Van Zwol Inez

# Limitations of Hand Tracking When Used for Rehabilitation

Supervisor: Boudry Agathe

Coach: Verspecht Marijn

Graduation Work 2023-2024

Digital Arts and Entertainment

Howest.be

# CONTENTS


Abstract ....3

Key Words....3

Abbreviations....3

Explanation of Jargon ....4

  Acquired Brain Injury (ABI)....4

  Neglect ....4

  Hemianopsia....5

  Apraxia ....5

  Aphasia....5

Preface....6

List of Figures....7

List of Tables ....7

Introduction....8

Literature Study ....9

  Hand & Arm Rehabilitation ....9

    Types of Limited Mobility ....9

    Exercises....10

  Hand Tracking....10

    Quest 2....10

    Packages....11

  Rehabilitation in VR Using Hand Tracking ....14

    Applications for Rehabilitation ....14

    Other....15

Case Study ....16

  Introduction ....16

  Hardware....17

    Quest 2 VR Headset ....17

  Software ....17

    Unity....17

    XR Interaction Toolkit ....17

    XR Hands ....18

  Setup ....18

Unity Project ..... 18
Unity Scene ..... 20
Menu ..... 21
Exercises ..... 23
Stacking Legos ..... 23
Putting Rings on Sticks ..... 24
Pressing Buttons ..... 25
Additional Attempted Adaptations ..... 27
Pointer Interactors ..... 27
Custom Gestures ..... 27
Playtest & Results ..... 27
Playtest One ..... 28
Playtest Two ..... 30
Discussion ..... 34
Comparison ..... 34
Patients ..... 34
Menu ..... 35
Simon Says ..... 35
Conclusion ..... 36
Future work ..... 37
Future Research ..... 37
Package Specific ..... 37
Extra ..... 37
Improvements on Current Project ..... 38
Menu ..... 38
Stacking Blocks ..... 38
Putting Rings on Sticks ..... 38
Simon Says ..... 39
Critical Reflection ..... 40
References ..... 41
Videos ..... 44
Acknowledgements ..... 45
Appendices ..... 46

## ABSTRACT

VR has made incredible progress during the past year, for example through updates of hand tracking or the release of the Quest 3 VR headset from Meta, as well as newly released video games that push the boundaries of what is possible in VR. A seemingly logical next step is testing the limits of hand tracking when used in the medical field.

A Unity application that uses the built-in hand tracking from a Quest 2 VR headset has limited capabilities, especially when used for rehabilitation of hand motoric. A case study is conducted where a VR application with three different exercises, each with three different variants in size, are tested on a total of ten test subjects from the target audience. This VR application is created in Unity, using some of the most accessible packages to implement VR and hand tracking. Each exercise is derived from exercises used for rehabilitation of fine motoric. The test subjects, from varying age groups, all suffer from various motoric and intellectual disorders as a consequence of their Acquired Brain Injury (ABI).

Based on the results of the case study, clear limits of the application are established.

VR heeft in het voorbije jaar enorme vooruitgang geboekt, bijvoorbeeld via updates van hand tracking of de recent uitgebrachte Quest 3 VR headset van Meta, maar ook de nieuwste VR videogames die de grenzen van het mogelijke in VR verleggen. Een logische volgende stap is het testen van de limieten van hand tracking wanneer toegepast in de medische sector.

Een Unity applicatie die gebruikmaakt van ingebouwde hand tracking van een Quest 2 VR headset, heeft gelimiteerde mogelijkheden. Zeker wanneer het gebruikt wordt voor rehabilitatie van hand motoriek. Er werd een casus gemaakt waarvoor een VR applicatie gemaakt werd met drie verschillende oefeningen die elk drie varianten in grootte hebben. Ze zijn getest op een totaal van tien testers van het doelpubliek. De applicatie is gemaakt in Unity met een aantal van de meest toegankelijke packages om VR en hand tracking te implementeren. Elke oefening is afgeleid van oefeningen die gebruikt worden in rehabilitatie van fijne motoriek. De testers hebben te maken met uiteenlopende motorische en intellectuele gevolgen die te wijten zijn aan een niet-aangeboren hersenletsel (NAH) en komen uit verschillende leeftijdscategorieën.

De limieten van de applicatie worden vastgesteld op basis van de resultaten van de casus.

## KEY WORDS

Hand tracking, virtual reality, rehabilitation, hand rehabilitation, acquired brain injury, fine motoric, gross motoric

## ABBREVIATIONS

VR – Virtual Reality

ABI – Acquired Brain Injury

XRI – XR Interaction Toolkit

# EXPLANATION OF JARGON

The following information has been provided and verified by Sarah Vercaemer, a parttime occupational therapist in rehabilitation of adults with ABI at UZ Ghent, parttime researcher / occupational therapist for Smartspace UZ Ghent and XRehab. XRehab is a Flanders Innovation & Entrepreneurship (VLAIO) project between Smartspace UZ Ghent and the occupational therapy department of Howest and Hitlab.

## ACQUIRED BRAIN INJURY (ABI)

Acquired Brain Injury or ABI is an injury to the brain that has been acquired after birth and can be caused in a lot of different ways, for example by a stroke, brain tumor, a car accident… ABI can be the cause of a wide range of functional disorders.

Symptoms of ABI vary widely and are strongly dependent on the kind, location and size of the brain injury.

Some are visible:

- Trouble with moving, both gross or fine motor skills.
- Disruption in function of senses.
- Difficulty talking or swallowing.

Others are not:

- Disruption in thinking, processing information more slowly, attention and concentration, remembering, organizing and planning.
- Change in personality and emotions, easily becoming angry, less patience, not being able to react correctly in specific situations. [UZ Leuven, 2023]

## NEGLECT

Neglect is a perception disorder where a person does not perceive stimuli originating from one half of the body, or objects and movement on one side of the body. Most of the time the left side of the body is affected. This can lead to complete neglect of said side of the body.

A person suffering from neglect does not realize they suffer from it, so it is very difficult for them to learn how to compensate for it.

## HEMIANOPSIA

Hemianopsia, also called semi-sided blindness, means blindness for half of the field of view of an eye. If both eyes are affected, it is called bilateral hemianopsia. Depending on where an optic nerve pathway from the retina to the visual cortex is damaged or has an abnormality, hemianopsia can differ. When dealing with hemianopsia, it is often seen that nothing is wrong with the eye itself.

A patient suffering from hemianopsia realizes they suffer from it, so they can learn to compensate for it by turning their head, or scanning with their eyes.

## APRAXIA

Apraxia is a neurological disorder that disrupts the ability to perform deliberate actions. Actions cannot be imitated or performed on command, or the order in which actions have to be carried out are confused.

## APHASIA

Aphasia is a language disorder that is caused by brain injury. It can make understanding in general, or expression difficult for a patient. Aphasia is often paired with paralysis in one half of the body and other disorders such as problems with concentration or emotional distress. It is not the same as dementia and is not obstinacy or unwillingness of a patient.

Aphasia can express itself in different ways among which are comprehension disorder, speech disorder where the patient has difficulty bringing their thoughts into words, trouble reading and writing. Other problems such as attention and concentration disorders, (partial) facial paralysis, trouble controlling muscles responsible for speech, trouble swallowing and emotional distress are also possible. [UZ Antwerp, 2023]

# PREFACE

Working on a group project revolving around rehabilitation of patients back into daily life, interest in VR used for rehabilitation was sparked. The group project involved creating a grocery shop in VR where patients could safely relearn how to go grocery shopping, guided by a therapist. A Quest 2 headset was the target platform. While working on this group project, the question arose what other possibilities there are for rehabilitation with VR.

Reading about the most recent update for hand tracking of the Quest 2 and how it had made a considerable difference in how well hand tracking currently works [Meta Blog, 2023], hand tracking proved to be an option for applications for rehabilitation. By researching how hand tracking is currently already being used in rehabilitation, an in hindsight obvious area of rehabilitation came up often: rehabilitation of hand and arm movement. Paired with the type of rehabilitation, hardware besides any type of VR headset was often mentioned as well. The extra hardware being used to enhance accuracy of the hand tracking. The scarcity of papers that research rehabilitation using the built-in hand tracking from a Quest 2 VR headset give the impression the extra hardware is a necessity, before hand tracking can even be considered useful for rehabilitation. Examples of other hardware mentioned are Leap Motion Controllers, vibrotactors [Bae & Park, 2023], and even haptic gloves to either enhance tracking of the hands, or provide tactile feedback. This extra hardware in combination with a VR headset is a lot less accessible than just a headset that has its own built-in hand tracking. Therefore, researching if built-in hand tracking of a VR headset, like the Quest 2, can be used to develop applications that can be used for rehabilitation of the hand seemed like useful research that should be done.

Generally, the fact that hand tracking in VR applications has its limits is known, but the limits are not defined clearly anywhere. By doing the case study detailed in the following chapters, an attempt is made to establish and define the limits clearly, for an application that is created in Unity, where hand tracking and VR are implemented using the XR Interaction Toolkit in combination with XR Hands. Motivation for the choice of the packages is explained in the following chapters.

As mentioned above, an application that is developed for a standalone VR headset like a Quest 2 is significantly more accessible than if extra hardware also needs to be set up before an application can be used. The accessibility is a benefit for both the patients that can make use of a VR application in their treatment, but also for any therapist that has to guide patients while they are performing exercises.

Besides the benefit of accessibility of the Quest 2 for the patients, it is also something new and refreshing. By making a game around the exercises, the exercises are more fun for the patient. Adding a competitive aspect to those games can motivate them even further to push their boundaries while performing the exercises. That way, the exercises do not feel like a chore, like some patients might experience them.

## LIST OF FIGURES

*Figure 1: Headset & tablet package Cureo* ............ 14
*Figure 2: Bubble popping finger exercise Cureo* ............ 14
*Figure 3: Difficulties in Beat Saber* ............ 15
*Figure 4: Extra settings in Beat Saber* ............ 15
*Figure 5: XR Plugin Management settings in Unity before installation* ............ 18
*Figure 6: XR Plugin Management settings in Unity after installation* ............ 18
*Figure 7: Open XR settings for Windows, Mac and Linux* ............ 19
*Figure 8: Open XR settings for Android* ............ 19
*Figure 9: Package Manager Packages in Project* ............ 20
*Figure 10: XR Interaction Toolkit Samples* ............ 20
*Figure 11: Simple table visual* ............ 20
*Figure 12: XR Interaction Hands Setup prefab location* ............ 20
*Figure 13: Menu first version* ............ 21
*Figure 14: Menu adapted version* ............ 22
*Figure 15: Editor menu* ............ 22
*Figure 16: Lego stacking exercise* ............ 24
*Figure 17: Rings exercise* ............ 25
*Figure 18: Simon Says exercise* ............ 26
*Figure 19: Simon Says exercise yellow cube lit up* ............ 26
*Figure 20: Extra menu buttons for Simon Says* ............ 26

## LIST OF TABLES

*Table 1: Quest 2 specifications (Meta table ding)* ............ 17
*Table 2: Playtest Results* ............ 34

# INTRODUCTION

As mentioned before, while working on a group project, called VR Shopping, the topic of VR and more specifically hand tracking used in rehabilitation came to attention. During the VR Shopping project, some issues using hand tracking came up, some more significant and drastically influential to the project than others. The package used to implement VR into Unity for this project was the Oculus Integration SDK, which has now been depreciated in favor of the newly released Meta XR UPM package bundle [Unity, n.d.].

A first example of a pretty influential issue is objects that were picked up and held, either by hands or controllers, could not collide with static objects in the scene. Other objects that could be grabbed and moved, did collide with the object held, but shelves, doors, or the shopping cart did not have collision with the object being held, unless said object was let go of. Objects dropped above the shopping cart came to a halt inside of the shopping cart.

A second example of an issue that had a big influence was the system used for teleportation and menu interaction. As the application supports both controllers and hand tracking, a system that worked for both had to be thought out. The solution that came up was using a ray that shot out from the controller when pressing a button. Said ray could interact with menu buttons or signs and teleportation points. For the hand tracking, the same ray shot out from the hand when a specific gesture was performed; pointing. Here the issue arose that gesture detection is really particular, in requiring the fist to be really tight, the thumb to be either inside of the fist or really tightly pressed against the other fingers, the hand to be held at a certain angle from the headset in order to really detect the hand and more.

The question arose if these issues were caused by the package chosen to implement VR and hand tracking into Unity, or if the lack of experience with VR of the whole group was the base for the trouble.

Apart from the VR Shopping application, in general hand tracking is painted as not being entirely accurate, or having a delayed reaction that makes applications feel unnatural. Even after the update from 1.0 to 2.0 of the Meta hand tracking during the summer of 2023 [Meta, 2023], which made a big difference for hand tracking, it is still painted as not very accurate. It is a very vague way to state hand tracking has its limitations, sparking the idea to attempt to define clear and specific boundaries or limits hand tracking currently has.

In order to conduct research, the following research question and hypotheses were formulated:

What are the limits for built-in hand tracking of a Meta Quest 2 VR headset when used for hand rehabilitation in a Unity application, implemented using accessible packages?

H1 - Hand tracking is accurate enough to detect precise finger positions and precise movement that can be implemented in a Unity application using the XR Interaction Toolkit and XR Hands packages.

H2 - Besides the options in the XR Interaction Toolkit and XR Hands packages, a lot more work elsewhere in the Unity project is necessary in order to ensure interactions feel good and look real.

H3 - The fisheye cameras are sufficient, if the right approach to implement hand interactions in Unity is chosen and exercises are adapted for VR use.

# LITERATURE STUDY

The preliminary research can be broken up into two over-arching topics that are looked at separately, as well as combined. The first being the topic of hand and arm rehabilitation, where it is important to find exercises that are useful for rehabilitation of hand movement, in order to attempt to recreate them in a VR application. The second topic being hand tracking and the implementation of it into Unity, where the different packages that are available are compared, after which a logical choice to create the experiment is made.

## HAND & ARM REHABILITATION

### TYPES OF LIMITED MOBILITY

Most of this information was obtained during the playtest moments of the case study, as a lot of these limitations were observed in person, or through personal communication with Sarah Vercaemer in between or after the playtest moments.

Every single person that suffers from limited mobility caused by ABI is different. During rehabilitation, there are no certainties of how well someone will recover, or even if they will. Some people barely suffer any consequences, others are not so lucky. The severity of the ABI and the location of it both go hand in hand with the severity of the consequences. The bigger the injury, the worse the consequences will be. But the uncertainty remains, nothing is set in stone for their recovery.

As a result of ABI, more often than not an entire half of the body is affected, instead of only the hand or arm. If the left half of the brain was injured, most likely the right side of the body is affected, and vice versa. Limitations that might occur for movement in legs will not be discussed, as they are less relevant to the context of this paper.

When thinking of paralysis, it is often assumed the affected limb is limp and can be moved freely when manipulated by another limb or person, which is called flaccid paralysis. But it can also translate to limbs being stiff and tensed up entirely, which is called spastic paralysis.

Besides paralysis, there are a ton of other possible limitations of motion. Coordination can be affected, making performing precise movement with hands or arms difficult, as well as using both hands to perform intricate actions together.

Fine hand motoric can be affected, making it difficult to grasp small objects and execute intricate series of movement with the fingers, such as writing, typing, tying shoelaces, doing buttons on clothing… Generally, extension of limbs is more difficult than flexion.

Movement of flexion or extension, and rotation of the wrists can also be affected.

Tremors are also a possible consequence of ABI, which is muscle contraction that is not intentional, leading to uncontrollable shaking in parts of the body. Both hands and arms are affected most often, but tremors can occur in pretty much the entire affected half of the body, in rare cases even the whole body. It is possible that tremors become more intense when limbs are moved farther away from the body.

Similar to tremors, clonus is also involuntary contraction of the muscles, resulting in shaking. This is more contained to one muscle group and can be stopped by stretching or resting, as it is the result of fatigue. Clonus occurs in just the affected half of the body.

Stretching the arms above shoulder height can prove to be difficult as well. Instead of using just the arm, affected patients often use their whole upper body to move their arm above shoulder height.

Any combination of the aforementioned limitations is possible after ABI, reiterating that every person with ABI is different.

### EXERCISES

Researching what type of exercises are useful for rehabilitating hand mobility, strokes are mentioned most often as one of the causes of limited mobility in hands, but it is definitely not the only cause. Anything that results in ABI in a person can become the cause of limited mobility. These limitations are often not contained to the hand, or arm, but can affect an entire half, left or right, of the body.

Exercises for rehabilitation such as tying shoelaces, solving puzzles, playing boardgames, closing clothing buttons, stacking Legos and stacking coins are exercises mentioned often as great exercise to practice fine hand motoric [Neurolutions, n.d.; Flint Rehab, 2020; Levey., n.d.; Saebo, 2018]. All of these require actions such as gripping small objects and moving the fingers in a particular, precisely coordinated way. Moving fingers separately can be a less intensely demanding exercise.

Some exercises more catered towards the mobility of the wrist include flexion of the wrist, both up and down as well as side to side. These exercises can be facilitated by laying the arm on a tabletop, for flexion up and down with the hand hanging of the table from the wrist, so the arm does not need to be held up while performing the exercises [Saebo, 2020a]. If the tabletop is not smooth enough to slide the hand from side to side, using something made out of some kind of fabric, such as a washcloth or dishtowel, can be put underneath the hand to allow the hand to slide over the tabletop more smoothly [Saebo, 2020b].

When one hand is severely affected and cannot be moved very well on its own, helping with the other hand is a way to exercise the severely affected hand. This can help for all kinds of movement, from stretching the elbow, to flexing the wrist and fingers, or helping with forming specific gestures.

## HAND TRACKING

### QUEST 2

A Meta Quest 2 headset is the most accessible VR headset currently available budget-wise. Additionally, at the onset of the research for this paper the Quest 3 headset was not even available yet. Both price difference and uncertainty about ease of implementation of Quest 3 support into Unity applications resulted in an early decision to not consider the Quest 3 an option.

For accessibility purposes, a headset with built-in hand tracking was a requirement, to facilitate setup of the application during possible playtest moments as well as development of applications. Besides ease of use while developing, a lot of instances interested in XR, such as big hospitals or schools often have access to their own headsets, which are often the Quest 2 headset because of its affordable price point.

## PACKAGES

In order to implement VR and hand tracking into a Unity application, packages can be installed that facilitate the process. These packages ensure developers do not have to start from scratch when implementing VR. There are a couple of different officially supported options that can be found in the Unity Asset Store, which are generally most accessible and well documented. Officially supported packages are created by companies such as Microsoft, Meta and Valve and generally have more users and are more likely to be kept up to date with bug fixes than packages developed by independent developers.

Packages by independent developers often serve specific purposes that the developer finds is missing from the accessible, officially supported packages.

A video called *VR Development for Beginners 2023 - How to get Started* [Valem Tutorials, 2022] nicely summarizes what different official packages there are and what they specialize in. Since the release of this video, some major changes have happened, but it is still a great starting point to find information.

Most recent release dates may have changed since this paper was written.

### XR Interaction Toolkit

XR Interaction Toolkit (XRI) is Unity their own officially supported package. The current latest fully released version is 2.5.2 since October 6 of 2023, according to the Package Manager in Unity. In the end, this package was deemed to be the most logical choice for the purposes in mind of the case study.

With focus on making sure the experience is similar while using different kinds of hardware, making an application with this package that works across different platforms should be easier than with other packages. It supports basic interactions such as grabbing and UI interactions, as well as two-handed grabbing. The package is straightforward to create applications with and its simplicity can be ideal for developers just starting with VR development.

According to a Unity blogpost [Unity Blog, 2023], in order to implement hand tracking, an additional package, called XR Hands, is necessary. The Hands Interaction Demo that is included in the XRI releases from 2.3 onward, is dependent on the XR Hands package, as it includes essential components that allow for implementation of hand tracking. This demo is part of the samples that can be optionally imported into Unity, through the Package Manager, when using the XRI package.

Besides the documentation Unity provides, a lot of tutorials about the XRI package can be found online. Which means a lot of developers are working with the package and have been figuring out more intricate aspects of it. This can prove to be notably convenient for beginner VR developers.

Asking around on top of researching, this package was recommended the most because of how well documented and maintained it is.

### Oculus Integration SDK

Oculus Integration SDK is the precursor to the newly released package bundle from Meta. Since the release of the video mentioned earlier [Valem Tutorials, 2022], this package and its successor are part of the major changes also mentioned. The latest release version is 57.0.1 since October 9, 2023 according to its Unity Asset Store page [Unity Asset Store, 2023]. This package became deprecated, because Meta decided to develop a new bundle of packages that renders this one obsolete. The new package bundle is looked at in more detail in the following chapter.

As an officially supported package from Meta / Oculus, it is logically catered towards their own hardware. The Oculus Interaction SDK allows for easy setup of a project that supports VR and hand tracking. It also makes implementation of Quest-specific features like passthrough and Meta avatars easy.

Even though this package is now considered deprecated, a lot of tutorial and instructional videos can be found that can facilitate the making of VR applications, notably for beginner VR developers.

Working on the VR Shopping application, this package was used and worked great for most of the interactions made with it. The only major issue that occurred, was the lack of collision with objects that were being held by either the hands or controllers.

### Meta XR UPM

Meta XR UPM is the favored package bundle for which the Oculus Interaction SDK has been deprecated. The latest release version is 60.0.0 since November 8, 2023 according to its Unity Asset Store page [Unity Asset Store, 2023].

Again, since the bundle is made by Meta / Oculus, the bundle is catered specifically towards their own headsets. The documentation also includes a page with information about cross-platform support, so the bundle is not exclusive for Meta devices [Meta, n.d.].

On first sight, the Meta XR UPM all-in-one bundle of different packages looks like a lot to manage, however it is well-documented on the Meta website [Meta, n.d.]. It mentions detailed information about the usage of specific packages from the bundle. The bundle encourages developers to install the packages they plan to use, opposed to downloading and importing every package that is included.

According to the Meta website [Meta, n.d.], in order to implement hand tracking and VR using the Meta XR package bundle, only the Meta XR Core and Meta Interaction SDK are essential, as the Interaction SDK includes standardized interactions and gestures which would be a challenge to recreate without the Interaction SDK. The website also includes an entire guide on how to enable and include hand tracking support into a Unity project.

Searching for tutorials, besides the written documentation, the options are very limited. Videos that walk through setup of a base project using the package bundle can be found, but they were posted at the very earliest in the beginning of November of 2023. More in depth tutorials are yet to be released it seems, which is logical for recently released packages. This also means the intricacies of the package bundle are yet to be discovered by developers and Unity enthusiasts alike, which could prove to be an added difficulty for beginner VR developers.

### Steam VR

Steam VR is the officially supported package from Valve for which the current latest release version is 2.7.3 since February 24, 2021 [Unity Asset Store, 2021]. The development of the package appears to have been abandoned.

This package initially tackled advanced interactions, including custom grabbing and shooting a bow and arrow where one hand holds the bow and the other pulls back the arrow, but updates have halted.

## MRTK

MRTK or Mixed Reality Toolkit was an officially supported package by Microsoft. The last release version of the package under Microsoft is 2.8.3 since December 8, 2022 [Microsoft, 2022].

MRTK was originally developed for their own specific headsets, but also made sure to support Meta devices along the way. According to the video mentioned above [Valem Tutorials, 2022], this package supports the most advanced interactions of all of the official packages, which is especially interesting for developers of a more advanced skill level.

In August of 2023, MRTK3 was released by a new organization called Mixed Reality Toolkit. It is said Microsoft supports the new version and urges users to update applications to the new MRTK3 version as soon as possible. The old MRTK2 GitHub repository remains under Microsoft their management, giving the impression the Mixed Reality Toolkit is a new organization independent from Microsoft [Mollis, 2023].

To implement this package in Unity, it has to be downloaded from the GitHub page MixedRealityToolkit-Unity [Mixed Reality Toolkit, n.d.].

Documentation on MRTK 3 [Microsoft, 2023] showcases a laundry list example scenes showcasing a ton of different possibilities for UI elements and interactions, while also being able to show cross platform input such as hand tracking, controller input or mouse input.

## Intricate Custom Packages

The aforementioned video [Valem Tutorials, 2022] briefly skims over the topic of packages made by independent developers. In the Unity Asset Store, *Auto Hand – VR Interaction*, *Hurricane VR* and *VR Interaction Framework* are at first glance the most popular examples of packages that were made by independent developers. Each package serves their own purpose. *Auto Hand – VR Interaction* combines high-quality physics with a lot of customizability, while still being user-friendly [Unity Asset Store, 2024]. *Hurricane VR* focuses on high-quality physics interactions [Unity Asset Store, 2023] and *VR Interaction Framework* aims to facilitate working in VR, specifically for beginner VR developers, also claiming they provide a great foundation to create polished VR experiences [Unity Asset Store, 2023]. All three have their own documentation, have been updated recently and provide support through either personal contact or their own Discord.

Another thing all three of the independently developed packages have in common is that they cost money. Opposed to the officially supported packages from the companies that also make VR hardware, which are all free to use, each of these packages costs at least $70 when not discounted.

A student paper brings attention to approaches implementing algorithms to make physics interactions more realistic [S. Verrelst, 2021]. While they are interesting and can definitely be beneficial to improve how realistic the exercises and interactions with objects feel, they are too niche for the question this paper tries to answer.

## REHABILITATION IN VR USING HAND TRACKING

### APPLICATIONS FOR REHABILITATION

Cureosity is developing all kinds of different exercises for rehabilitation in VR [Cureosity, n.d.]. Ranging from gross motoric exercises, to fine motoric exercises with controllers or hand tracking. The goal ranges from picking fruits from a tree and putting them in a basket, to mirror-therapy exercises where the patient uses their least affected arm, while in VR the other arm shows the movement that is performed to stimulate the brain and help in regaining movement in the affected limb. Examples of fine motoric exercises include pinching or bending the fingers in order to pop a bubble on the palm of the hand (Figure 1) or the interactive therapy cube that reflects activities performed often in daily life, such as operating a switch, pressing buttons or turning a wheel [Cureosity, n.d.]. This application is only available when bought in a bundle that includes a headset and tablet, on which a dashboard is shown that includes information about the user of the headset (Figure 2).

**Figure 1: Headset & tablet package Cureo**

**Figure 2: Bubble popping finger exercise Cureo**

Besides Cureosity, finding applications that are similar to the application in mind for the case study is difficult, but there are some other interesting applications used in different fields of rehabilitation that are worth taking a look at. The XR 4 Rehab website [XR4Rehab, n.d.] has an amazing library of existing projects in VR that are used or can be used for all kinds of different fields of rehabilitation.

Some of those projects are:

*GRAIL*, Gait Real-time Analysis Interactive Lab, used for the rehabilitation of walking, of which one is present in UZ Ghent.

*Augmented Rehab*, intended to increase motivation for rehabilitation in patients with spinal cord injuries.

*Enhance VR*, used to test and train a range of cognitive abilities with their library of different games.

## OTHER

Sarah Vercaemer mentioned that at UZ Ghent different games for VR that were not specifically designed for rehabilitation are still very useful for it, because they either allow a lot of customization through settings, or are in general fun ways to perform movement that would otherwise be done in the form of exercises outside of VR.

Beat Saber is one of the games that allow for a lot of customization through settings, but is played using controllers instead of hand tracking. Starting off with the five standard options for difficulty (Figure 3, pink), which can each be altered by the additional settings that are available for every song. These include, but are not limited to slowing down the song a set percentage, speeding up the song a set percentage, removing the direction in which the cubes need to be sliced through, allowing the player to just hit the cube in any direction, shrinking cubes in size, making the arrows on the cubes disappear, requiring the player to remember in which direction the cubes need to be sliced through (Figure 4). Some additional settings are available for a limited number of songs. These include but are not limited to, removing the bombs that are present in the standard level, removing the boxes a player is not allowed to touch that are present in the standard level, a version of the level that only uses one saber, so only one hand (Figure 3, green).

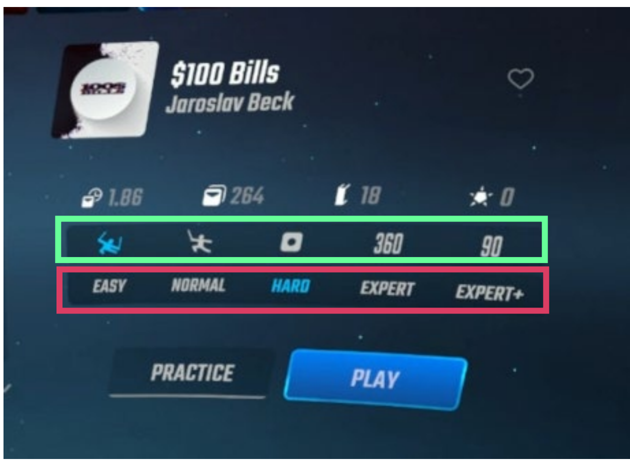




**Figure 3: Difficulties in Beat Saber**

**Figure 4: Extra settings in Beat Saber**

Physics Lab, played using hand tracking, and Fruit Ninja, played with controllers, are two other games that were not created with the intent for them to be used for rehabilitation, but require the user to perform actions and movement that is great for rehabilitation of hands and arms. Both of these games do not have the extensive list of settings that make them more accessible, but are still useful.

# CASE STUDY

## INTRODUCTION

After research, XR Interaction Toolkit in combination with XR Hands is chosen as the most logical package to use for the experiment. The decision to only make an application using one combination of packages was made due to limited time and experience working with VR in Unity.

With the research question of this paper “What are the limits for built-in hand tracking of a Meta Quest 2 VR headset when used for hand rehabilitation in a Unity application, implemented using accessible packages?” the goal is to figure out and define the limitations any application in VR that uses hand tracking runs into. The time frame for this case study only provides enough time to tackle one approach to implement hand tracking into a Unity application. The approach to implement hand tracking means the package or combination of different packages that are necessary to implement VR with hand tracking into a Unity project. Ideally the same research should be done using all of the most common packages currently used to implement both.

By setting up an experiment in the form of three different exercises and testing it with people from the target audience, the research question is answered, for the packages used. The three exercises are derived from exercises that are used in rehabilitation of fine motoric in hands. Derived from typing, the first exercise requires pressing buttons while playing the classic Simon Says memory game with four colors. Keeping Legos in mind, the second exercise involves stacking cubes that attach to each other. Lastly, the third exercise is derived from stringing beads, and involves putting donuts on a stick. Every exercise has three variations in size, which each serve different purposes. There is a neutral size for each exercise to showcase what the exercise entails. Then there is a small version of every exercise that targets fine hand motoric and precise coordination. Finally, there is a big version of every exercise that targets gross motoric, where movement of the arm becomes important.

Hand tracking is making progress in how well it works and for what purposes it can be used. In the first iterations of hand tracking on the Oculus Quest devices, if one hand occluded the other, the headset showed error messages signaling occluded hands are not tracked well and to try to avoid this. Currently, this message no longer appears and entwining fingers of both hands is nicely tracked and replicated by the VR hands. Even though hand tracking has made a lot of progress, there are still some imperfections to it. H1 is drawn up to draw attention to hand tracking and testing how accurate it currently is, and if it can be used for rehabilitation exercises that require very precise finger movement.

H1 - Hand tracking is accurate enough to detect precise finger positions and precise movement that can be implemented in a Unity application using the XR Interaction Toolkit and XR Hands packages.

When recreating anything in VR, especially using hand tracking there is always the discrepancy between the objects that are present in VR, but not in real life. Besides that, often when using hand tracking, a specific gesture is required to pick up objects, like touching the fingertips of the thumb and pointer finger together in a pinching motion, or making a completely closed fist. When grabbing small objects, the pinching motion is logical, but not when grabbing bigger objects. H2 is drawn up so the effort necessary to smooth out these differences is kept track of.

H2 - Besides the options in the XR Interaction Toolkit and XR Hands packages, a lot more work elsewhere in the Unity project is necessary in order to ensure interactions feel good and look real.

As there is a complete lack of papers that detail research about specifically the hand tracking that is built-into a Quest 2 headset, there is no clarity if this kind of hand tracking works well enough to make exercises that are actually useful for rehabilitation. H3 is drawn up to answer the question if extra hardware is actually essential before hand tracking can be useful for rehabilitation.

H3 - The fisheye cameras are sufficient, if the right approach to implement hand interactions in Unity is chosen and exercises are adapted for VR use.

## HARDWARE

### QUEST 2 VR HEADSET

| | |
|---|---|
| HARDWARE | PC optional<br>Enjoy advanced all-in-one VR with just a headset and controllers. (Smartphone app required.) Or connect to a gaming computer to access Rift titles with Link cable |
| TRACKING | Six degrees of freedom<br>With 6DOF, the headset tracks the movement of both your head and body, then translates them into VR with realistic precision. No external sensors required. |
| OPTICS | Specifications<br>Fast-switch LCD display<br>1832 x 1920 resolution per eye<br>60, 72, 90 Hz refresh rate supported<br>Glasses compatible |
| STORAGE | 128 GB \| 256 GB |
| META QUEST 2 | Advanced all-in-one VR gaming<br>Starting at €349.99 |

**Table 1: Quest 2 specifications [Meta, n.d.]**

## SOFTWARE

### UNITY

The Unity version used for the project is 2022.3.15f1 because it is the latest Long Term Support (LTS) version when the project is created.

### XR INTERACTION TOOLKIT

In order to implement VR into Unity, it was ultimately decided the best choice of package at the time of making the exercises is XR Interaction Toolkit (XRI). This package is developed by Unity itself.

The installed version in the project is 2.5.2, which is the current latest full release version.

This package on its own is does not allow for implementation of hand tracking, and because of the dependency of XRI on the XR Hands package, a hands interaction demo scene, with associated assets, can only be downloaded and imported into a project if the XR Hands package is installed as well.

## XR HANDS

XR Hands is the package on which XRI depends in order to support hand tracking in a Unity application.

The installed version of this package is 1.3.0, which is the current latest full release version.

# SETUP

## UNITY PROJECT

A Unity 3D project is created in the latest Long Term Support version, 2022.3.15f1.

In the project settings, in the XR Plugin Management tab the button "Install XR Plugin Management" is pressed (Figure 5).


**Figure 5: XR Plugin Management settings in Unity before installation**

When everything is done installing, in the same tab in the project settings there are now three different tabs. In the tab for Windows, Mac and Linux settings, the checkboxes next to Initialize XR on Startup and OpenXR are checked (Figure 6). For a build to function when installed on a Quest 2 VR headset, the same boxes need to be checked in the tab for Android settings.

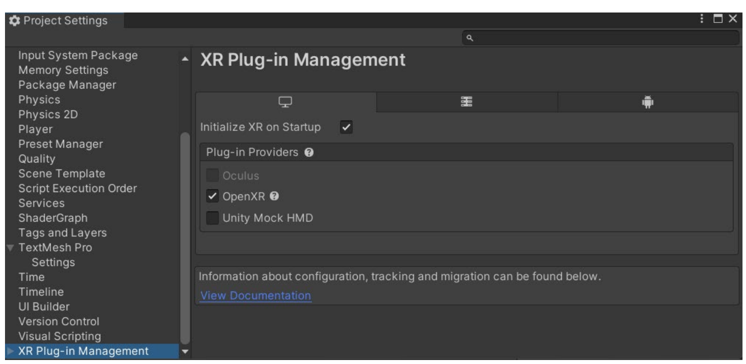



**Figure 6: XR Plugin Management settings in Unity after installation**

The XR Plug-in Management has a tiny arrow next to it that expands different options. In the OpenXR sub-menu there are the same three tabs as seen in the XR Plug-in Management section. In the Windows, Mac and Linux settings tab, the Render Mode is set to Single Pass Instanced. The only thing in the list of Enabled Interaction Profiles is the Oculus Touch Controller Profile. In the OpenXR Feature Groups, the boxes next to Hand Tracking Subsystem and Meta Hand Tracking Aim are checked (Figure 7).

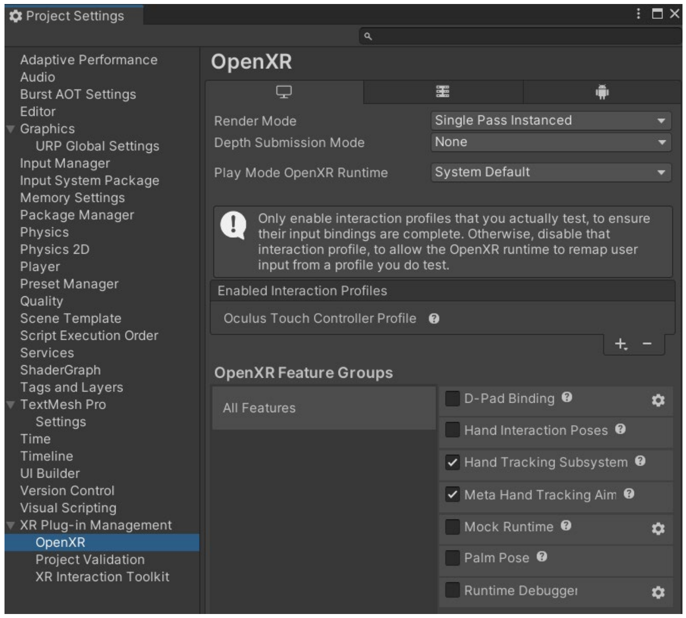



Figure 7: Open XR settings for Windows, Mac and Linux

Again, to ensure a build of the project also works on the Quest 2 VR headset, the same is done in the Android settings tab. The Render Mode is set to Single Pass Instanced \ Multi-view. In the OpenXR Feature Groups, the boxes next to Hand Tracking Subsystem, Meta Hand Tracking Aim and Meta Quest Support are checked (Figure 8). Other settings are the same as in the Windows, Mac and Linux settings tab.

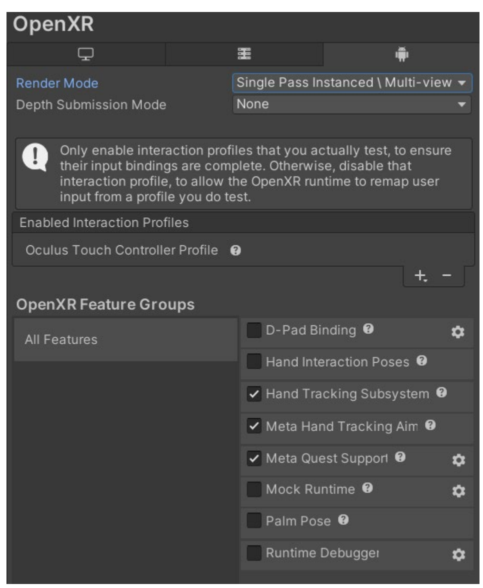



Figure 8: Open XR settings for Android

In the Package Manager, the XR Interaction Toolkit and the XR Hands packages are installed from the Unity Registry (Figure 9). From the XR Interaction Toolkit, the Hands Interaction Demo samples are imported (Figure 10).

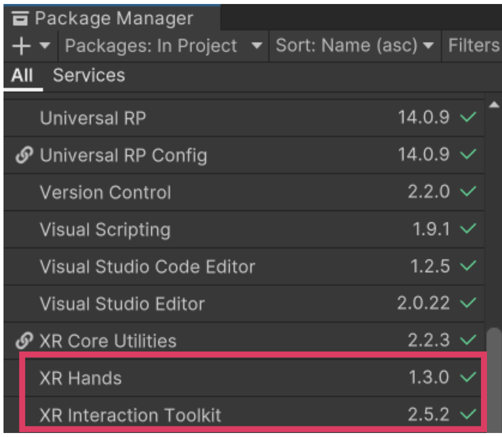



Figure 9: Package Manager Packages in Project

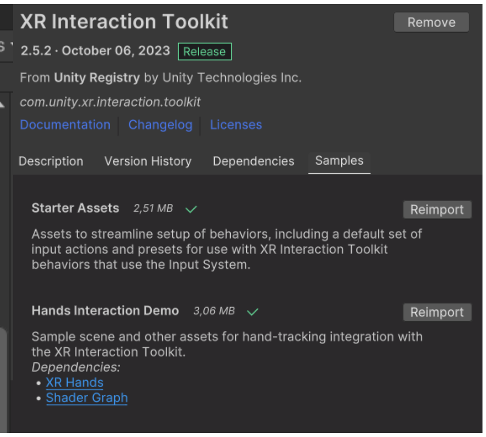



Figure 10: XR Interaction Toolkit Samples

## UNITY SCENE

Starting off in an empty scene, the main camera is deleted and the directional light is made to not cast any shadows.

A plane is placed in the scene as a floor, and a simple visual for a table is placed on top of that floor (Figure 11). Near the table, the XR Interactions Hands Setup prefab is put down (Figure 12). This prefab is found in the imported samples belonging to the XRI. This asset marks where the user appears when starting up the application.

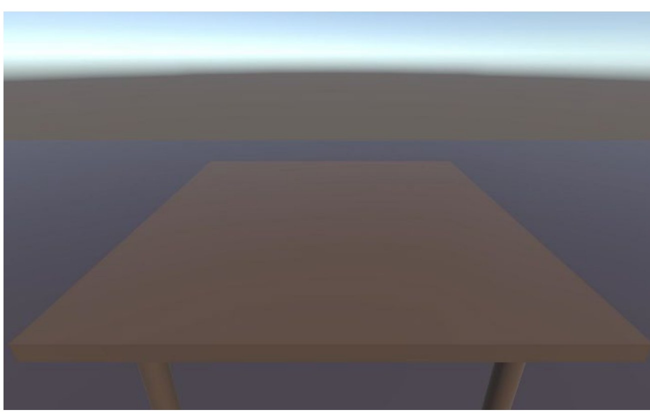


Figure 11: Simple table visual

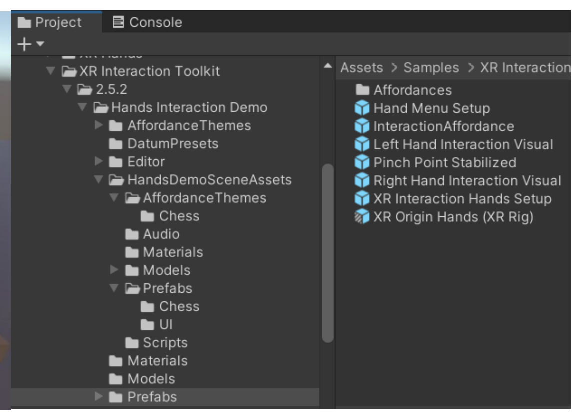



Figure 12: XR Interaction Hands Setup prefab location

Every element that is necessary for the exercises is placed on the tabletop. Objects that are interactable are put close to the edge of the table so they are easily reachable.

Components of different exercises are grouped in an empty object to create a clean scene structure.

To ensure ease of performing the exercises and account for possible issues with calibration of the floor in the Quest 2 headset, a handle is added to the table so it can be moved around.

## MENU

### First Version

A menu with buttons is placed right next to the XR Interactions Hands Setup, facing towards it.

The buttons used on the menu are the same buttons that are found in the Hands Demo Scene demo menu. A button for every exercise in the three different size variants is put on the menu. Via pressing these buttons, the different exercises become visible on the table.

In the first version of the application, just nine buttons corresponding to the different sizes of the exercises are present (Figure 14). Pressing the button while the application is running makes an exercise appear on the table. An exercise disappears when a button for a different exercise is pressed. Exercises are simply activated or deactivated, but items that were spawned in, like donuts or cubes, do not disappear.

By default, the menu is placed on the right side of the XR Interactions Hands Setup. To account for possible left-handed users, a handle to move the menu is added. This handle allows movement in all three different axis, as well as rotation around the Y axis.

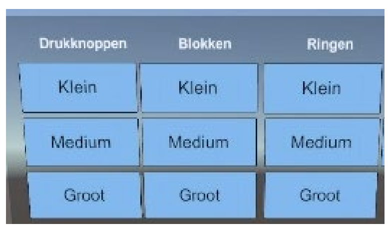



**Figure 13: Menu first version**

### Adapted Version

Based on insights from the first playtest, the following changes were made.

By default, the menu is now placed right above the table, in front of the XR Interactions Hands Setup, facing towards it.

The menu now has 6 new buttons.

Two of which make the Simon Says exercise more enjoyable, or playable at all, for the user and are located underneath the pre-existing buttons that activate any of the size variations of the Simon Says exercise. (Figure 14, pink)

Three buttons underneath the title “Tafel Verplaatsen” (Move table) make handles to move the table either appear or disappear (Figure 14, green). The two most left-hand buttons make different handles appear, the third button makes these handles disappear. One handle allows for the table to be moved up or down, the other handle allows moving the table closer to the user, or farther away. The table can be no longer moved side to side, or rotated. These handles are no longer visible by default. In order to make them visible, the buttons on the menu are pressed.

The last new button makes two grabbable cubes appear (Figure 14, orange).

Underneath the menu there is a handle that allows the user to move the menu on both the X and Y axis of the scene, meaning the menu can be moved up or down and side to side, but not closer to or farther away from the user (Figure 14, blue). It can also no longer be rotated. This handle is placed rather far below the menu, because it otherwise can make pressing the buttons on the bottom even more difficult.

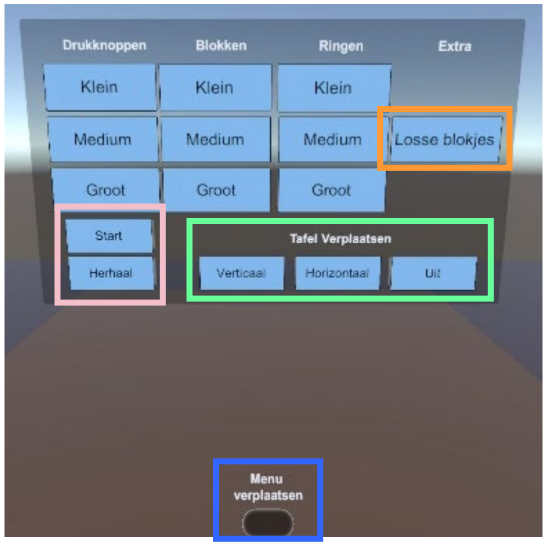



**Figure 14: Menu adapted version**

Besides the menu in the application itself, a menu in the Unity Editor is also created (Figure 15). If the user has difficulty navigating the menu, the application can be controlled by someone else, using buttons with the same functions of the menu in the application. This menu only exists in the Unity Editor, meaning the application has to be run from the Unity Editor on a computer that is connected to a Quest 2 headset in order for this menu to be available, and not from a build that is installed on the headset itself.

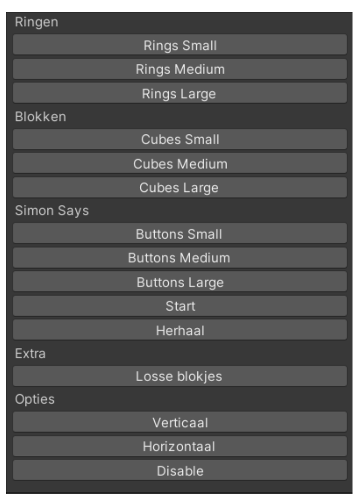



**Figure 15: Editor menu**

# EXERCISES

All three exercises are explained more in detail in following chapters. For each of the three exercises, there are three different sizes. The smallest and largest size each target a different kind of rehabilitation, while the middle exercise is there as a proof of concept, or to fall back on when the user has difficulty completing the other size variations of the same exercise.

Directly derived from exercises used in fine motoric rehabilitation outside of VR, the smallest exercise logically targets rehabilitation of fine motoric.

The largest size is an exercise that targets rehabilitation of gross motoric and often requires more arm movement. Sometimes the exercise is altered additionally, compared to the small exercise, to make completion easier.

Besides the three main exercises, an extra is included that showcases the importance of the Lego imitation. This extra has one set size and includes just loose blocks the user can stack freely on the table.

## STACKING LEGOS

Lego bricks, opposed to independent cubes, are most interesting to translate into VR. As physics are not entirely accurate for objects that are held in VR, be it with hands or controllers, stacking independent cubes is difficult. Making cubes that snap onto each other when in close enough proximity allows for more freedom in the exercise, as building a tower with considerably large, independent cubes proves difficult even for people that do not have any limitations in mobility.

### First Version

A simple visualization of an imitation of Lego bricks is created by adding four studs on top of a cube with rounded edges.

In the middle of the table, four studs are placed to function as a starting point for where to start building a tower of cubes. Letting go of a cube when it is in close proximity to the studs, changes its position to snap straight above the studs. Letting go of cubes in close proximity to studs on top of other cubes, snaps the cubes together by aligning the bottom of one cube to the studs of the other.

For the smallest exercise, the Lego bricks are small, so the player has to be precise when grabbing and placing them onto each other.

The bigger exercises make the Lego bricks larger.

### Adapted Version

Based on insights from the first playtest, only a tiny adaptation was made to every size variation of the exercise, being a pointer to the starting point for where to build the tower of cubes.

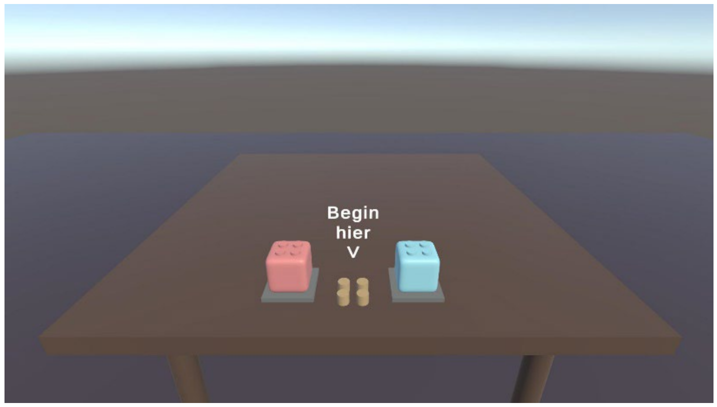



**Figure 16: Lego stacking exercise**

### Loose Blocks

Not counted as an exercise, but interesting to show to testers of the application is the difference between stacking the imitation Legos and independent, loose cubes. In the first version of the application, the loose cubes are made visible by activating them by hand in the Unity Editor. During adaptations, a button is added so the user can navigate to the loose cubes independently.

## PUTTING RINGS ON STICKS

Derived from the fine motoric exercise of stringing beads, putting rings on a stick is a visually clearer adaptation of the exercise. In order to string beads, a patient needs to use both hands and has to be really precise in aligning the little hole in the beads with the tip of the yarn. Looking at a ring, it is visually clearer how the object is rotated than a bead, when aligning the hole with the piece of twine or stick it is to be strung onto.

Static sticks that are rotated along different axis are placed on or above the table for the two largest size variants. These static sticks are placed more towards the sides of the tabletop. A stick with a flat base, that allows it to stand relatively stable on its own, and can be picked up is also placed on the table, more central. Next to the interactable stick, a donut is spawned in on top of a gray rectangle. This donut can be picked up. When the donut is moved away from the rectangle, a new one spawns in its place. A mesh from the *Food FREE* asset pack was used as the donut [Unity Asset Store, 2023].

### First Version

The interactable stick is one of a kind and placed in the scene, instead of spawned in. When it is moved from its initial spot, it is not respawned, unlike the donut.

### Adapted Version

Based on insights from the first playtest, the following changes were made.

Instead of placing the interactable stick in the scene, it is now spawned in when a size variant that requires one is activated. When the stick falls to the ground, it can be respawned by clicking the button to activate the exercise again.

The static sticks now have bright colors, making them easier to see for the user. It is also easier to point out a specific stick for the therapist.

**Figure 17: Rings exercise**

## PRESSING BUTTONS

This exercise is originally derived from typing. It is adapted heavily, in comparison to the other exercises, because typing in VR does not feel natural at all. Mostly because of the complete lack of tactile feedback, there is no way to make typing feel natural. Besides this, the XR Interactions Hands Setup only supports interactions with menu items or buttons with the tip of the pointer finger.

Four buttons, each a different color, are set up near the edge of the table that is closest to the XR Interactions Hands Setup. On the opposite side of the table, four cubes are placed in the corresponding colors of the buttons. The colors of the buttons are the following, in order from left to right: Red, yellow, blue and green. (Figure 18) By pressing any button, the corresponding cube in the same color simulates being lit up by changing into a lighter shade of the same color. (Figure 19) After a delay of 1,5 seconds, the cube reverts back to its original, dark shade.

A script is written that executes the logic behind the classic Simon Says game with four different colored buttons that light up.

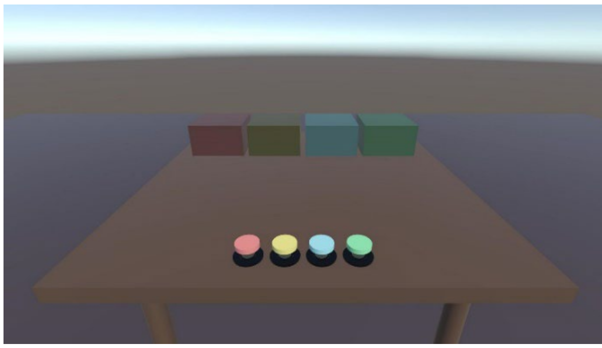
In the different variations of sizes, the only difference is the size of the buttons. The smallest exercise requires more precise coordination to press the buttons, while the large size requires more movement from the entire arm.

An attempt was made to save time, by using existing code for Simon Says, but eventually the script was written independently, as the exercise in VR was made slightly different than the classic game.

### First Version

When any size variant of the Simon Says exercise, called “Drukknoppen”(Buttons) on the menu, is activated, Simon takes its first turn after a delay of only three seconds. Simon shows a random combination of four colors by changing the material of the cubes, simulating the cube lighting up (Figure 19). After the four cubes have lit up, the user should press the buttons corresponding to the cubes that lit up earlier. If the right buttons are pressed in the right order, Simon will take its turn again, increasing in difficulty. This means, every time the user manages to press the buttons in the right order, another combination of colors is lit up, the amount equivalent to the starting four plus the amount of times the user has been able to correctly press the buttons.

If the user does not manage to press the right buttons in the right order, Simon takes its turn again, starting over with the default amount of four cubes lighting up.



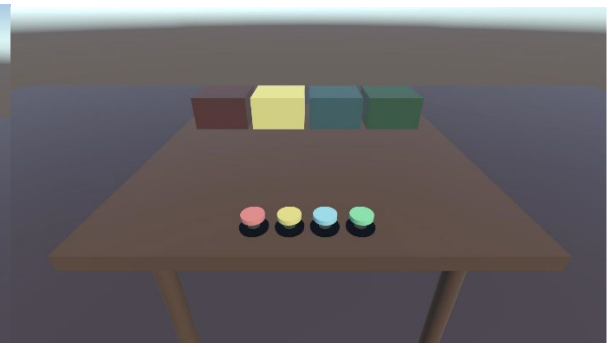


Figure 18: Simon Says exercise

Figure 19: Simon Says exercise yellow cube lit up

While Simon is taking its turn, this version of the exercise allowed for the user to press buttons and light up cubes. After pressing the right buttons in the right order, the exercise sometimes stopped working instead of continuing with Simon its turn and adding difficulty. The same thing sometimes happened when the player pressed the buttons in the wrong order. All of these things were not supposed to happen.

### Adapted Version

Based on insights from the first playtest, the following changes were made.

When any size variant of the Simon Says exercise, called “Drukknoppen”(Buttons) on the menu, is activated, the components for the exercise become visible on the table. The user now has to start the exercise by pressing the “Start” button on the menu. Simon then takes its turn, lighting up only two colors instead of four. The user can no longer light up other cubes by pressing buttons while Simon is taking its turn. When the user presses the correct buttons in the right order, feedback in the form of an affirmative word above the exercise, is shown and the exercise increases in difficulty. When the user does not manage to press the right buttons, a word floating above the table lets the user know the exercise will reset, which then also happens. The exercise starts over by lighting up only two cubes, after a delay of 6 seconds.

If the user forgets which cubes have lit up, pressing the button “Herhaal” (Repeat) on the menu repeats Simon its turn.


Figure 20: Extra menu buttons for Simon Says

## ADDITIONAL ATTEMPTED ADAPTATIONS

### POINTER INTERACTORS

Every exercise was derived from an exercise used for rehabilitation of fine motoric, outside of VR. One of the exercises that served as a base was typing, but as recreating that in VR is difficult and also feels notoriously unnatural, it was adapted to Simon Says. The initial idea, to make sure there still was a small link with typing, was for the smallest exercise to be just the right size for the buttons to be pressed using different fingers.

By default in XRI, only the pointer finger can interact with menu and 3D buttons. A pointer interactor is what allows for said interactions. A few attempts were made to put these interactors on the other fingers, but more research lead to the realization multiple pointers are not recommended. Research done by Microsoft lead to the conclusion only one pointer interactor on the pointer finger is the most efficient. Putting them on other fingers is possible, but very difficult as of now. Work is being done to facilitate it. [Unity Forum, 2023]

When this information was discovered, the Simon Says exercise was made to be the exercise it is now, pressing buttons using the pointer finger.

### CUSTOM GESTURES

In order to pick items up in XRI, the default gesture is making a pinching motion by touching the tip of the pointer finger and thumb together. As this gesture can be difficult for people with ABI, another gesture would allow more patients to use the application.

Finding any information about gesture detection in XRI proved difficult. Eventually, comments in a Unity questions thread brought to attention gesture detection is not a feature that is available in XRI version 1.3.0. It is a feature currently in works and should be released soon. [Unity Forum, 2023]

As a result, the pinch gesture is still required to pick up items, making the application not inclusive for patients that cannot perform the gesture.

## PLAYTEST & RESULTS

Thanks to Sarah Vercaemer, it was possible to test the application with people from the target audience. All of the patients that participated in the playtest suffer mobility and / or other disorders of different kinds, due to ABI. Sarah is present and helping during all of the playtesting. Information mentioned below about patients was gathered by Sarah from both her own knowledge and experience with said patient, as well as input from her colleagues at UZ Ghent.

Each playtest moment, five patients were asked to try and complete as many exercises as they could. The gender and an estimation of age of each patient is noted down. Exercises that are not completed are noted, and if possible also the reason why the exercise is not completed. If reasons are not clear, the opinion from the patient is asked after attempting all of the exercises. When the patient is done executing the exercises, a list of questions is asked. These questions try to gain insight on a few different topics, for example how much experience the patient has with VR, what consequences they suffer from ABI, if they would like to keep using VR during the remainder of their treatment, what improvements could be made in the exercises and more.

Every patient had at most one hour to try all of the exercises and answer the questions afterwards.

## PLAYTEST ONE

Because picking up objects is only possible by making a pinching motion with the thumb and pointer finger, Sarah kept an eye out for patients that are able to perform the gesture. The patients are from varying age groups and all of the participants for this playtest moment were male.

### Patient One

Male, younger than 20 years old.

Patient has no previous experience with VR.

All of the exercises could be completed, though the Simon Says exercise starts fast, has no clear feedback, and sometimes stops working on its own, making it difficult to complete multiple sequences.

Movement the patient has trouble with are fine motoric, picking up small objects and rotation of the wrists, and the most affected hand of the patient is the right one. The patient is aware of these difficulties and indicates the smallest variation of the donuts exercise is the most difficult in their opinion.

The patient experienced the exercises in a positive way and would like to continue to use VR during the remainder of their treatment.

### Patient Two

Male, between 20 and 30 years old

Patient has no previous experience with VR.

Simon Says exercise was not completed in any size variation, partly because of the issues the exercise has of starting fast, lacking clear feedback and stopping on its own, but also partly because the patient had trouble either seeing the different colors or remembering them.

Patient indicates they have no trouble with fine motoric and only sometimes struggle seeing things far away. Sarah added the patient likely has neglect on his left side and also struggles with memory.
When asked what exercises were difficult, the patient indicated the colors for Simon Says were not right.

The patient experienced the exercises in a positive way and would like to continue to use VR during the remainder of their treatment.

### Patient Three

Male, between 50 and 60 years old.

Patient has no previous experience with VR.

Simon Says exercise was very difficult, partly because known issues with the game, but also because the patient struggles with memory and sight. The medium and small donuts exercise were difficult, notably the part with the interactable stick. Said stick ended up on the floor a few times during both exercises, for which the application was restarted so the stick reappeared on the table. Eventually the patient did succeeded in putting donuts on both the interactable sticks.

Patient indicates they suffer from hemianopsia and their right arm reacts slower, and is difficult to stretch out. When asked which exercises were difficult, the patient said Simon Says due to sight and memory, and the donuts because of coordination with both hands.

The patient experienced the exercises in a positive way and would not mind continuing to use VR during the remainder of their treatment. Patient does not seem super enthusiastic, but at the same time not opposed to the idea of VR either.

### Patient Four

Male, between 50 and 60 years old.

Patient has no previous experience with VR.

Simon Says exercise was very difficult, again partly due to know issues, but also partly due to patient struggling with memory. The smallest variant of the donuts exercise takes some getting used to, but the patient eventually does succeed in putting donuts on the stick.

Patient indicates they struggle with stretching out their right arm and that they suffer from neglect on their left side, but hardly notice it. Sarah adds to this the neglect translates into not using the left arm for this patient. When asked which exercises are difficult, the patient says Simon Says because of memory and the smallest variant of the donuts because of coordination.

The patient experienced the exercises in a positive way and would like to continue to use VR during the remainder of their treatment. Patient says there is a lot of room for improvement, but as a first experience it was great.

### Patient Five

Male, between 50 and 60 years old.

Patient has previous experience with VR, specifically has used Physics Lab before.

Simon Says exercise was difficult, because of known issues.

Patient indicates they struggle with movement in the right shoulder such as lifting the arm above their shoulder, and fine motoric and coordination with their right hand. Patient also indicated they had difficulty seeing the horizontal sticks in the middle and largest size variant of the donuts exercise.
When asked what exercises were difficult, the patient says the smaller exercises were the most challenging.

The patient experienced the exercises in a positive way and would like to continue to use VR during the remainder of their treatment.

### Therapists

During playtesting, a colleague of Sarah, called Fleurine, who is also an occupational therapist at UZ Ghent, came to watch and gave some feedback while a patient was performing the exercises:

The Simon Says exercise starts very quickly after it is activated. This can be countered by adding a button to start the game instead of starting it automatically when the exercise is activated. The exercise also does not give any feedback if the player makes a mistake, or is correct. Any feedback that indicates how the patient is doing would be useful. Adding a button that repeats the sequence of Simon his turn can give patients more chances to reach higher scores.

In the donuts exercise, the interactable stick should be able to respawn on the table, so patients don not have to reach underneath the table to pick it back up.

Navigating the menu is a hassle for the patients, so removing it seems like the best option.

Another occupational therapist from UZ Ghent and colleague from Sarah, called Hebe, tested the exercises herself, resulting in very similar feedback. Using the menu took some attempts, but it ended up working a lot better than when patients tried to use the menu.

### General Notes

Every single patient struggled with navigating the menu, to a point where using the menu would be frustrating. After having a patient try to press some buttons, the decision was made to make objects visible and invisible by hand in the Unity Editor, as to not cause frustration for the patients. Besides navigating the menu, moving the menu and the table proved difficult as well.

The therapist that tested the application had less trouble navigating the menu. It took some getting used to exactly how to press the buttons, but once they got the hang of it, navigating the menu worked, not perfectly, but it was at the very least manageable.

Before the playtest moments in UZ Ghent, the application had only been tested by people without any limitation to their movement. They were able to navigate the menu after some trial and error, and moving the table or menu had not proven to be as difficult.

## PLAYTEST TWO

During this moment of playtesting again 5 patients tested the exercises. A mix of patients that tested during the first moment, to compare their experience, and different patients. Once again, the patients are from varying age groups. Returning patients are asked questions to compare their experience from the previous playtest moment to this one, new patients are asked the same questions that were asked in the first playtest moment, with addition to some questions about the environment.

### Patient Six

Patient six is the same person as patient one from the first playtest moment. Male, younger than 20 years old.

Patient was able to complete all of the exercises.

During this playtest moment, the patient tried more exercises with both hands. It became clear the patient has tremors that intensify the further his left hand is away from his body. Movement with the left hand is less restricted, but it results in tremors.

Even with adaptations, navigating the menu still proved too difficult to be useful for this patient.

When asked which exercises are difficult, patient says the smaller exercises are more difficult.

As for the environment, the patient indicates an environment in theme of the exercises could be fun, but if there are people in the environment it could become a distraction.

## Patient Seven

Male, between 40 and 50 years old, seated in an electric wheelchair

Patient has experience with VR, but only with exercises that do not require interaction with hands or controllers. The application used eye tracking and looking at objects as interaction.

Important note:
This patient only has gross motor skills and cannot make precise movement with their arms. Making a pinch gesture is difficult for them, but manageable if they concentrate. They are seated in an electric wheelchair and cannot speak, only nod or shake their head in order to answer yes/no questions. During playtesting it also became apparent the patient has tremors that intensify the farther the hands are from the body.

Patient was not able to perform the middle and small variant of Simon Says, the small variant of the Lego stacking and the middle and small variant of the donut exercise due to their physical limitations.
The large Simon Says exercise was altered a bit to facilitate completion. Altered meaning putting the buttons further away from one another, ensuring the patient did not accidentally press a button they did not intend to press. Sometimes the patient pressed the same button twice when they did not intend to, when they did not lift their hand in time. The exercise with the donuts was the one the patient enjoyed the most.

The patient experienced the exercises in a positive way and would like to continue to use VR during the remainder of their treatment.

## Patient Eight

Male, between 40 and 50 years old

Patient has no previous experience with VR.

Navigating the menu took some trial and error, but eventually this patient succeeded.

All of the exercises were completed.

Patient says they have no issues moving their arms, but Sara indicates the patient has some issues with coordination, as well as walking. When asked which exercise was the most difficult, the patient says the smaller variants were the most difficult. While building a tower with Legos, the patient stood up to build a higher tower, which can also be a good exercise. Additionally, playing with the loose blocks the patient really wanted to break the record for highest tower built. It became very clear this patient can be motivated by some competition.

The patient experienced the exercises in a positive way and would like to continue to use VR during the remainder of their treatment.

## Patient Nine

Patient nine is the same person as patient five from the first playtest moment. Male, between 50 and 60 years old.

Note: During the playtesting with this patient, the Quest 2 had some issues with hand tracking. After the headset was turned off and back on again, this issue was fixed, but the patient did not entirely realize the issues were caused by the headset, instead of the application, because they indicated the exercise of stacking Legos was difficult. After the reset of the headset, the patient had no issues stacking Legos of any size.

After some trial and error, this patient was able to navigate the menu.

All of the exercises were completed.

When asked about environment, the patient indicated an environment in theme of the exercises could be fun, but the boring environment in the current application did not bother either.

### Patient Ten

Female, between 50 and 60 years old, seated in a wheelchair.

Patient has no previous experience with VR.

Simon Says exercise was difficult, as the patient seemed to have difficulty understanding what the purpose of the game was, while also struggling with remembering the correct order of the lit up cubes.

The patient indicated they have a lot of limitations in movement of their right arm, it is tightly pressed against their body by default and stretching it requires an effort. Making a pinching motion with the right hand is possible, but extending the fingers, wrist and arm all requires effort. Sara adds the patient generally has trouble understanding, has both apraxia and on a lower level also aphasia.

All of the exercises were completed, with some trouble understanding and remembering the colors during the Simon Says exercise. Pressing the buttons was not an issue in any size variation. For the middle version of stacking Legos, which was the first size variation the patient attempted, it took some time before they understood what to do. Once the exercise became clear, the patient had no trouble. When asked which exercises were the most difficult, the patient answered the exercises where they had to reach up high were the most difficult.

When asked about the environment, the patient indicated environments in theme of the exercises would be too distracting.

The patient experienced the exercises in a positive way and would like to continue to use VR during the remainder of their treatment.

Notes:

Apraxia translated into difficulty making a pinching motion. When the patient was interacting with bigger objects, such as the donuts or Legos, pinching did not come naturally. Once the patient tried the smallest size variation, the pinch gesture seemed more logical and seemed to be much easier.

This patient seemed to become frustrated easily. During stacking the Legos, the patient seemed to get annoyed by the cubes snapping onto each other at first, and tried to wipe all of the cubes off the table a few times. The same thing happened during the donuts exercise, where the patient tried to wipe all of the donuts and sticks off the table when she had trouble putting the donut on a stick.

### General Notes

Patient eight and patient nine were able to use the menu during this playtest session albeit with some hiccups.

Less patients had issues with the Simon Says exercise, compared to the first playtest moment, as the initial issues the game had are solved.

When patient seven was performing the stacking Legos exercise, they sometimes accidentally picked up Legos when they did not mean to. When a patient cannot perform a pinch gesture in a coordinated manner, sometimes objects are picked up, even if the hand is not entirely next to the object, as if there is a bit of a radius around the whole hand where objects can be picked up from.

# DISCUSSION

## COMPARISON

| | Simon Says S | M | L | Lego S | M | L | Donuts S | M | L |
|---|---|---|---|---|---|---|---|---|---|
| P1 | Yellow | Yellow | Yellow | Green | Green | Green | Green | Green | Green |
| P2 | Red | Red | Red | Green | Green | Green | Green | Green | Green |
| P3 | Yellow | Yellow | Yellow | Green | Green | Green | Yellow | Yellow | Green |
| P4 | Yellow | Yellow | Yellow | Green | Green | Green | Yellow | Green | Green |
| P5 | Yellow | Yellow | Yellow | Green | Green | Green | Green | Green | Green |
| P6 =P1 | Green | Green | Green | Green | Green | Green | Green | Green | Green |
| P7 | Red | Red | Blue | Red | Green | Green | Red | Red | Green |
| P8 | Green | Green | Green | Green | Green | Green | Green | Green | Green |
| P9 = P5 | Green | Green | Green | Green | Green | Green | Green | Green | Green |
| P10 | Yellow | Yellow | Yellow | Green | Yellow | Green | Green | Green | Green |

**Table 2: Playtest Results**

Green = Exercise succeeded.
Yellow = Exercise was very difficult and barely succeeded, or about succeeded.
Red = Exercise did not succeed
Blue = Exercise was adapted to patient in order to succeed.

### PATIENTS

The patients that tested the exercises during the first playtest moment all have versatile abilities with both arms, none of them were heavily limited in their mobility.

During the second playtest moment, two of the patients had more severe limitations in their mobility, specifically patient 7 and patient 10.

Taking a look at table 2, during the first playtest moment a lot of patients struggled with the Simon Says exercise. These struggles were caused by faulty exercise, rather than the patients being unable to perform the exercise correctly. Seeing patient 1 and 5 were able to complete the Simon Says exercise during the second playtest moment, it is safe to assume most of the patients from the first playtest moment would have been able to complete the exercise, had it not been faulty.

During playtest moment two, it is clear patient 7 and 10 had difficulty, or were unable to perform some exercises. For patient 7, this was due to their limited mobility affecting both hands rather than one hand. Exercises requiring precisely coordinated movement were not physically possible for this patient.

Patient 10 on the contrary, had one arm that was less or hardly affected, allowing them to perform the exercises easily with said arm. When asked to perform exercises using the severely affected arm, it required greater effort and sometimes help from their other hand in order to complete the exercise. The difficulty for this patient stems from their difficulty understanding. This patient was able to press the buttons of different sizes easily, but could not remember what colors to press in which order. They were also able to pick up the Legos, but had trouble understanding they should build a tower using them.

### MENU

During the first playtest moment the combination of being able to move the menu or table in three different dimensions all at once, while also being able to rotate them, seemed to be too much to keep track of at once. Especially for patients that have trouble rotating their wrists, rotating the table or menu was nearly impossible as the handle specifically requires the wrist to bend for rotation to happen.

Even after adaptations, the menu was not very usable for most patients. People that do not have limitations to their mobility seem to subconsciously alter their movements in order to make the menu work, which is something the patients were seemingly unable to do.

From here, there are a few options to look into. Either the menu has to be completely redone, which can be a research topic on its own, or an external menu that can be controlled by someone outside of the VR environment should be made and connected to the application, like Cureosity has done.

### SIMON SAYS

Again taking a look at table 2, it is clear that during the first playtest moment all of the patients that tested the exercises had trouble playing Simon Says. Most or all of the trouble was caused by the exercise itself having multiple issues. The timer before the exercise began automatically, was set to only three seconds. At the time of development it had seemed like a long time, but when playtesting with patients there was no time to explain what the exercise entails. Besides the delay being too short, the exercise gave no feedback about if the player was wrong or right, causing even more confusion. The third issue was the exercise sometimes just stopped working entirely, which did not allow the player to reach any high scores.

The second playtest moment, all of the issues mentioned above were resolved by giving the player the power to choose when to start the game, adding feedback and an additional button was added so the player can choose to repeat the sequence of Simon. Players could much more easily play the game and reach a score of up to seven consecutive right repetitions.

## CONCLUSION

Making exercises that are useful for both rehabilitation of fine and gross motoric is possible using the XRI and XR Hands packages.

Looking at the different hypotheses, not all of them have been proven or disproven.

H1 - Hand tracking is accurate enough to detect precise finger positions and precise movement that can be implemented in a Unity application using the XR Interaction Toolkit and XR Hands packages.

The first hypothesis was not proven or disproven, as the exercise in mind to gauge this was ended up being not possible to make. However, during playtesting the movement of the ring and pinky finger in VR did not always match the movement the player performed with their fingers.

H2 - Besides the options in the XR Interaction Toolkit and XR Hands packages, a lot more work elsewhere in the Unity project is necessary in order to ensure interactions feel good and look real.

For the current latest fully released version of the XRI and XR Hands packages, this hypothesis is proven partly. Currently there is no gesture detection support. The player always has to pick up items using a pinching gesture, however big or small the object is. Secondly, pressing buttons is currently only possible using the pointer finger. Even though there is a difference between reality and VR, patients did not mind it and they indicated the interaction did not feel off or uncomfortable, so the interactions felt good to them even if they did not seem exactly real.

H3 - The fisheye cameras are sufficient, if the right approach to implement hand interactions in Unity is chosen and exercises are adapted for VR use.

The last hypothesis was proven, as none of the patients struggled with hand tracking specifically. When they struggled, it was caused by other factors such as faulty exercises or a generally difficult to navigate menu. The menu being difficult to navigate was not a result of the fisheye cameras not being sufficient to track the hands properly, as people without limited mobility were able to navigate the menu more easily.

Answering the research question, the XRI and XR Hands packages are limited by the current lack of gesture detection and single digit pointer interactors, as well as the current state of menu interaction. Seeing the exercises made for the case study were not very intricate, the aforementioned limits are most likely not the only limitations of the packages.

It seems that currently, it is easier for a user to adapt to the application made, rather than adapting the application to the user. For applications used in rehabilitation, it would be much more convenient the other way around.

# FUTURE WORK

## FUTURE RESEARCH

### PACKAGE SPECIFIC

#### Gesture Detection

As mentioned in the chapter Additional Attempted Adaptations, custom gestures for the XRI and XR Hands packages is in development and predicted to be released in a future version of the packages. Once this feature is released, it can be implemented into the currently existing application made, or another application can be made that implements the feature, to see if people with more severe consequences due to ABI can also benefit from using the application.

#### Pointer Interactors

Also mentioned in the chapter Additional Attempted Adaptations, pointer interactors are advised to be limited to one per hand, which did not allow for development of an exercise that resembles typing. Facilitating the implementation of multiple pointer interactors is currently under development. Once the version of XRI and XR Hands that includes this feature is released, recreating an exercise that resembles typing can be revisited.

#### Menu Interactions

Delving into the topic of menu interactions with the XRI and XR Hands packages, as research on its own, seems viable after experiencing a substantial amount of trouble with it during the creation of the case study for this paper. Possibly specifically for patients that have limited mobility in hands and arms, as specifically the patients had the most trouble navigating the menu.

#### More Detailed

The exercises made for the case study of this project were not super intricate, meaning there are most likely more limits to be discovered when making more intricate VR applications using the XRI and XR Hands packages.

### EXTRA

#### Mirror Therapy

Mentioned rather often during playtest moments and even outside, during conversation with Sarah and her colleagues from both UZ Ghent and XRehab and Hitlab, was implementing mirror therapy into the exercises. Mirror therapy is when a patient uses their least affected arm to perform exercises their more severely affected arm would not be able to, next to a mirror, placed in a specific way to make it look like the arm in the mirror is their more severely affected arm. This tricks the brain to believe the more severely affected arm is performing the exercises, which sometimes aids in rehabilitation. Translated into VR, the arm performing the exercises could be entirely hidden, making it seem like only the more severely affected arm is performing the exercises.

### Dashboard

Because of the significant issues with menu interactions, it became apparent an external menu is necessary in some cases. Additionally, being able to watch what a patient is doing and can see is also very useful. For this the Unity Editor was used during the playtest moments, but if the application is installed onto a VR headset, that is not possible. Therefore, developing and attaching a dashboard that supports custom menus and streaming of the application can be useful research.

XRehab is currently developing a dashboard that allows for the aforementioned streaming and menu support. Sarah asked if they can use the exercises of the application that was created for the case study in their own application that is in development, which will be able to connect to the dashboard and has improved versions of features, such as adjusting height of the table.

### Similar Research With Different Packages

The initial idea for this paper was recreating the same exercises using different packages to implement VR and Hand tracking into Unity. Very early on, it became apparent this was too big of a scope for someone just starting off with VR development, so the decision was made to start off with just a singular version of the application. Performing the same research using different packages, in order to compare results is useful research that can be performed in the future.

## IMPROVEMENTS ON CURRENT PROJECT

### MENU

Menu currently in the app should be external. Ideally a therapist should be able to watch what a patient is doing while they are doing the exercises in VR as well, while controlling an external menu for the patient. For the group project of VR Shopping, a dashboard has been developed. The same dashboard, or something similar, could be used to create the external menu for these exercises, while also supporting streaming what the patient can see in the VR Headset.

### STACKING BLOCKS

To make the exercise less repetitive and a bit more challenging, more different colors of blocks can be added, as well as slightly different shaped blocks. A pattern of blocks can be generated, which the patient has to copy while building their tower of blocks.

Another level of difficulty can be added by giving blocks two colors which requires the patient to also take the rotation of blocks into account while building their tower.

The indicator for where to start the tower currently says “Start here” but to be less confusing it should be changed to “Build here”.

### PUTTING RINGS ON STICKS

For both the medium and large size variation of this exercise, the table is very cluttered. It would be better to have the option to activate either the interactable stick, or either of the horizontal or vertical static sticks. Paired with the choice to enable or disable either, where they are placed in relation to the user. On the left or right side of the table, far away from the edge or very close.

Like for the blocks, making a pattern of different colored donuts can make the exercise a bit more challenging. Even more difficult could be adding another layer of detail, different colored sprinkles on top of the glazing for example.

### SIMON SAYS

For patients that struggle with memory, it can be useful the exercise does not reset entirely when the wrong order of buttons is pressed, allowing the patient to attempt the same sequence multiple times.

## CRITICAL REFLECTION

The topic of this paper was an unexpected turn of events, as before the start of the school year of 2023-2024 I had not been interested whatsoever in VR development, nor games or game technology in a medical context. From the moment the different projects we could choose between for our Group Projects course were pitched, that interest was sparked. Throughout the development of the VR Shopping application, said interest only grew, resulting in a paper with a topic I could never have seen coming.

Going into the topic, I expected I would face some difficulties, notably with VR development itself, but also with taking into account the limitations of people suffering the consequences of ABI, as it was something I had a very vague understanding of. Having a general understanding of the possible consequences someone can suffer from ABI does not mean you can account for them while making an application. The issues I had expected to face were completely different from the issues we actually encountered during the playtest moments, which threw me off a bit as it was happening, but I think I adapted accordingly.

Other expectations, or maybe even prejudices, that I had about the patients were proven wrong. While making the first iteration of the application, I stressed a lot about making sure to include at least one version of the exercises every patient that came to test would be able to complete, because I did not want to cause any form of distress in patients by asking them to perform exercises they were not able to perform. Subconsciously, I assumed all of the patients would be fragile and easily demotivated, but I am glad I could not have been more wrong. When exercises did not succeed immediately, every single patient just kept trying until they did succeed. Even laughing about the difficulty they were having. I was really blown away by the resilience of these patients.

In the end, I do not believe the research I did was exceptionally ground breaking, but I do believe it can provide a great base, or starting point, for a lot more research, and I am happy with the end result.

## REFERENCES

*25 Hand Exercises For Stroke Recovery at Home | Stroke Rehabilitation*. (2018, July 13). Saebo. https://www.saebo.com/blog/reclaim-your-dexterity-with-hand-exercises-for-stroke-recovery/

admin_n3ur01utions. (2022, October 25). The Most Common Types of Tremors After Stroke What They Mean. *Neurolutions*. https://www.neurolutions.com/after-stroke/the-most-common-types-of-tremors-after-stroke-what-they-mean/

*Afasie | UZA*. (2023, June 30). Retrieved January 5, 2024, from https://www.uza.be/behandeling/afasie

*Auto Hand—VR Interaction | Game Toolkits | Unity Asset Store*. (2024, January 9). Retrieved November 9, 2023, from https://assetstore.unity.com/packages/tools/game-toolkits/auto-hand-vr-interaction-165323

Bae, S., & Park, H.-S. (2023). Development of Immersive Virtual Reality-Based Hand Rehabilitation System Using a Gesture-Controlled Rhythm Game With Vibrotactile Feedback: An fNIRS Pilot Study. *IEEE Transactions on Neural Systems and Rehabilitation Engineering, 31*, 3732–3743. https://doi.org/10.1109/TNSRE.2023.3312336

De Meta Quest 2: Onze nieuwe, meest geavanceerde all-in-one VR-headset | Oculus. (n.d.). Retrieved January 13, 2024, from https://www.meta.com/nl/quest/products/quest-2/tech-specs/

Levey, R. (n.d.). *Exercises and Activities to Improve and Maintain Fine Motor Skills: Reddy Care Physical & Occupational Therapy: Physical Therapists*. Retrieved January 9, 2024, from https://www.reddycare.net/blog/exercises-and-activities-to-improve-and-maintain-fine-motor-skills

*Eyes, hands, simulation, and samples: What's new in Unity XR Interaction Toolkit 2.3*. (2023, March 13). Unity Blog. Retrieved November 30, 2023, from https://blog.unity.com/engine-platform/whats-new-in-xr-interaction-toolkit-2-3

Food FREE | 3D Food | Unity Asset Store. (n.d.). Retrieved December 20, 2023, from https://assetstore.unity.com/packages/3d/props/food/food-free-260726

*Get Started with Meta Quest Development in Unity | Oculus Developers*. (n.d.). Retrieved November 9, 2023, from https://developer.oculus.com/documentation/unity/unity-gs-overview/

Hand Therapy Exercises: Strengthening & Restorative Techniques. (2020, November 6). *Flint Rehab*. https://www.flintrehab.com/hand-therapy-exercises/

*Hurricane VR - Physics Interaction Toolkit | Physics | Unity Asset Store*. (2023, November 18). Retrieved November 9, 2023, from https://assetstore.unity.com/packages/tools/physics/hurricane-vr-physics-interaction-toolkit-177300

*Meta Quest v56 Update: Meta Quest v56 Update: Hand Tracking Improvements, Facebook Livestreaming, & More | Meta Quest-blog*. (2023, July 20). Retrieved October 24, 2023, from https://www.meta.com/blog/quest/v56-software-update-hand-tracking-improvements-live-captions-facebook-livestreaming

*Meta XR Core SDK | Integration | Unity Asset Store*. (2023, November 8). Retrieved November 9, 2023, from https://assetstore.unity.com/packages/tools/integration/meta-xr-core-sdk-269169

*Niet-aangeboren hersenletsel (NAH)*. (2023, August 10). Retrieved January 5, 2024, from https://www.uzleuven.be/nl/niet-aangeboren-hersenletsel-nah

Oculus Integration (Deprecated) | Integration | Unity Asset Store. (2023, October 9). Retrieved January 13, 2024, from https://assetstore.unity.com/packages/tools/integration/oculus-integration-deprecated-82022

OTR/L, K. M., OTD. (2023, August 21). *Fine Motor Exercises for Hands for Stroke Survivors: Techniques and Benefits*. Neurolutions. https://www.neurolutions.com/post/fine-motor-exercises-for-hands-for-stroke-survivors-techniques-and-benefits

*Projects Archive*. (n.d.). XR4REHAB, Share for Future Care. Retrieved November 23, 2023, from https://vr4rehab.org/projects/

*Question—How to recognize gestures in XR Hands?* (2023, December 29). Unity Forum. Retrieved December 20, 2023, from https://forum.unity.com/threads/how-to-recognize-gestures-in-xr-hands.1485675/

Van Zwol Inez

*Question—XR Poke Interactors on each XR Hands finger?* (2023, November 16). Unity Forum. Retrieved December 24, 2023, from https://forum.unity.com/threads/xr-poke-interactors-on-each-xr-hands-finger.1513418/

Mollis, A. (2023, August 21). *Release MRTK v3.0.0 Preview 18 Release & New Mixed Reality Toolkit Organization · MixedRealityToolkit/MixedRealityToolkit-Unity · GitHub*. https://github.com/MixedRealityToolkit/MixedRealityToolkit-Unity/releases/tag/v3.0.0-pre.18

Microsoft. (2022, December 8). *Releases · microsoft/MixedRealityToolkit-Unity*. GitHub. https://github.com/microsoft/MixedRealityToolkit-Unity/releases

Microsoft. (2023, December 21). MRTK3-voorbeeldscènes verkennen—MRTK3. https://learn.microsoft.com/nl-nl/windows/mixed-reality/mrtk-unity/mrtk3-overview/getting-started/exploring-features/mrtk3-sample-scenes

Mixed Reality Toolkit. (n.d.). Mixed Reality Toolkit. GitHub. Retrieved November 9, 2024, from https://github.com/MixedRealityToolkit

*Set Up Hand Tracking | Oculus Developers*. (n.d.). Retrieved November 9, 2023, from https://developer.oculus.com/documentation/unity/unity-handtracking/

*SteamVR Plugin | Integration | Unity Asset Store*. (2021, February 24). Retrieved November 9, 2023, from https://assetstore.unity.com/packages/tools/integration/steamvr-plugin-32647

*UPDATE*. (n.d.). CUREOSITY. Retrieved November 30, 2023, from https://www.cureosity.de/en/update

Verrelst, S. (2021). *Hand Tracking for VR Revalidation* [Bachelor paper]. Howest University of Applied Sciences, Digital Arts and Entertainment (DAE).

*VR Interaction Framework | Systems | Unity Asset Store*. (2023, November 22). Retrieved November 9, 2023, from https://assetstore.unity.com/packages/templates/systems/vr-interaction-framework-161066

*VR-THERAPY*. (n.d.). CUREOSITY. Retrieved November 30, 2023, from https://www.cureosity.de/en/vr-therapie

Van Zwol Inez

*XR Interaction Toolkit | XR Interaction Toolkit | 2.5.2*. (n.d.). Retrieved November 9, 2023, from https://docs.unity3d.com/Packages/com.unity.xr.interaction.toolkit@2.5/manual/index.html

## VIDEOS

Saebo, Inc. (Director). (2020a, April 1). *Stretches For Hand Spasticity—Best Stroke Recovery Hand Exercises*. https://www.youtube.com/watch?app=desktop&v=dBWRuy_hdoc

Saebo, Inc. (Director). (2020b, April 2). *Best Stroke Recovery Hand Exercises—Stage 1*. https://www.youtube.com/watch?v=ZKR1nOtCNKU

Valem Tutorials (Director). (2022, May 29). *VR Development for Beginners 2023—How to get started*. https://www.youtube.com/watch?v=i3DbJwy0R6E

## ACKNOWLEDGEMENTS

Sarah Vercaemer

For making it possible to test my application with patients from the target audience. For validating and providing information such as medical terms used to discuss different patients that tested the exercises in VR, or existing applications for rehabilitation in VR, or about useful exercises I could recreate for my application. For always answering my questions, emails and messages with so much enthusiasm. Thank you!

My parents

For dealing with my nearly permanent presence in the living room, either at the little desk in the corner or on the sofa. For feeding me, providing caffeine and snacks. For bringing me to the hospital so early on the day after Christmas Day, so I didn't have to drive myself (for playtesting, nothing serious!). For testing my application. For proofreading and helping improve some awfully written English sentences.

Agathe Boudry

For providing insightful feedback and both while establishing the case study and on my paper, and for answering all of my questions.

Patients that tested my application

For eagerly and enthusiastically testing and praising the application of the unfamiliar student that followed Sarah around in the hospital those two Tuesdays, and for providing valuable feedback.

# APPENDICES

Unity Build, guide how to install a build, Unity source code and video showcasing the application:

https://drive.google.com/drive/folders/15_eadFhh5ocxyYpOFxC5--YDz7vbpKgA