover, start interaction, success interaction and the minimum successful interaction. ER = escape room's order, I. = interaction, Mod. = Modality, Min. = minimum. The last row shows significance of the mean differences with p-value: *p < 0.1, **p < 0.05, ***p < 0.01. (N = 18)

Modality	ER	Task	Hover	Start I.
Slider	358.08	62.99	34.87	17.9
	(274.39)	(71.3)	(29.62)	(10.05)
Button	239.25	36.42	6.58	3.86
	(94.35)	(25.8)	(3.89)	(2.2)
p	***	**	***	***

Mod.	Hover	Start I.	Success I.	Min. I.	Errors I.	Errors Hover
Slider	28.41	8.91	8.06	9	0.85	20.35
	(34.88)	(2.34)	(1.72)	(1.43)	(1.25)	(35.21)
Button	11.67	10.93	10.93	9	0	0.74
	(4.05)	(3.86)	(3.86)	(1.43)	(0)	(1.14)
p	***	***	***	n.a.	***	***

Table 10: Population A: For each type of task, the mean and standard deviation of the duration and count of the phase of an action: hover, start interaction, success interaction and the minimum successful interaction. ER = escape room's order, I. = interaction, Mod. = Modality, Min. = minimum. The last row shows significance of the mean differences with p-value: *p < 0.1, **p < 0.05, ***p < 0.01. (N=18)

Task	ER	Task	Hover	Start I.
Pipes	298.67	57.79	24.59	9.37
	(214.77)	(89.29)	(36.15)	(8.56)
Clock	298.67	43.85	18.49	10.32
	(214.77)	(27.78)	(18.43)	(10.52)
Tower	298.67	47.47	19.09	12.96
	(214.77)	(19.95)	(17.28)	(11.01)
p p:c				
p p:t				
p c:t				

Task	Hover	Start I.	Success I.	Min. I.	Errors I.	Errors Hover
Pipes	22.22	7.44	7	7	0.44	15.22
	(42.8)	(1)	(0)	(0)	(1)	(42.8)
Clock	19.86	10.67	10.25	10	0.42	9.61
	(13.18)	(3.39)	(3.26)	(0)	(1.13)	(14.76)
Tower	18.03	11.64	11.22	10	0.42	6.81
	(8.26)	(3.42)	(3.57)	(0)	(0.81)	(9.41)
p p:c		***	***			
p p:t		***	***			
p c:t						

7.1.2 Quantitative results from experiment

For population A, 9 participants started the experiment with the slider modality and 9 participants started the experiment with the button modality. The data is balanced with 18 data observation for each possible pair of interaction modality (slider, button) and task (pipes, clock, and tower). For hypothesis 1 and 2, I conducted ANOVA tests to understand the impact of the interaction modalities and the type of tasks in general with the data of both escape rooms and all three tasks. I conducted additional ANOVA tests to understand if interaction modalities and type of tasks have different impact when I consider a specific escape room order or a specific task.

Hypothesis 1: Time. The hypothesis 1 is on the time required to complete any of the three tasks. My assumption was that a task with sliders requires more time than the same task with buttons. To understand if the interaction modality or the type of task influences the time, the Table 11 shows the results from a two-ways repeated measures ANOVA on time spent to complete the tasks using the entire data of population A. The first line indicates that the interaction modality has a significant impact on time spent to complete any of the three tasks. The second line shows no significant impact from the type of task on time. The third line shows no interaction effect between the interaction modality and the type of task.

Table 11: Two-ways repeated measures ANOVA on time on the entire data of population A.

	Df	Sum Sq	Mean Sq	F value	Pr(>F)
Interaction modality	1	19074.16	19074.16	6.57	0.0118
Task type	2	3769.85	1884.93	0.65	0.5247
Interaction modality:Task type	2	4718.56	2359.28	0.81	0.4466
Residuals	102	296220.63	2904.12		

The Table 12 shows the results from a two-ways repeated measures ANOVA on time for each escape room order: second column of the table is for escape room with sliders, and last column is for escape room with buttons. The first line indicates that the interaction modality has a significant impact on time spent to complete any of the three tasks with the slider. However, there is no significant impact with a button.

Table 12: Simplified ANOVA results with only the p-value results from a two-ways repeated measures ANOVA on time in task. There is one test for each escape room (ER) order: second column is ER with sliders, and last column is ER with buttons.

	ER Slider: Pr(>F)	ER Button: Pr(>F)
Interaction modality	0.0093	0.6727
Task Type	0.3216	0.7653
Interaction modality:Task Type	0.1941	0.5787

The Table 13 shows the results from a two-ways repeated measures ANOVA on time for each task type: second column of the table is for pipes, third for clock, and last for tower. The first line indicates that the interaction modality has a significant impact on time spent to complete the clock and tower tasks, but no significant impact regarding the pipes task.

Hypothesis 2: Error. Each of the two considered modalities contain several phases and errors can be made a different moment of the gesture. As such, I want to check for error made at two different moments: I consider a type of error made when the user hovers a slider or a button, and a type of error made when the user interacts with the slider or the button. My assumption was that a user makes more errors in a task with a slider.

The Table 14 shows the results from a two-ways repeated measures ANOVA on interaction

Table 13: Simplified ANOVA results with only the p-value results from a two-ways repeated measures ANOVA on time in task. There is one test for each type of task: second column of the table is for pipes, third for clock, and last for tower.

	Pipes: Pr(>F)	Clock: Pr(>F)	Tower: Pr(>F)
Interaction modality	0.1330	0.0245	0.0294

errors. The first line indicates that the interaction modality has significant impact at 1% level on the number of interaction errors made while completing any of the three tasks. The second line shows no significant impact from the type of task on the number of interaction errors made. The third line shows no interaction effect between the interaction modality and the type of task.

Table 14: Two-ways repeated measures ANOVA on interaction error.

	Df	Sum Sq	Mean Sq	F value	Pr(>F)
Interaction modality	1	19.59	19.59	24.14	0.0000
Task type	2	0.02	0.01	0.01	0.9887
Interaction modality:Task type	2	0.02	0.01	0.01	0.9887
Residuals	102	82.78	0.81		

The Table 15 shows the results from a two-ways repeated measures ANOVA on interaction errors for each escape room order. The first line indicates that the interaction modality has a significant impact on interaction errors made, whether I consider only the escape room with sliders (second column) or only the escape room with buttons (last column).

Table 15: Simplified ANOVA results with only the p-value results from a two-ways repeated measures ANOVA on interaction errors in task. There is one test for each escape room (ER) order: second column is ER with sliders, and last column is ER with buttons.

	ER Slider: Pr(>F)	ER Button: Pr(>F)
Interaction modality	0.0003	0.0019
Task Type	0.7461	0.9564
Interaction modality:Task Type	0.7461	0.9564

The Table 16 shows the results from a two-ways repeated measures ANOVA on interaction errors for each type of task. The first line indicates that the interaction modality has a significant impact on interaction errors made, whether I consider only the pipes task (second column), the clock task (third column) or the tower task (last column).

Table 16: Simplified ANOVA results with only the p-value results from a two-ways repeated measures ANOVA on interaction errors in task. There is one test for each type of task: second column of the table is for pipes, third for clock, and last for tower.

	Pipes: Pr(>F)	Clock: Pr(>F)	Tower: Pr(>F)
Interaction modality	0.0057	0.0248	0.0010

The Table 17 shows the results from a two-ways repeated measures ANOVA on hover errors. The first line indicates that the interaction modality has significant impact at 1% level on the number of hover errors made while completing any of the three tasks. The second line shows no significant impact from the type of task on the number of hover errors made. The third line shows no interaction effect between the interaction modality and the type of task.

Table 17: Two-ways repeated measures ANOVA on hover error.

	Df	Sum Sq	Mean Sq	F value	Pr(>F)
Interaction modality	1	10384.08	10384.08	16.80	0.0001
Task type	2	1322.35	661.18	1.07	0.3470
Interaction modality:Task type	2	1393.72	696.86	1.13	0.3279
Residuals	102	63050.61	618.14		

The Table 18 shows the results from a two-ways repeated measures ANOVA on hover errors for each escape room order. The first line indicates that the interaction modality has a significant impact on hover errors made, whether I consider only the escape room with sliders (second column) or only the escape room with buttons (last column).

Table 18: Simplified ANOVA results with only the p-value results from a two-ways repeated measures ANOVA on hover errors in task. There is one test for each escape room (ER) order: second column is ER with sliders, and last column is ER with buttons.

	ER Slider: Pr(>F)	ER Button: Pr(>F)
Interaction modality	0.0015	0.0000
Task Type	0.2563	0.5560
Interaction modality:Task Type	0.2382	0.8290

The Table 19 shows the results from a two-ways repeated measures ANOVA on hover errors for each type of task. The first line indicates that the interaction modality has a significant impact on hover errors made, whether I consider only the pipes task (second column), the clock task (third column) or the tower task (last column).

Table 19: Simplified ANOVA results with only the p-value results from a two-ways repeated measures ANOVA on hover errors in task. There is one test for each type of task: second column of the table is for pipes, third for clock, and last for tower.

	Pipes: Pr(>F)	Clock: Pr(>F)	Tower: Pr(>F)
Interaction modality	0.0363	0.0003	0.0000

7.1.3 Answers from questionnaire

The first data presented is to understand the past experiences of population A around video games, escape room, VR and AR. Then, I present and compare the data about their experience with the two interaction modalities. The answers are based on a 5-point Likert scale from 1=strongly disagree to 5=strongly agree.

Past experiences. In Figure 35, population A shows a relative comfort in doing escape room with a mean rating of 4.22 (1.06). But the comfort in doing video games in general, 3.61 (1.38), and using either an AR, 2.72 (1.23), or VR, 3.17 (1.25) headset is relatively well spread across the different answers and no clear tendencies.

Interaction modalities. For population A (sighted individuals), Table 20 shows the means and standard deviations of ratings for questions on the slider and the button modalities. Table 21 shows the number of answers on each task and overall for the slider modality, the button modality, or for no preference.

With respect to Table 20, population A (sighted individuals) has a mean above 4 and a standard

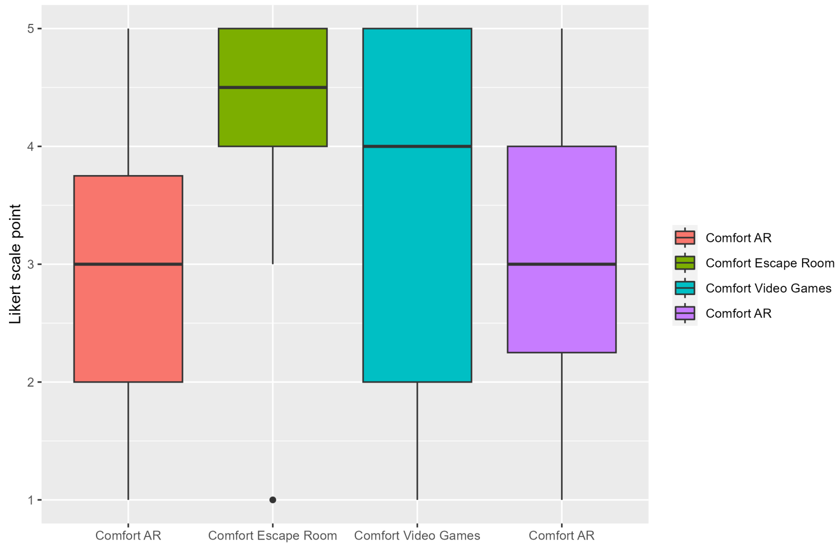


Figure 35: Boxplots of the answers from population A about their level of comfort on a Likert scale from 1 = strongly disagree to 5 = strongly agree (Y-axis). Population A has a relatively high level of comfort in escape room (median = 4.50) and video games (median = 4.00), and moderate comfort in both VR (median = 3.00) and AR (median = 3.00).

deviation below 1 on every questions on each modalities and overall. There is a significant difference at a 1% level between the means of managing to control the respective task with ease: slider = 4.11 (0.96), button = 4.83 (0.38), and p-value = 0.007259. In a similar way, there is a significant difference at a 5% level between the means of receiving a clear confirmation when performing actions: slider = 4.50 (0.79), button = 4.94 (0.24), and p-value = 0.032450. There is also a significant difference, at a 10% level, between the means of the certainty of the functions of the user interface (UI) elements: slider = 4.72 (0.46), button = 4.94 (0.24), and p-value = 0.080400. The other questions have no significant difference in means.

Table 20: The ratings (mean and standard deviation) from population A on a 5-point scale for the use of slider and button modalities. The last column shows the significance, if any, of the mean differences t-tests' results: *p < 0.1, **p < 0.05, ***p < 0.01. (UI = user interface)

Question	Slider	Button	p-value
I managed to control these tasks with ease	4.11 (0.96)	4.83 (0.38)	***
I was sure about the functions of the UI elements.	4.72 (0.46)	4.94 (0.24)	*
I could position myself easily to have the best experience.	4.11 (0.96)	4.50 (0.79)	
I received clear confirmation of the actions I was performing.	4.50 (0.79)	4.94 (0.24)	**
I could select the UI elements because their size was sufficient.	4.78 (0.55)	4.83 (0.38)	
I could select the UI elements because their contrast was sufficient.	5.00 (0.00)	5.00 (0.00)	
I could select the UI elements because their shape was distinctive.	4.89 (0.32)	4.94 (0.24)	

In Table 21, population A shows a relative preference overall for the button modality (10 counts) against the slider modality (6 counts) and no preference (2 counts). Population A shows a relative preference in the tower task for the slider modality (10 counts) against the button modality (6 counts) and no preference (2 counts). No clear preference in interacting with either the slider modality or the button modality on the pipes and clock tasks.

Table 21: The preference counts (slider, button, or no preference) of population A on each tasks and overall.

Question	Slider	Button	No preference
In the Pipes task, I preferred to interact using the gesture to...	8	9	1
In the Clock task, I preferred to interact using the gesture to...	8	10	0
In the Tower task, I preferred to interact using the gesture to...	10	6	2
Overall, I preferred to interact with a task using the gesture to...	6	10	2

7.1.4 Analysis of the final interview

I conducted an open discussion for the final interview of population A. Some of the most relevant comments are listed below:

- **Feedback and haptic**: "In real life, if I take my mouse, I can feel it when I grab it. But with the slider, I do not know what kind of precision I need to have to actually grab it.", (Participant15). "Would it have been interesting to do in VR (vibrating haptic feedback) and see VR so better?", (Participant3).
- **Colors**: "Technology side, colors could be more vivid" (Participant10)
- **Modality**: "Advice: it must be said to exaggerate the gesture for the pinch, slowly.", (Participant1). "Nice slider especially for the last one" (Participant3)
- **Hardware**: "the AR headset is more comfortable to wear than a VR headset. you're not bad after using it, and it's good to always see your environment.", (Participant4).
- **General**: "It reminds me of the little simple games where you have to place the cubes in the right forms, etc.", (Participant18).

The takeaways from the open discussion will complement the discussion in the next section 8 Discussion.

7.2 Accessibility of the interaction modalities

Even though I used basic interaction modalities such as sliders and buttons, their accessibility to a population with visual impairments is not necessarily guaranteed. To try to understand to which extend it is accessible, it is interesting to explore the accessibility of the specified modalities through the developed escape room. This subsection has 4 parts. First, it gives an overview of the data from the experiment. Then, it presents the results on the experiment, the questionnaire and the final interview are presented in separated parts below.

I explored the accessibility of the interaction modalities with population B which is composed of PVI. This subsection has 4 parts. First, it gives an overview of the data from the experiment. Then, it presents the results on the experiment, the questionnaire and the final interview are presented in separated parts below.

7.2.1 Data overview of population B's experiment

Similar to population A, the data collected during the experiment of population B is presented from three different perspective to give an overview. I will only briefly present the tables because, to the difference of population A, no tests of difference in means are computed for population B. The data is from 4 participants only because PVI1 could not finish the experience because the size and contrast of virtual elements were not adapted to her visual conditions. To keep a maximum of information, the data is kept unbalanced: 1 participant started the experiment with the slider modality, and 3 participants started the experiment with the button modality. Table 23 presents the data per escape room order: A if the participant started her first escape room with slider gesture, and B if the participant started with the button gesture. Table 23 presents the data per interaction modality: slider and button. Table 24 presents the data per type of task: pipes, clock and tower. The data is presented with means and standard deviations. Each table has a sub-table (left) for duration data and a sub-table (right) for counts data. The duration data is the time spent in an escape room, time spent on a task, and time for the phases of an interaction. The count data is the number of attempts for each phases of an interaction, and for a relative reference, the minimum interaction required to complete a given task.

Escape room order. The Table 22 presents in two sub-tables the duration (left) and count (right) data per escape room order. Only one participant represents the data of the first line.

Table 22: Population B: For each escape room order (A = slider modality, B = button modality), the mean and standard deviation of the duration (left, in seconds) and count (right) of the phase of an action: hover, start interaction, success interaction and the minimum successful interaction needed to complete a task. Abbreviations: ER = escape room's order, I. = interaction, Min. = minimum. (N=4)

ER	ER	Task	Hover	Start I.
A	839 (347.4)	128.64 (36.59)	8.39 (14.84)	5.02 (8.09)
B	412.51 (110.79)	68.32 (27.35)	27.97 (25.26)	13.12 (12.36)

ER	Hover	Start I.	Success I.	Min. I.	Errors I.	Errors Hover
A	6.17 (7.78)	3.17 (3.54)	3.17 (3.54)	9 (1.55)	0 (0)	3 (5.62)
B	21.56 (14.21)	9.61 (2.89)	9.28 (2.99)	9 (1.46)	0.33 (0.59)	12.28 (14.55)

Interaction modality. The Table 23 presents in two sub-tables the duration (left) and count (right) data per interaction modality.

Table 23: Population B: For each interaction modality, the mean and standard deviation of the duration and count of the phase of an action: hover, start interaction, success interaction and the minimum successful interaction needed to complete a task. (ER = escape room's order, I. = interaction, Min. = minimum). (N = 4)

Modality	ER	Task	Hover	Start I.
Slider	582.1 (347.28)	93.72 (36.07)	38.43 (25.05)	18.47 (12.98)
Button	456.16 (137.79)	73.08 (41.46)	7.72 (10.04)	3.73 (2.34)

Modality	Hover	Start I.	Success I.	Min. I.	Errors I.	Errors Hover
Slider	26 (16.09)	7.25 (3.6)	6.75 (3.33)	9 (1.48)	0.5 (0.67)	19.25 (13.69)
Button	9.42 (5.25)	8.75 (4.63)	8.75 (4.63)	9 (1.48)	0 (0)	0.67 (1.07)

Type of task. The Table 24 presents in two sub-tables the duration (left) and count (right) data per type of task.

Table 24: Population B: For each type of task, the mean and standard deviation of the duration and count of the phase of an action: hover, start interaction, success interaction and the minimum successful interaction needed to complete a task. Abbreviations: ER = escape room's order, I. = interaction, Min. = minimum. (N=4)

Task	ER	Task	Hover	Start I.
Pipes	519.13 (278.66)	95.71 (54.86)	33.72 (26.21)	12.17 (7.94)
Clock	519.13 (278.66)	69.49 (28.37)	16.1 (19.42)	8.27 (8.44)
Tower	519.13 (278.66)	85.01 (30)	19.4 (26.23)	12.84 (17.65)

Task	Hover	Start I.	Success I.	Min. I.	Errors I.	Errors Hover
Pipes	19.88 (14.26)	7.38 (0.74)	7 (0)	7 (0)	0.38 (0.74)	12.88 (14.26)
Clock	18.12 (16.82)	8.62 (4.41)	8.38 (4.37)	10 (0)	0.25 (0.46)	9.75 (15.4)
Tower	15.12 (13.64)	8 (5.93)	7.88 (5.87)	10 (0)	0.12 (0.35)	7.25 (11.56)

7.2.2 Quantitative results from experiment

Due to the limited size of 4 participants, no statistical test is conducted for the population B. Only an overview of the data is given above in 7.2.1 Data overview of population B's experiment.

7.2.3 Answers from questionnaire

The first data presented is to understand the past experiences of population B (PVI) around video games, escape room, VR and AR. Then, I present and compare the data about their experience with the two interaction modalities. The answers are based on a 5-point Likert scale from 1=strongly disagree to 5=strongly agree.

Past experiences. In Figure 36, population B has a mean rating of 4.00 (SD=1.41) for being comfortable exploring an escape room activity. It has a mean rating of 2.60 (1.67) for being comfortable playing video games. The mean ratings for being comfortable using a VR and an AR headset is 2.20 (1.79) and 2.60 (1.67) respectively.

Interaction modalities. For population B (PVI), Table 25 shows the means and standard deviations of ratings for questions on the slider and the button modalities. shows the mean and standard deviation for the preferred interaction modality on each task and in general. Table 26 shows the number of answers on each task and overall for the slider modality, the button modality, or for no preference.

With respect to Table 25, Population B has a mean between 3.00 and 4.00, and a standard deviation 1.52 and 1.95 across the different questions on a 5-point scale. There is no significant difference between the slider and button modalities on any questions.

In Table 26, population B shows no clear preference in interacting with either the slider modality or the button modality on each task (pipes, clock and tower) and overall.

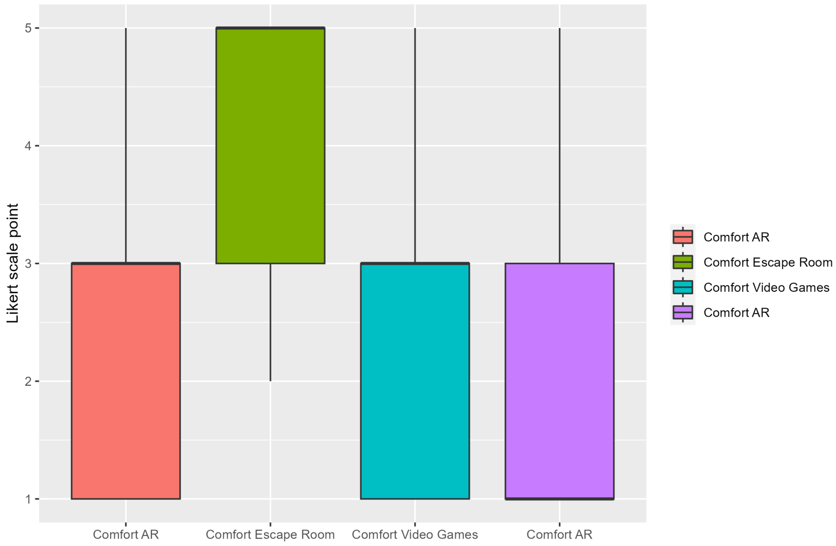


Figure 36: Boxplots of the answers from population B (PVI) about their level of comfort on a Likert scale from 1 = strongly disagree to 5 = strongly agree (Y-axis). Except for escape room, population B has a relative low to medium comfort in AR, video games and VR.

Table 25: The ratings (mean and standard deviation) from population B (PVI) on a 5-point scale for the use of slider and button modalities. The last column shows the significance, if any, of the mean differences t-tests' results: $*p < 0.1$, $**p < 0.05$, $***p < 0.01$. (UI = user interface)

Question	Slider	Button	p-value
I managed to control these tasks with ease	3.60 (1.67)	3.00 (1.58)	
I was sure about the functions of the UI elements.	3.80 (1.64)	3.80 (1.64)	
I could position myself easily to have the best experience.	3.40 (1.82)	3.40 (1.52)	
I received clear confirmation of the actions I was performing.	3.20 (1.79)	3.80 (1.79)	
I could select the UI elements because their size was sufficient.	3.60 (1.95)	3.40 (1.82)	
I could select the UI elements because their contrast was sufficient.	3.40 (1.82)	3.20 (1.79)	
I could select the UI elements because their shape was distinctive.	4.00 (1.73)	3.60 (1.95)	

Table 26: The preference counts (slider, button, or no preference) of population B (PVI) on each tasks and overall.

Question	Slider	Button	No preference
In the Pipes task, I preferred to interact using the gesture to...	1	2	2
In the Clock task, I preferred to interact using the gesture to...	1	2	2
In the Tower task, I preferred to interact using the gesture to...	3	2	0
Overall, I preferred to interact with a task using the gesture to...	2	2	1

7.2.4 Analysis of the final interview

As a final interview, I conducted a semi-structured interview for each PVI. PVI1 data is not taken into account in the quantitative analysis but his qualitative feedback are taken into consideration. This interview is an important part in my exploratory work to gather valuable insights from the PVI on their experience with the AR escape room. As such, I present below an extended and consequent analysis of the final interview. I consider the comments made on the aesthetic and mechanic of the developed escape room, the comments related to the rehabilitation itself, and some more general comments to conclude the analysis of the final interview.

AESTHETIC

Size. The size of virtual elements can be of importance to interact with them and to be relevant for the low vision rehabilitation. PVI0, PVI2, PVI4 had no particular problem with the size of the elements. PVI1 and PVI3 had a more difficult time with the sizes. For the clock task, PVI0 participant mentioned that the task "needs to be enlarged to really use the vision points [ndlr: eccentric and new PRL]".

In term of feedback, the use of an increased size is relevant and welcomed by the participants in the developed tasks. For example, the default white box around the button might not be enough. But a bigger button with an effect similar to the slider may be interesting.

Depth. Because PVI may already have difficulties to perceive depth in real life, increasing the depth of the virtual element may help some PVI participants distinguish the different states of them. Also, the "3D effect" of the icons on the buttons (in contrast to a flat icon on a button) may help to distinguish the button better: the user can move around the shape to perceive it as a button. In the clock and tower tasks, the icons with left and right arrows and the icon of check seemed to be well perceived due to their relative in-depth 3D effect.

Shape. Some of the shapes used may be perceived as too similar by some PVI participants. The shapes are uses in the clock and the tower tasks: a round and a sun-like figures may be confusing if the spikes of the sun-like figure is not distinctive enough; a square and a diamond (i.e. a rotated square) may be confusing.

Contrast. In order to discriminate between two colors, color contrast, or the difference in brightness between the foreground and background colors, is a crucial notion. In the developed tasks, yellow was a problem when coupled with orange or with light blue. For example in the pipes task, the yellow bar of the slider next to the orange pipes was difficult to distinguish and the controller (the slider) was difficult to interact with. In the tower, the yellow shapes to identify were difficult to distinguish because the background was in light blue. For the tower, PVI3 participant said the yellow and light blue felt like "bright on bright". An improvement would be to use a darker blue.

The color red can also be an issue for different reasons. If coupled with orange for example, in the pipes task, the cursor of the slider is red and is sometimes near the orange pipes. "The red buttons on the yellow of the pipes are difficult to perceive." said PVI3 participant. In addition, red and green can commonly be confused by some PVI. In term of brightness, a dark red may be less perceived than a bright red. PVI3 participant mention for the sliders in general that the "contrast from light red to dark red does not help. We lose where we are going.".

Each of tasks was developed with a virtual black background. This was perceived as a very good foundation for a task. In the developed escape room, this created sufficient contrast when the virtual elements were colored red, yellow, orange or magenta. The red and the yellow of the slider was well perceived over the virtual black background in any of the three tasks. Similarly, the orange pipes of the pipes task was easily distinguished. In each task, the magenta of the start slider or button over a virtual black background was well perceived.

MECHANIC

Feedback. Some of the virtual elements are outside of the field of vision. A problem arises when these elements change but the user does not receive any visual or audio feedback. They are outside of the field of vision for rehabilitation purposes and train visual skills. Audio feedback is an interesting way to go, as noted by PVI4 participant who said that "the sounds help a lot", and PVI0 said "it's funny, the noises". For example, the slider requires a constant hold and it is sometimes not clear for user if they are still holding it. PVI1 participant noted that a "background noise could be useful for feedback when holding the slider or button".

Visual feedback is also appropriate, such as the size of the slider changing when we first pinch it. However, a feedback too bright and too surprising is to be avoided. An example, of something too bright and too surprising, is the green box that surround a task when it is completed in the developed escape room.

Timer is a classic element of gamification to add a note of thrill and challenge. In low vision rehabilitation, a client should take her time to accomplish the task correctly and not necessarily as quickly as possible. As such, a count down timer like the one used in the developed escape room might not be optimal for everyone: PVI0 participant said "time is my pet peeve, so with the timer, I can get demoralizing feedback". A solution could be to add an option to deactivate the timer at the client's wish. Another one would be to have an incremental timer which, if recorded, would help both the client and the low vision specialist to understand the progression in the rehabilitation and be a motivating factor.

Control. From the questionnaire, the preferences of the interaction modality are mixed. With only 4 PVI completing the experience, interpretation from the escape room order and the preference of the modality is complicated. The only PVI starting with the slider modality actually preferred the button modality. From the three PVI starting with the button modality, two of them preferred the slider and one of them the button. The participants preferring the slider said that it was more fun, more playful, and more to do than just going through a button. The participants preferring the button said that it was easier, easier to understand if the interaction is done, and the feedback from the slider was not really clear. From the final interview, a few clearer points emerge from the 5 PVI participants. The buttons are seen as easier than the slider generally speaking and at the beginning. However, with enough time to get used to it, the slider may have its advantages. For example, the use of the slider in the tower to rotate the cube was well suited: PVI0 participant noted "It's smart". The slider is also appreciated when a choice must be made along a long linear list like the choices in the clock task. When only a yes-no or a confirmation action is required, the button modality is better suited.

REHABILITATION

From the 5 PVI participants, PVI0 participant is in intermediate stage of rehabilitation and PVI2 participant just started her rehabilitation. PVI0 participant shared that "[I] put in practice what I do at FSA" and "I need to use what I have learned at the FSA". PVI2 participant shared that AR is interesting because everything appears in the right size and not all small, even though the contrast may be improved. PVI2 participant noted that the slider modality could be useful to turn pages (i.e. of a book or newspaper).

The low vision specialist repeated typical instructions to her client. For the pipes task: to keep central vision at the intersection of pipes, and look in periphery to identify where to go next. The low vision specialist suggested to her client, PVI3 participant, to sit down to reduce the movements of the head and body. PVI3 participant said that it helps for the bottom part of task but not for the top.

CONCLUSIVE INSIGHTS

The experience of the developed AR escape room by the 5 PVI from the FSA seemed to be well received in general. "It's awesome" said PVI0 participant and "it is more interesting than the others" relating to the rehabilitation software on PC. More importantly, PVI0 participant said that "the playful side with AR makes the passage to 'I am visually impaired' less difficult to do the exercise because it is less real, therefore less painful.".

Contrasts seemed to have been an issue overall and seem to require the most improvement for future work. Sizes and shapes of virtual elements may benefit from customizable settings with respect to each client's specific vision conditions. The three developed tasks were placed at a desk-level in the experiment room. The low vision specialist may benefit from an option to choose the level at which the task is optimally placed for the client during her rehabilitation training.

The room was lit with two floor lamps. A room that is dark avoids the risk of glare. But at the same time, user may have difficulties to perceive her own hands. A room that is too bright may disrupt the context around the virtual objects. Not only because of glare on the real objects, but also because white spot from the light may be taken for a false virtual object.

8 Discussion

Valuable results were obtained from the experiments on both the usability of the system and the accessibility of the interaction modalities. I discuss them separately in the next two subsections.

8.1 Usability of the system

The **interaction modality** has significant impacts on the time spent to complete any task in the developed escape room, and on the number of errors made to complete them. The significant impact on time and on errors is present whether I consider every tasks at once, or whether I consider each task separately. The type of tasks, whether it is pipes, clock or tower task, has no significant impact on either time or errors. This clears the possibility that my design and implementation choices of any of the three tasks developed influence the results significantly. In addition, the average time spent in a task and the average number of errors made per task are significantly greater when sliders are used compared to buttons in the developed escape room.

The discussions with the sighted participants support in general the above findings. In the sense that the button modality is preferred by around two thirds of them because it is easier to master, more direct and quicker: "The gesture was quicker and only one click was necessary" said Participant7. However, around one third of the sighted participants highlighted a preference for the slider for the challenge of mastering it, because it is more intuitive and faster when choosing something or turning a cube, and offers a more natural side for certain tasks like the clock or the tower. Participant4 said that "the actions performed with the slider were more playful", Participant3 "found the sliders more playful", and Participant18 said "I felt like I was acting, which was less the case with the pressure".

Mixed comments arise regarding the **limited field of vision**. Some stated that they would have preferred to have the entire task included the sliders and buttons in their field of vision. Others stated that it was relatively easy to position themselves such that everything was in their field of vision. While I did not test directly for what was seen in the field of vision, the mixed comments show the importance to customize the size of the tasks to each individuals to ensure that the desired outcome is obtained.

The lack of **haptic feedback** was mentioned. There was interest to experience a VR version of the escape room with haptic feedback and compare the experience with the developed AR escape room. "In real life, if I take my mouse, I can feel it when I grab it. But with the slider, I do not know what kind of precision I need to have to actually grab it." said (Participant15).

8.2 Accessibility of the interaction modalities

To explore the accessibility of the interaction modalities with the PVI population, I made the assumption that the slider modality is less intuitive than the button modality. The results from 5 PVI participants, excluding one who could not finish the developed escape room, were mixed in term of interaction modalities' preferences. An interaction modality can be preferred for its ease of use, like the button, or for its more fun aspect despite the difficulty to use it, like the slider. As such, it seems important to let the user enough time to get used to the chosen interaction modality to overcome that first barrier of a new modality. The low vision specialist noted that button modality seems to require less movement with the head and more movements of the eyes. "very interesting", she said. Slider modality seems to require more head movements and more effort for the eye-hand coordination relative to the button modality. In the end, the optimal choice may well be a mix of the two modalities depending on the design choices made and the goal of the task.

Another important topic of discussion in the interviews was the contrast. The contrast between two colors is well established and numerous guidelines are available to implement elements with appropriate contrasts. The design and implementation of a serious game may require the use of more than two colors. In that context, it is challenging to find the appropriate balance of contrast between three, four or more colors. On the size of virtual elements in general, their size is a matter of preferences and the user should be able to customize those sizes. For low vision rehabilitation, it is interesting to distinguish between the size of the virtual elements with which the user interacts, and the overall size of the task at hand. The overall size should be big enough to encourage sufficient use of residual vision in eccentric training.

The developed escape room was received with enthusiasm by the 5 PVI participants. The use of an AR HMD does not seem to be an issue for them on a short period of time and with sufficient break when needed. This potentially encourages the use of such technology in addition to traditional rehabilitation to offer a gamified experience that may help PVI lessen the negative feeling of being "visually impaired" and focus on the gamified training.

8.3 General takeaways

The experience of the developed AR escape room was generally well appreciated by sighted population: "very interesting, thank you" (Participant1), "It was a great experience, thank you" (Participant2), "The tasks are very intuitive, it was nice." (Participant4), "I want to keep 'playing'. It's really fun." (Participant8), "well prepared, well done game" (Participant9). As mentioned in the previous subsection, the PVI population also appreciated the experience overall.

The AR HMD used offer promising possibility for gamified rehabilitation task if sufficient consideration is taken during the development and with respect to the PVI population and individual needs. The importance to customize the experience to each PVI individual seems to make the most difference in the end. In addition, the duration of the training with such technology and device should be kept to an acceptable time to reduce any fatigue to the maximum.

9 Limitations and Future Work

While I had the chance to have 20 sighted people complete the experience, the limited number of 5 PVI participants make it difficult to analyze and discuss the results in a constructive way for future work. Both the low vision specialists and the PVI population are generally enthusiastic about projects that may support them in their journey. In future work, sufficient effort should be made to include this population early enough in the development and in sufficient numbers despite the barriers to do so.

For the implementation in AR, I used a device that offers spatial mapping[22]. However, I kept my implementation to a simpler method to position my three tasks in the escape room: I used fixed pre-defined positions relative to where the HMD and application were started (i.e. the origin (0,0,0)). While not crucial for this exploratory study, this features would add considerable in context possibilities and an improved experience for ambulatory rehabilitation.

The attempt to change the contrasts based on the pretests and commentaries was not optimal. There should have been a more systematic approach with calculated contrasts between more than two elements. Contrasts between two elements are known. But to design a serious game, more than two colors is easily preferable and this complicates the optimal contrasts. This may be a valuable setting or tool to have in future serious game for PVIs, or even in the game engine itself as an add-in.

It was interesting to offer three type of tasks (pipes, clock, and tower) to explore different uses of the slider and button modality. But some of the time spent in sketching and prototyping might have been allocated to create a level of customization. One example could have been to offer 2 or 3 predefined sizes for each tasks. Another one could be to have 2 or 3 predefined set of colors to adjust the aesthetic of the virtual elements.

10 Conclusion

In my thesis, I collaborated with the FSA, an association for PVI, in the form of a formative study to gather knowledge that was not available due to limited resources in the specific domain. I presented an AR escape room that I implemented with three tasks and with two interaction modalities. I evaluated the usability of the system with a population of 20 sighted participants. I evaluated the accessibility of the interaction modalities with a population of 5 PVI participants. The quantitative analysis with the sighted population showed significant impact from the interaction modalities on time and error on any task in the developed escape room. The qualitative analysis with the PVI population showed that the use of an AR HMD can be appreciated if the appropriate settings are made to match the individual needs of the PVI.

The formative study with the FSA initiated the creation of a process and a framework for the low vision rehabilitation. While in an early stage development and not included in my work, these two documents may offer valuable information and structure for future research. With my exploratory work, I hope that it provides a valuable starting points for others to develop inspiring and adapted solutions to support the PVI in their challenging journey.

11 Acknowledgment

I thank my supervisor Prof. Dr. Denis Lalanne for its guidance. I thank my supervisors Dr. Simon Ruffieux and Yong-Joon Thoo for their continuous feedback, encouraging comments and patience all along my thesis. I thank the people of the Human-IST department at the university of Fribourg for their feedback and suggestion. I thank the people from the "Fédération suisse des aveugles et malvoyants" (FSA), in Fribourg, and especially Laurie Schmutz for her explanations, preparation of documents, and availability. Finally, I thank all the participants.

[22]Spatial mapping on HoloLen2: `https://learn.microsoft.com/en-us/windows/mixed-reality/design/spatial-mapping`

Glossary

basic visual skills are fixation, scotoma awareness, scanning, tracing, spotting, tracking and visual closure. Definition from Fletcher[6]..

eccentric vision is a technique to look around a blind spot and view the desired target using the peripheral vision..

gamification is the use of game design elements in non-game contexts.

ophthalmologist Ophthalmologists are doctors who care for patients with eye conditions. They diagnose, treat and prevent disorders of the eyes and visual system, using medical and surgical skills. source: `https://www.healthcareers.nhs.uk/explore-roles/doctors/roles-doctors/ophthalmology` visited 12.05.2023.

Acronyms

AMD Age-related Macular Degeneration.

AR Augmented Reality.

FSA Fédération suisse des aveugles et malvoyants.

GRT Gamified Rehabilitation Task.

HMD Head-Mounted Device.

LV Low Vision.

LVR Low Vision Rehabilitation.

PRL Preferred Retinal Locus.

PVI People with Visual Impairments.

RQ Research Question.

RT Rehabilitation Task.

VR Virtual Reality.

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A Notes from interviews with FSA

This section regroups the notes taken during some of the meetings with the FSA. The notes were only partially reformatted.

A.1 Meeting 2: Presentation for FSA

Initial visit at the FSA: salle de test et processus d'entrainement

- Lieu: Fédération suisse des aveugles et malvoyants (FSA), Service de consultation Fribourg, Rue Georges-Jordil 2, 1700 Fribourg.
- Date: November 8, 2022.
- Personnes présentes: Laurie Schmutz (FSA), Yong Joon Thoo (UNIFR), Cedric Membrez (UNIFR)
- Next steps [DONE]:
  - Envoyer un email Laurie Schmutz: prendre rdv pour faire le processus en tant que patient afin d'avoir ses commentaires de spécialiste. [Envoyé le 16.11.2022]
  - Demander si la lampe torche pour suivre la ligne est utile comme exercice de coordination [asked by supervisors, 17.11.2022: following the line with a torch is very different from following a line with the finger/pen. But it can still have interesting use; for example, some patients use a laser to point to objects and texts in supermarket to get an audible description of it. But pointing with the laser is not an easy task and it requires training.]

Questions

- Could you illustrate rehabilitation tasks through concrete plan of actions (i.e. a sort of steps taken to train the patient for her residual vision)?
- What experience and advice (related to these plan of actions) could you share?

Context

- Processus d'entraînement aux mouvements oculaires en cas de déficience visuelle

But de l'entraînement

- Favoriser la réorganisation rétino-motrice. Cycle oculomoteur: succession continue de saccades et fixations dont l'activité de freinage, arrêt, et redémarrage est pilotée par le cerveau.

Takeaways

- Il est important de (1) balayer tout le champ visuel, et (2) revenir au centre.
- L'entraînement des mouvements oculaires dans un contexte concrets, grâce à la réalité augmentée (e.g. exercices en cuisine), sont prometteurs et intéressants.

- Pour les exercises, une troisième dimension (e.g. un cube vs un carré) demande beaucoup plus au patient de manière général. Soit rester en 2D, ou passer à la 3D de manière progressive: présenter la problèmatique sous une forme 2D, puis dans un second temps, en 3D.
- Eviter la transparence
- Eviter les reflets. Un simple reflet sur une table, est comme regarder directement le soleil pour une personne sans visual impairment.
- Favoriser plutôt les couleurs chaudes (rouge, orange, jaune), tout en faisant attention aux individualités de chacunes et chacuns! En considérant le spectre de lumière, et la préférence "générale" d'utiliser des filtres dans les couleurs chaudes, les couleurs bleu et violet ont tendance à être sombre et difficile à déscerner.
- Utiliser un fort contraste. Comme contrastes, le noir/blanc, noir/jaune sont très appréciés (lettre noire background blanc/jaune, ou l'inverse), ainsi que lettres vertes sur fond noir. Le bleu et jaune (dans les deux sens) est une bonne combinaison, et notament pour les panneaux de signaletique.
- Quand un patient utilise un écran tactile, le retour tactile est apprécié pour se repérer. Perdre ce retour, e.g. avec un bouton en réalité augmentée, peut potentiellement être problématique et gênant.
- La créativité est primordiale pour renouveler le set d'exercices effectués dans le processus d'entraînement.

Salle de test, de lecture, appareils assistifs La FSA a une salle pour effectuer des testes de la vue, de lecture, et la recommendation d'appareils assistifs. Les différentes lampes dans la salle permettent d'ajuster l'éclairage, avec des intensités variées. Il y a divers appareils de lectures[23], des loupes avec ou sans support, des Kepler system[24], des loupes avec prisme, et des filtres Irlen[25].

Pour la loupe à main, il faut ajuster la distance yeux-loupe, et la distance loupe-texte. Sans oublier la possibilité d'une correction avec des lunettes et un prisme.

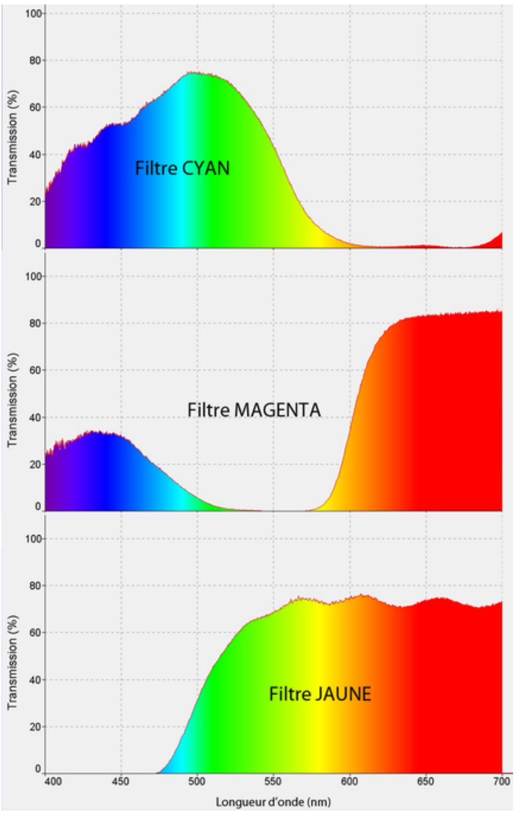
Les filtres utilisés vont faire barrage sur le spectre de lumière. Les filtres chauds, soit dans le jaune à rouge par example, aident à marquer les contrastes et éviter les éblouissements. Lorsque ces filtres chauds sont utilisé, le spectre de lumière vers le bleu et violet deviennent nettement moins visible voir plus du tout.

Pour les filtres Irlen, il y a une première phase de **dépistage**, effectuée par la spécialiste en réadaptation basse vision, et une deuxième phase de **diagnostique**, effectuée par une personne mandatée spécialisée. La première phase consiste a utilisé des feuilles de couleurs (dix couleurs): elles jouent le rôle de filtre sur des textes, motifs (tête dessinée avec des "%" ou "#"), des cubes avec des arrêtes plus ou moins contrastées et nombreuses, des portées de musiques, des tables de multiplications. Ensuite, en deuxième phase, la spécialiste utilise une palette de verre de lunettes avec plus de degrées de variations par couleurs (des centaines potentiellement), et offre la possibilité de mixer les différentes couleurs et degrées afin d'arriver à une solution adaptée à la personne et à ses diverses attentes, avec potentiellement plusieurs choix si la personne a des activités (avec leurs besoins) séparées et spécifiques. De plus, la lentille va filtrer toute la lumière (celle qui arrive sur l'oeil également) et pas que celle qui arrive sur le papier.

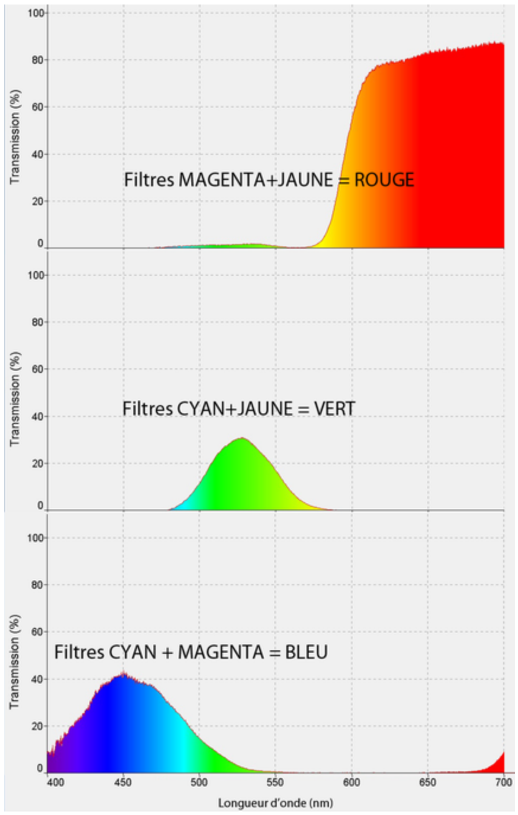
[23] Example de la marque Humanware `https://www.humanware.com/low-vision-exam/index.php`, visited Nov 8 2022: "Digital handheld magnifiers", "desktop video magnifiers"

[24] Example/Explication: `https://www.optik-akademie.com/eng/info-portal/ophthalmic-optics/special-visual-aids/telescopic-systems/keplerian-systems.html`

[25] some selected info, Wiki page: `https://en.wikipedia.org/wiki/Irlen_filters`, irlenboston info: `http://www.irlenboston.com/assets/Irlen_Introduction.pdf`



(a) Cyan filter blocks the right with yellow/orange to red. Magenta blocks around the middle on green and yellow. Yellow blocks on the left from blue to purple.



(b) Red filter blocks what is left of yellow. Green will block what is on its left and right. Blue will block what is right of green.

Figure 37: Impact of filters on the color spectrum

A.1.1 Processus d'entrainement aux mouvements oculaires en cas de déficience visuelle

La première étape est d'évaluer la zone lésée et situer le scotome. Ensuite, il s'agit d'entraîner certaines compétences visuelles avec différents moyens d'entraînements. Le but de l'entraînement étant de favoriser la réorganisation rétino-motrice.

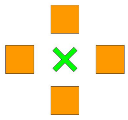
Evaluation scotome et zone lésée

Pour le cas de trouble centrale, utilisation de la vision excentrée, et discussion avec le patient pour comprendre ses envies et ses méchanismes d'adaptation (coping mechanisms). Pour l'anamnèse, les questions suivantes pourraient être utilisées: où est le scotome? où est localisée la gêne? Est-ce genant de prêt ou de loin? dans quelle situation, ou activité en particulier? Est-ce qu'il y a déjà des méchanismes d'adaptation?

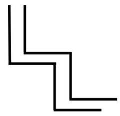
Pour évaluer la taille et la localisation du scotome, une série de test avec une croix et des cibles à 3h-6h-9h-12 sont utilisées.

Un autre exemple de test peut être une suite de chiffres alignés, de 1 à 9, où la personne doit fixer le 5 au milieu et lire les chiffres à gauche ou à droite. Une difficulté de lecture pourra aider à localiser le scotome.

Il est aussi important de savoir si la personne est consciente et perçoit le scotome (on parle alors



(a) Un example de test: (1) le patient fixe la croix au centre, (2) et fixe les carrés dans le sens horaire (clockwise). Des variations du test sont faites par example avec des carrés plus éloignés ou plus nombreux.



(b) La personne doit tracer un trait au milieu des deux lignes. Similaire à la suite de chiffre, une difficulté de traçage pourra indiquer la localisation du scotome.

Figure 38: Evaluation scotome

de scotome positif) ou si elle n'en ait pas consciente (scotome négatif). A noté que ces tests sont effectués en monoculaire sur chaque oeil, puis en test binoculaire, afin de comparer monoculaire contre binoculaire.

Compétences visuelles à entraîner

This section illustrates rehabilitation tasks used to train specific visual skills: stability, precision with bounce/shake, spotting, tracing, scanning, tracking, horizontal and vertical mobility, hand-eye coordination, and reading and writing as functional tasks.

Stabilité lors de fixation excentrée: Le rôle de la fixation est d'extraire de l'information.

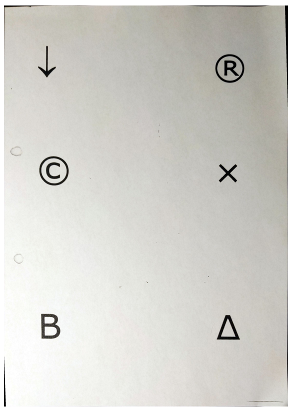


Figure 39: Stabilité: La patiente doit fixer une des cibles données et rester stable le plus longtemp possible.

Précision lors de saccades: Une saccade peut être définie comme de rapides sauts d'un point à un autre, généralement vers la droite (i.e. sens de lecture). Le rôle des saccades est d'amener une nouvelle information en fovéa.

Spotting: Localisation et identification d'une cible. La patiente doit (a) identifier globalement où sont les cibles, puis (b) identifier précisément e.g. le 1 et le 2, afin de (c) relier ces points. Ensuite le 2 et le 3, et ainsi de suite.

Tracing: suivre une ligne d'intérêt immobile. Utilisation d'une ligne immobile, et la suivre soit avec le doigt, soit avec un stylo. Il peut s'agir de courbes, plus ou moins complexes, avec des centres intérêts à décrire ou non.

Scanning: balayage visuel. L'idée de l'exercice est de trouver un méchanisme et avoir quelque chose de consistent. Un example de méchanisme est de

1. balayage horizontal de gauche à droite,

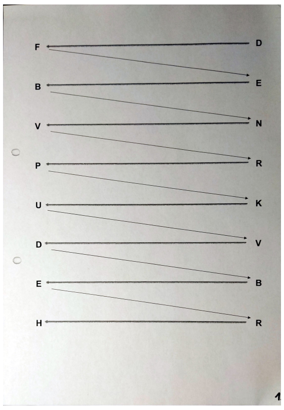
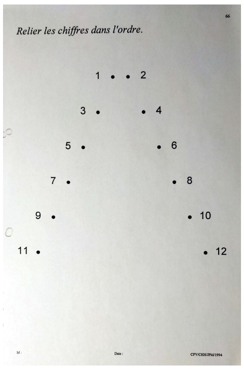
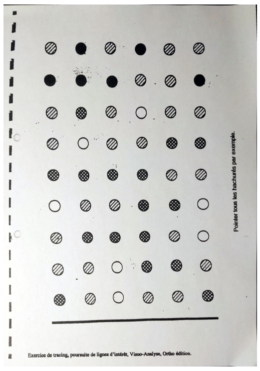


Figure 40: Saccade: Passer d'une lettre à l'autre: suivre la ligne horizontal, puis passer à la ligne suivante.



(a) La patiente doit (a) identifier globalement où sont les cibles, puis (b) identifier précisément e.g. le 1 et le 2, afin de (c) relier ces points. Ensuite le 2 et le 3, et ainsi de suite.



(b) La patiente doit pointer vers le motif demandé parmis tous ceux sur la feuille.

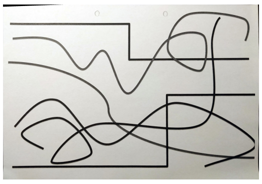
Figure 41: Spotting rehabilitation tasks

2. revenir de droite à gauche sur cette même "ligne",
3. descendre verticalement à la prochaine zone à cibler ou lire.
4. effectuer le balayage horizontal: gauche à droite, puis retour.
5. descendre verticalement.
6. etc.

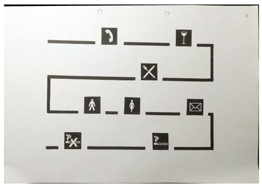
Un autre méchanisme serait d'effectuer un balayage en spiral, en partant du centre et s'éloignant par cercle grandissant (comme les lignes d'un escargot...).

Tracking: poursuite oculaire (object en mouvement). Aussi appelé ligne mobile. Une cible, unie blanche, en forme de spatule est tenue dans la main par la spécialiste. La spatule bouge et la patiente doit la suivre du regard. Une seconde spatule avec des motifs noirs peut être utilisée comme repère afin de faciliter le tracking par la patiente.

Mobilité horizontale et verticale (nécessaire pour la lecture). Il peut s'agir d'une suite de mots, de textes, à lire.



(a) Une copie noir et blanc de lignes et courbes à complexité et couleurs variées

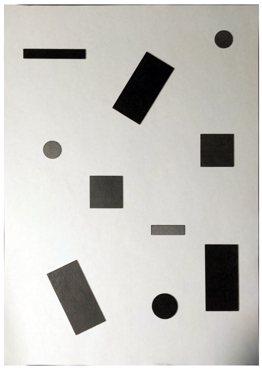


(b) Tracing: follow the line, and stop at icon to describe it

Figure 42: Tracing rehabilitation tasks

Coordination oeil-main: La coordination entre l'oeil et la main peut être fait avec un bâton magnétique pour récolter des jetton, ou comme l'exercice illustré ci-dessous.

(a) Utilisation d'un kit pour le loto pour entraîner la coordination oeil-main.



(b) Des carrés et ronds de couleurs différentes sont sur une feuille. Des cubes et sphères en bois sont à disposition de la patiente qui doit les placer aux endroits cibles sur la feuille de papier. The target sheet might have a white background and colored shapes, or a black background. Or simply black shapes with white background. Considering a reduced acuity might impact the perception of colors, the black and white might be preferable for some patients.

Figure 43: Coordination hands-eye rehabilitation tasks

Tâches fonctionnelles: lecture et écriture. Lire en vision excentrée est difficile pour se repérer quand on veut passer de la fin de la ligne à une nouvelle ligne. L'utilisaton d'un guide en forme de "L" peut s'avérer utile. Pour l'écriture, des zones rectangulaires avec des bordures plus ou moins marquées sont utilisées.

Moyens d'entraînements/processus

- Sans puis avec moyens auxiliaires
- Séances d'environ 45min/1h avec spécialiste / durée indétemrinée (selon besoins individuels
- Matériel d'entraînement transmis à domicile
- Exercices avec logiciel (Oculy (`https://www.oculy.app/`), VISIOcoach (`https://www.lowvision-shop.de/software/visiocoach/`), etc.), rehatt MR (a MSc thesis giving away some insights: `https://www.diva-portal.org/smash/get/diva2:1573830/FULLTEXT01.pdf` and RehAtt DiSTRO (official page: `https://www.brainstimulation.se/#ourproducts`)
  - La recherche d'image est le plus l'important.

- L'utilisation de vrais photos, telle qu'une photo d'un marché, peut être considérée plus pratique, que quelques fleurs artificiellements posées sur un champ (e.g. Oculy).

- D'autres idées sont l'utilisation du jeu Mahjong [26], de suspendre des cibles au mur comme des guirlandes.

But de l'entraînement

Favoriser la réorganisation rétino-motrice (cycle oculomoteur = succession continue de saccades et fixations dont l'activité de freinage/arrêt/redémarrage est pilotée par le cerveau).

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  - Entraînement vision excentrée (pdf slides): `http://www.basse-vision.ch/site-html/SM/Formations/pdf/ASE_5_Vision_excentree_2018.pdf`

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- Markus Sutter: ? less information, `https://www.schlechtsehen-gutleben.ch/fileadmin/user_upload/3_Fachbeitrag_Markus_Sutter_Dienstleistungserbringung_ohne_Umwege.pdf`, `https://www.szblind.ch/fuer-fachpersonen/fachbibliothek/bibliothekskatalog/low-vision`

- Joseue Duquette: possible reference `https://www.researchgate.net/profile/Josee-Duquette`, `https://crir.ca/en/member/josee-duquette-m-sc/`

- Figure: Impact of filters on the color spectrum, source: `https://www.123couleurs.fr/exp%C3%A9riences/exp%C3%A9riences-mati%C3%A8re/em-filtrescd/`, visited 11/13/2022.

[26] wiki: `https://en.wikipedia.org/wiki/Mahjong`

A.2 Meeting 3: Diagnostic session at FSA

VISITE A LA FSA: suivie de sessions diagnostiques

- Lieu: Fédération suisse des aveugles et malvoyants (FSA), Service de consultation Fribourg, Rue Georges-Jordil 2, 1700 Fribourg.
- date: November 8, 2022.
- Personnes présentes: Laurie Schmutz, Cedric Membrez. Et Karin Schwarz (`https://www.optic-picto.ch/`, indépendante, mandatée par la FSA pour la partie diagnostique.

A.2.1 Diagnostic sessions

This part is not directly relevant to my thesis, but it helps immerse myself and be aware of the social aspect, the psychological aspect, and other important aspects such as coping mechanisms that the persons endure and encounters.

Person A

- reduced vision on its left eye from birth
- following a heart attack, an artery occlusion occurred on the right eye. The person deals with blurriness and is tired when looking at the screen or focusing on small details at work. The person sees a diluted stain (scotoma) in the distance, but close, the stain is more compact.
- Coping mechanism: the person has always managed to play volleyball and continue to do so. Working in metallurgy, the person was used to wear protection glasses, and took advantage of the yellowish lenses of such glasses to improve and ease seeing with better contract, less light reflection.
- the willingness of the person to use the new filters is not too high; the person has lost the glasses lent by the FSA, has not tested the filters, and refused to even try filter of pink color for example. An important point to consider when suggesting devices and other help to patients.

Person B

- After an allergic reaction to a medic, lost the vision for two years
- After an operation, recover 80% of the vision in one eye only. Use of a plexiglass tube to replace the "cristallin", il n'y a plus d'accomodation et un flou persiste. Cornée brûlée, pas d'iris, donc luminosité fixe. Following another complication, the central vision is reduced.
- At some point, the vision gets worst again. No Irlen filter helps.
- Still manage to do climbing, reading. When the person goes to not so familiar places, the person uses a guide cane to communicate to others, more than use it for herself.
- After 7 years of dealing with these above issues, the person finally meets with the specialist in diagnostic to chose the right filters. The person is impressed and positive about the use of filters.
- suggestion to use glasses with "blinds" on the side, verre polarisant to bloque horizontal light.

- The person works a couple hours per week as a physiotherapist for her own friends and family. She uses the maximum zoom on Word, but for the physio software, it is not very accessible and it is difficult for her.
- on a more social/psychological aspect, the person is still positive and fighting to find better solutions and keep doing her work and hobbies.

Person C

- do not see the red color at all. Coped with it until the age of 13, by dealing with the different degrees of greys. The Irlen filters seem to have only a limited help and use.

A.3 Meeting 4: Training day at FSA

Training at the FSA: in the role of the patient with simulation glasses

- Location: Fédération suisse des aveugles et malvoyants (FSA), Service de consultation Fribourg, Rue Georges-Jordil 2, 1700 Fribourg.
- Date: November 22, 2022.
- People present: Laurie Schmutz (FSA), Cedric Membrez (UNIFR)

Questions

- I have questions on what is important when a client is training on a rehabilitation task:
  - what are you focusing on?
  - what are the important aspects for you as a specialist?
  - what are the important aspects for the client's training and progress?
- Considering the potential of a gamified rehabilitation task in augmented reality, what data would be interesting as a specialist?

Takeaways

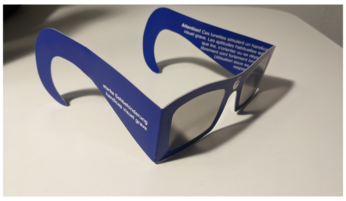
- Specialist needs more feedback and information on where the patient is looking at (eye tracking more than AR?)
- Regarding data, specialist sees more value on a trend rather than an immediate result of a single training session. The trend may give information on how and where the patient is improving.
- Specialist needs the patient to explain and share what she is seeing and what is difficult for her. Otherwise, the specialist might not understand if the patient is doing the eccentric vision correctly and whether there is any improvement.
- Patient's motivation: could/would a training in context (i.e. at home in an important room of you: your kitchen, in your bathroom, etc.) improve motivation and willingness to execute the rehabilitation tasks? Rather than sitting on a desk and doing the pen-paper exercises.
- Training for eccentric vision, with a scotoma, requires going against our general reflex and is not an easy task; at least as experienced with simulation glasses. The blurriness around the scotoma increases considerably the difficulty to train new habits (i.e. eccentric vision).
- Some patient will find their coping mechanisms automatically, some will struggle to train for the eccentric vision, and some might give up from the start.
- AR and tubular vision: by having to cope with a tubular vision, we could have added-value by the depth that a Gamified Rehabilitation Task (GRT) may offer compared to a tablet version.

Context

After some following questions regarding the first interview of November 8th, I spent an hour in the role of the patient under the supervision of the specialist. Wearing different glasses to simulate a mix of glaucoma, tunnel vision and blur, I went through a selected few exercises presented in the first interview.

Sensibilization setup

The specialist in low vision uses glasses with blurred lenses and tape to simulate a scotoma. For the tunnel vision, a tiny hole is made in one of the lens.



(a) Blurred glasses

(b) AMD and right scotoma

(c) Right tubular vision and blur

Figure 44: Set of glasses used by the FSA.

To play the role of the patient, we determine the dominant eye (i.e. by holding at arm-length a plate with a hole in front of you, and bringing the plate towards yourself. The hole will instinctively get closer to the dominant eye) and choose the tunnel vision or scotoma to match that dominant eye.

Instructions to a patient

To train the eccentric vision, the patient is usually asked to shift the gaze or fix on the side ("décaler le regard", "fixer à côter"). Further instructions are given depending on the task at hand:

- Fixation: fix the side of this
- Saccade: move from one letter to the next the most directly possible.
- Tracing: trace a line one the dashed line in the direction given by the arrow, either clockwise or counterclockwise.
- Spotting: Variant (1) take each piece and place it on the similar shape on this piece of paper. Variant (2): take each piece in front of you and place it on the squared board here.

What matters for the specialist

The most important aspect of the training is the continuous feedback from the patient. The more talkative the patient is, the more information the specialist gets. Because the special may notice some eye shift, e.g. when the patient should be instead fixing a target, but it is usually difficult to know if the patient is effectively practicing eccentric vision.

In theory, the patient should be looking into the closest peripheral vision around her natural center vision , at least as shown on a field-of-vision test (i.e. a circle-shape on a x-y axis, with the natural ...). However, the patient might choose to look somewhere not theoretically efficient, and the specialist has no way to know it unless the patient explain her coping mechanism or her difficulties.

It seems that technology (AR, eye tracking, etc.) might be of added-value for the specialist if the data and feedback about the patient create new insights. With new information, the specialist might drive the rehabilitation in a more effective way. The ease to create a new variety of exercises might be of second interest for the specialist - as compared to added-value of understanding their patients better.

Interesting data and feedback to consider in a GRT, in the words of the specialist:

- Precision of the answers by the user (related to hand-eye coordination)
- Response time
- Parts of the visual field that is the most/least used/invested in.

Perspective of the patient

The willingness to train the eccentric vision may vary from patient to patient. So is their ability to adapt and find coping mechanisms on their own.

Technology (digitalized tasks, gamified tasks, AR, tablet, etc.) offers more creative and more diverse exercises for the patient, a possibility to train in context (i.e. at home, in your own kitchen, etc.) and this may drive their motivation and discipline to stick with the rehabilitation training consistently and on a longer period to obtain new habits, new coping mechanisms. The feedback from data, showing her that she is making progress in her rehabilitation, might help her to keep going in case she is not realizing the progress by herself.

Technical notes

Some technical notes taken during this session at the FSA.

- As acuity decreases, so is the perception of colors. As such, to adjust contrasts, it might be sufficiently helpful to consider black and white. This is a general preference perceived from patients by the specialist; sometimes the black and yellow contrast is also appreciated.
- When choosing contrast settings, one should consider a contrast greater than 70%.
- When the vision is blurred and we want to adjust the light, a white cold light might improves the contrast more than a yellow warm light.

Personal experience

A few notes on how I perceived this experience:

- As a person with myopia, the simulation with the blur glasses feels similar to seeing without my lenses or glasses. You can try to comprehend your environment by advancing step by step, touching, getting closer, etc.
- The simulation for the tunnel vision had two types of glasses: one with blur, one without. The one without blur felt easier to focus only on the tunnel vision, and not be distracted by what was around and blurry. With tunnel vision, one is required to move the head a lot more to explore the environment, and getting a clear overall picture is not an easy task.
- The simulation for AMD with left or right scotoma was the most difficult to experience, and realize even slightly what a patient with AMD might have to go through and adapt. After defining my dominant eye (the right for me), I wore glasses with scotoma on the right. The exercise was to fix the scotoma and use the peripheral vision to explore what was in front of me. Naturally, my right eye wanted to cheat and look away from the scotoma. By properly fixing the scotoma, it was extremely difficult to decipher what was on periphery as it gets blurrier.

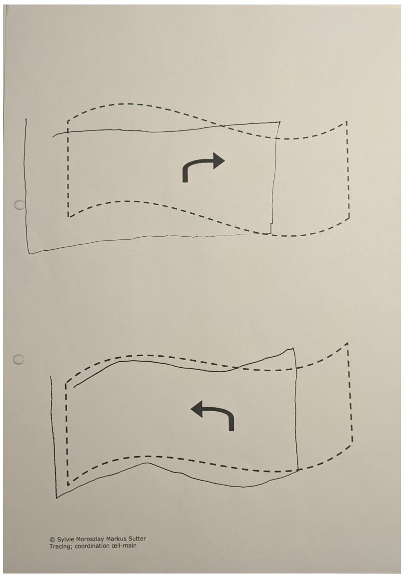


Figure 45: My attempt with simulated scotoma on the right and blur vision around it. The above task was done without proper attention to the curved line, and a difficulty to recognize what was in the peripheral vision. The task below might have been done with slight cheating as the eye naturally deviate away from the fake scotoma towards a more visible area of the lens.

A.4 Meeting 5: GRT mockups presentation at FSA

Presentation and discussion of GRT mockups at the FSA

- Location: Fédération suisse des aveugles et malvoyants (FSA), Service de consultation Fribourg, Rue Georges-Jordil 2, 1700 Fribourg.
- Date: December 7, 2022.
- People present: Laurie Schmutz (FSA), Cedric Membrez (UNIFR)

Questions and Answers

Q1 How much time is necessary to plan the clients' meetings to have them do the experiment with the AR?

A1 2-3 weeks.

Q2 After I show you the mockups that I have today, can we go once more over the data need you have as a specialist?

A2 See document from FSA "Feedback tâches de réhabilitation en réalité augmentée" by Laurie

Q3 Are the visual skills aimed for training in the gamified rehabilitation tasks correctly specified? In other words, are we creating tasks that do train for the mentioned visual skill(s)?

A3 See Google Slides "InterviewFSA_1207_SupportSlidesToShowMockups"

Q4 Which visual skill, if any, is trained when the user needs to interact with a button (or slider) in augmented reality? Spotting? Others?

A4 Interestingly, using a slider (i.e. the pinch & slide gesture) will likely train the hand-eye coordination. The user will need to use her hand to hold the cursor on the slider, pinch it, hold it and finally slide it toward the desired direction.

Elements to present to the specialist

- My schedule for the rest of thesis:
  - Jan. 30: escape room implemented with 3 GRTs and full pipeline (data export, analysis possible)
  - Feb. mid to end: iterate on feedback from midterm presentation of Jan. 30
  - March 1st: have everything ready for experiment (full escape room, data export, protocole explanations to users for experiment)
  - March 1-15th: user experiments
  - April end: final presentation
- Three chosen mockups which are aimed to be the one in the final escape room
  - Pipes: tracing and spotting
  - Clock
  - Tower

Takeaways

- The pinch & slide gesture is be interesting for hand-eye coordination

B Evaluation's Consent Form and Questionnaires

B.1 Consent Form

Afin de participer à la présente étude, merci de prendre connaissance de ce formulaire de consentement[27], puis de le dater et signer en fin de document.

Droit de retrait: en tout temps et sans conséquence négative, vous avez le droit de vous retirer de cette étude et demander la suppression des données vous concernant.

Contexte: étude exploratoire dans le cadre de la thèse "AR Escape Room to Support the Rehabilitation of People with Visual Impairment" pour l'obtention du Master en informatique pour l'étudiant *Cédric Membrez* (contact pour toute demande d'information et de retrait: *cedric.membrez@unifr.ch*), sous la supervision de Prof. Denis Lalanne, Dr Simon Ruffieux et doctorant Yong Joon Thoo.

Objectif: dans le cadre de la réhabilitation effectuée par les personnes atteintes de malvoyances, la présente étude exploratoire évalue la faisabilité de transformer certaines tâche traditionnelles en jeux sérieux en utilisant la réalité augmentée. Ainsi, l'idée est de soutenir leur réhabilitation par des tâches plus engageantes et ludiques (i.e. gamifiée) avec possibilité d'utilisation dans un contexte ambulatoire.

Procédure: vous utiliserez un casque de réalité augmentée HoloLens 2 de Microsoft[28] avec lequel il est possible de percevoir des objets virtuels dans son environnement réel. Après une introduction sur les deux gestes possibles à effectuer, vous porterez le casque pour une première phase où il vous sera demandé de résoudre 3 tâches sous la forme d'une escape room (temps: 5-10min) avec un premier type de geste. Puis, vous enleverez le casque pour répondre à la première partie d'un questionnaire. Ensuite, vous porterez à nouveau le casque pour une seconde et dernière phase dans un même jeu mais avec un autre type de geste. Finalement, vous enleverez le casque pour répondre à la seconde et dernière partie du questionnaire. L'étude se terminera par une discussion ouverte sur votre expérience pendant ce jeu sérieux.

Risques: L'utilisation de dispositifs de réalité augmentée peut entraîner des nausées, des vertiges ou des sueurs chez certains utilisateurs, notamment lors d'une utilisation prolongée. Pour réduire ces risques, l'utilisation est limité à deux fois 5-10 minutes. Toutefois, si vous ressentez l'un de ces symptômes, veuillez en informer immédiatement l'expérimentateur.
De plus, si vous avez des antécédents d'épilepsie, vous devez immédiatement vous retirer de l'étude car l'utilisation de la réalité augmentée pourrait provoquer des crises.

Données Récoltées: L'utilisation du casque de réalité augmentée permet d'enregistrer les données suivantes

- les types d'interactions que vous avez avec les objets virtuels
- le temps nécessaire pour détecter et interagir avec ces objets virtuels

[27]Formulaire inspiré des documents du doctorant Yong Joon Thoo.
[28]https://www.microsoft.com/en-us/hololens

- (optionnel - consentement à donner en base de document) enregistrement vidéo des deux phases de l'expérience de votre point de vue. Ainsi, seuls vos mains et les objects virtuels seront enregistrés. Votre visage ne sera pas visible.
- vos réponses à un questionnaire anonyme
- vos remarques lors d'une discussion ouverte

Confidentialité:

1. Toutes les données récoltées seront codées afin que votre anonymat soit préservé lors de présentation et ne comporteront aucune trace de votre nom ou de votre identité.
2. Nous créerons une liste papier (aucun enregistrement numérique) qui contiendra un alias qui vous sera fourni et un ID unique (codé et numérique). Cet identifiant nous permettra de distinguer vos données de celles des autres. Seuls les chercheurs mentionnés dans la section "Contact" auront accès à cette liste qui sera conservée dans une armoire fermée à clé au bureau de Human-IST (A428, Boulevard de Pérolles 90, 1700 Fribourg).
3. Seuls les chercheurs mentionnés dans ce formulaire de consentement auront accès aux données récoltées. En outre, les données ne seront à aucun moment partagées avec qui que ce soit (y compris les collaborateurs du projet, les employeurs, les partenaires industriels, etc.).

Temps Requis: L'ensemble de l'étude devrait prendre environ 30-45 minutes

- ~10 minutes pour l'introduction et les explications
- ~10 minutes (2x~5min) pour l'expérience
- ~10-20 minutes pour les questions et une discussion ouverte

Contact: Si vous avez d'autres questions sur l'étude, la procédure ou les résultats, contactez l'étudiant Cédric Membrez (cedric.membrez@unifr.ch), ou l'un des superviseurs: Yong-Joon Thoo (yongjoon.thoo@unifr.ch), Dr. Simon Ruffieux (simon.ruffieux@unifr.ch), ou Prof. Denis Lalanne (denis.lalanne@unifr.ch) de l'Institut Human-IST, Université de Fribourg, Suisse.

B.2 Questionnaire

AR Escape Room to Support the Rehabilitation of People with Visual Impairment [29]

Following the introduction and signing of the consent form, this questionnaire is intended to collect your opinion and experience to better understand the important points when gamifying rehabilitation tasks. The rest of the survey is divided into 5 parts and will take 30-40 min:

- Answer 7 general questions
- Perform the escape room with the slider modality and answer 7 questions related to it
- Perform the escape room with the button modality and answer 7 related questions
- Answer 7 questions related to the two types of interaction
- Final interview

Thank you for your contribution!

Disclaimer: Data is handled anonymously. Questionnaire is read to the participant when appropriate.

Sources: SPINE questionnaire (Spatial Interaction Evaluation, from ”Evaluating Augmented Reality” by Fridolin Wild, Alla Vovk, and Will Guest, February 2020), and questionnaire from Yong Joon Thoo, University of Fribourg.

B.2.1 Demographic data and past experiences

- What is your age? *(¡18; 18-24; 25-34; 35-44; 45-54; 55-64; ¿65; Prefer not to say.)*
- I am... *(Left-handed; Right-handed; Ambidextrous; Prefer not to say.)*
- I am comfortable exploring an escape room activity. *(5-point Likert scale from ”Strongly disagree” to ”Strongly agree”)*
- I am comfortable playing video games. *(5-point Likert scale from ”Strongly disagree” to ”Strongly agree”)*
- I am comfortable using a virtual reality headset (e.g. the Oculus/Quest 2 from Meta/Facebook). *(5-point Likert scale from ”Strongly disagree” to ”Strongly agree”)*
- I am comfortable using an augmented reality headset (e.g. the Microsoft Hololens 2). *(5-point Likert scale from ”Strongly disagree” to ”Strongly agree”)*
- I am prone to epileptic seizures. *(Yes; No.)*

B.2.2 Tasks with Slider Modality

(Each question requires an answer on a 5-point Likert scale from ”Strongly disagree” to ”Strongly agree”.)

- I managed to control these tasks with ease. (SPINE SC1)

[29] For better readability of the questions, this is a transcribed version of the original Google Form. Link to the English version with slider modality in the first escape room: `https://forms.gle/5KTafaAbSPk8n3zk7`

- I was sure about the functions of the user interface elements. (SPINE SC2)
- I could position myself easily to have the best experience. (SPINE NG4)
- I received clear confirmation of the actions I was performing.
- I could select the user interface elements because their size was sufficient. (SPINE SL1)
- I could select the user interface elements because their contrast was sufficient.
- I could select the user interface elements because their shape was distinctive.

B.2.3 Tasks with Button Modality

(Each question requires an answer on a 5-point Likert scale from "Strongly disagree" to "Strongly agree".)

- I managed to control these tasks with ease. (SPINE SC1)
- I was sure about the functions of the user interface elements. (SPINE SC2)
- I could position myself easily to have the best experience. (SPINE NG4)
- I received clear confirmation of the actions I was performing.
- I could select the user interface elements because their size was sufficient. (SPINE SL1)
- I could select the user interface elements because their contrast was sufficient.
- I could select the user interface elements because their shape was distinctive.

B.2.4 Interaction Modalities and Comments

- In the Pipes task, I preferred to interact using the ... modality. *(Slider; Button; No preference.)*
- In the Clock task, I preferred to interact using the ... modality. *(Slider; Button; No preference.)*
- In the Tower task, I preferred to interact using the ... modality. *(Slider; Button; No preference.)*
- Overall, I preferred to interact with a task using the ... modality. *(Slider; Button; No preference.)*
- I preferred this gesture because... *(free answer)*
- (Optional) I would have preferred the other gesture if... *(free answer)*
- (Optional) I would like to add the following (any positive/negative comments, ideas, etc.) *(free answer)*

C Details on Results

C.1 Details of PVI Participants

Table 27: Full and detailed demographic information of the 5 PVI participants. Information collected from questionnaire and FSA documents, and WHO's notation (www.who.int). When available, data is presented for each eye and binocular vision in the order: left eye; right eye; binocular. LCS = Low Contrast Sensitivity (a SZB-LCS test www.szblind.ch), CVD = Color Vision Deficiency.

Alias	Visual acuity (afar)	Visual acuity (near)	Low Contrasts Perception	Magnification needs	Colors Perception	Lighting Requirements	Glare
PVI0	n.a.; 0.16; 0.25	0.05; 0.125; 0.16	n.a.; 0.04; 0.03	10x; 10x; 8x	RE: low CVD in blue-yellow LE: normal	Direct: 820 lux, 2700 K, 30cm. Indirect: 500 lux, 4000 K	strong / strong / strong
PVI1	0.05; 0.06; 0.06	n.a.; 0.1 to 10cm; 0.1 to 6cm	n.a.; n.a.; n.a.	20x; 8x; n.a.	CVD: red-green	n.a.	n.a.
PVI2	0.8; 0.128; 0.8	n.a.; n.a.; 0.16	better than the norm; altered; better than the norm	3x; 7.6x; 3x	RE: low CVD in red-green LE: low CVD in blue-yellow	Direct: 1400 lux, 2700K, 25cm	strong /severe (dazzled, white spots) / strong
PVI3	0.025; n.a.; 0.025	n.a.	n.a.	4x; n.a.; 4x	n.a.	n.a.	n.a.
PVI4	0.32; n.a.; n.a.	0.16; n.a.; n.a.	LCS -5 = altered; n.a.; n.a.	3x; n.a.; n.a.	RE: n.a. LE : no CVD tested	Direct: 2380 lux, 5000 K, 20cm. Indirect: 660 lux, 5000 K	strong / severe (reflections) / severe (aniridia)

C.2 Quantitative Data Exploration

C.2.1 Nomenclature and definition of data from buttons and sliders

This part presents very detailed information related to the nomenclature used in the game engine Unity. Namely, this part describes the differences and similarities between the button and slider interactions' nomenclature. In addition, I detail what I consider a success phase for a button and for a slider, and what is an error.

Nomenclature differences between the current version of the report and the annex After the implementation, I have decided through discussion with my supervisors to rename the "Pinch & slide gesture" into "slider modality", and "press gesture" into "button modality". The naming that I have used in the development in Unity used the "pinch & slide" and "press" references most often and has not been changed for the explanation below for consistency with the Git's repository.

Button

- Button Touch Count: it increments by one at each "TouchBegin" event (UnityEngine .Events.UnityEventPresable
- Button Touch Duration: it increments from "TouchBegin" to "TouchEnd" events
- Button Pressed Count: it increments by one at each "ButtonPressed" event
- Button Released Count: it increments by one at each "ButtonReleased" event
- Button Pressed Duration: it increments from "ButtonPressed" to "ButtonReleased" events

Button's difference between nbSuccessClicks, ButtonPressed, ButtonReleased, ButtonTouch

- ButtonTouch: it is similar to Hover for the slider. When you get close to the button
- ButtonPressed: the button is pressed and your finger is still pushing it. Not yet released
- ButtonReleased: the button interaction ends as the finger goes away from the button and releases it.
- NbSuccessClicks: they are ButtonReleased counts. NbSuccessClicks increment using other Listener functions (see below) but are attached to the same ButtonReleased events.
  - in GRTPressPipes (ButtonReleased event): increments by one at each MoveKeyToThisButtonAndHiteIt()
  - in GRTPressClock (ButtonReleased events): increments by one at each MoveCursorLeft(), MoveCursorRight(), ValidateChoice()
  - in GRTPressTower (ButtonReleased events): increments by one at each UpdateMechanismAndCheckSolution(int), RotateLevel(int), ValidateChoice()

Slider

- Slider Hover Count: it increments by one at each "OnHoverEntered" event (SliderEvent)
- Slider Hover Duration: it increments from "OnHoverEntered" to "OnHoverExited" events
- Slider OnInteraction Count: it increments by one at each "OnInteractionStarted" event
- Slider OnInteraction Duration: it increments from "OnInteractionStarted" to "OnInteractionEnded" events

Slider's difference between nbSuccessPinches and OnInteraction Counts. NbSuccessPinches are OnInteractionEnded events related, while the OnInteraction counts are "OnInteractionStart" events related.

- NbSuccessPinches:
  - in GRTPinchSlidePipes (OnInteractionEnded event): increments by one at each SliderReleased() call when SliderController.SliderValue == 1.
  - in GRTPinchSlideClock (OnInteractionEnded events): increments by one at each ValidateChoice() and at each UpdateSelectionIndex() calls.
  - in GRTPinchSlideTower (OnInteractionEnded events): OnInteractionEnded event it increments by one at each ValidateChoice(), and at each RotateLevel().

Button vs Slider

- Touch and Hover are similar: they hover the controller (button or slider)
- Pressed or OnInteractionStart: the actual "click/pinch" begins
- Released or OnInteractionEnded: the "click/pinch" has completed its cycle and is finished.
- NbSuccess "clicks/pinches": they both relate to the "released/OnInteractionEneded" event and as such, related to the full cycle of an interaction with a controller (button or slider).

Success phases

- Button in 3 steps: (1) touch (hover), (2) go through to press (i.e. "click" the button), (3) release
- Slider in 4 steps: (1) hover, (2) pinch (i.e. "grab" or "air tap" the cursor), (3) slide to desired position, (4) release

Error

- Error: it is a partial attempt to a success. It includes some of the success phases, but not all
- Button error: (touch) or (touch + press without release)
- Slider error: (hover) or (hover + pinch without release)
- if a user has 100% success with button: touch (hover) count == press count == nbSuccess
- if a user has 100% success with slider: hover count == OnInteractionStart == nbSuccess
- percentage of errors = nb errors / (nb success + nb errors)

Presentation of data structures. In my final data used for data exploration and statistical analysis, I use the nomenclature in the third and last column of the Table 28. The first and second column of the same table relate to: (1) in Unity, the pinch & slide gesture and slider use a nomenclature with "hover", "onInteraction" start and end, and (2) the press gesture and button use a nomenclature with "touch", "pressed" and "released".

Table 28: Nomenclature used for the columns names in the final data

Slider Columns Names	**Button Columns Name**	**Final Columns Names for both data (with type)**
PlayerAlias	PlayerAlias	PlayerAlias (character)
GRT_Gesture_Type_FromPinchSlide	GRT_Gesture_Type_FromPress	GestureType (character)
EscapeRoomPinchSlide Duration	EscapeRoomPress Duration	EscapeRoomDuration (double)
GRT_PinchSlide_Type	GRT_Press_Type	TaskType (character)
SliderTaskDuration	ButtonTaskDuration	TaskDuration (double)
_hoverCount	_touchCount	HoverCount (double)
_hoverDuration	_touchDuration	HoverDuration (double)
_onInteractionCount	_buttonPressedCount	StartInteractionCount (double)
_onInteractionTime	_buttonPressedDuration	StartInteractionDuration (double)
_nbSuccessPinches	_nbSuccessClicks	SuccessInteractionCount (integer)
EscapeRoomsOrder	EscapeRoomsOrder	EscapeRoomsOrder (character)

The number of minimal interactions to accomplish each task is: 7 for the Pipes, and 10 for the Clock, and 10 for the Tower. Minimal interactions detailed:

- Pipes (for both button and slider): 7 presses or pinches & slides
- Clock (for both button and slider): 10 presses (4x Validation + 1x Left + 2x Right + 1x Right + 2x Left = 10x) or pinches & slides
- Tower (for both button and slider): 10 presses (4x Validation + 1x Left + 2x Left or Right + 2x Left or Right + 1x Right = 10x)

C.2.2 Usability of the system - population A

Additional information related to data analysis for the sighted participants' data. In other words, for the exploration of the usability, and the hypotheses 1 and 2.

Balanced data

9 sighted participants started the experiment with the pinch & slide gesture, and 9 sighted participants started with the pressure gesture. The number of sighted participants is balanced between the two types of gesture, Table 29.

Table 29: Number of Sighted-Participants Per Escape Room Order (N=18)

Escape Rooms Order	**Number of Sighted-Participants**
A: pinch & slide gesture first	9
B: press gesture first	9

Table 30: Balanced data: number of observations per gesture type and task type

	Clock	**Pipes**	**Tower**
PinchSlide	18	18	18
Press	18	18	18

ANOVA: assumptions' plots

Hypothesis 1: Time (quantitative). Figure 46 is two plots on the assumptions of homogeneity and normality for the ANOVA test on time for population A.

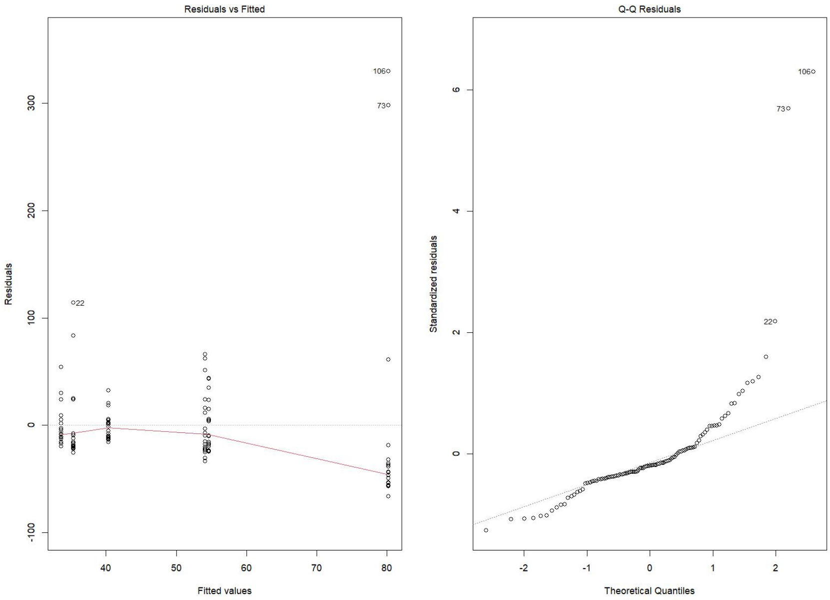


Figure 46: ANOVA Assumption's Homogeneity and Normality: Time

Hypothesis 2: Error (quantitative). Figure 47 is two plots on the assumptions of homogeneity and normality for the ANOVA test on interaction errors for population A.

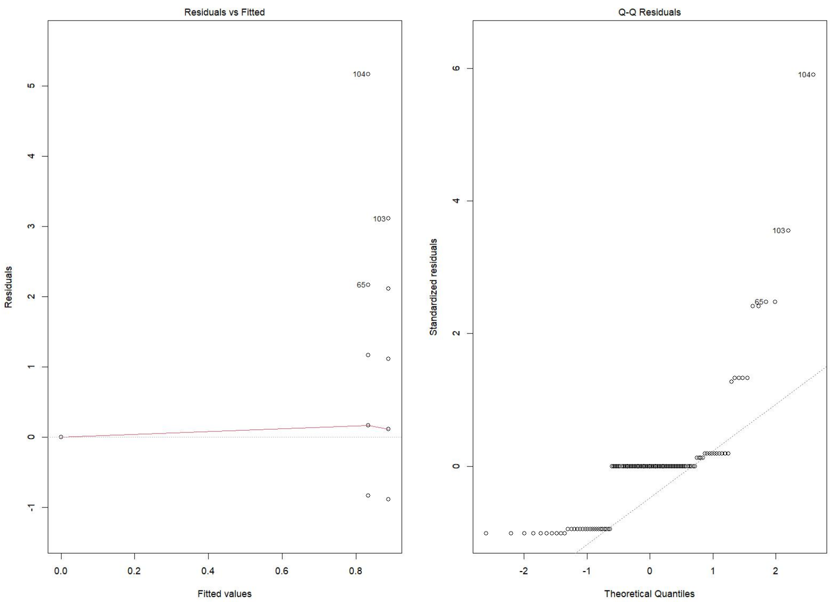


Figure 47: ANOVA Assumption's Homogeneity and Normality: Error Interaction

Figure 48 is two plots on the assumptions of homogeneity and normality for the ANOVA test on hover errors for population A.

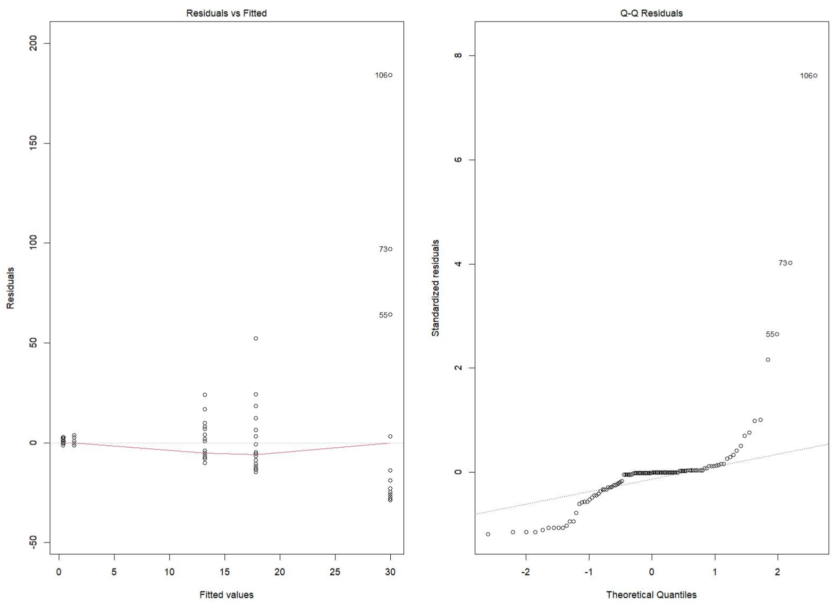


Figure 48: ANOVA Assumption's Homogeneity and Normality: Error Hover