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Training neurosurgeons in Augmented Reality

Master's thesis in Informatics

Supervisor: Simon McCallum and Ekaterina Prasolova-Førland

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Abstract

This study aims to see how *Augmented Reality* can be used to train and teach neurologists and neurosurgeons in a newly developed neurological procedure called *SPGblock*. The procedure is developed at St. Olavs University Hospital in Trondheim, Norway, and aims to treat chronic migraine and cluster headaches with a newly developed surgical instrument called Multiguide. It has shown promising results, and the team behind the procedure seeks to offer the procedure to a broader audience. Training physicians and surgeons is a time-consuming and expensive exercise. Because of this, there is a need for better ways to train and educate new surgeons and physicians in the procedure. This project will continue the development of a *SPGblock* training simulator developed for the Microsoft HoloLens. The goal of this project is to add new functionality to the simulator and enhancing the existing functionality. The most necessary functionality to implement being more layers of anatomy and improving the tracking of the Multiguide. It will also include testing which of the HoloLens, the Magic Leap One and the Meta 2, is most suited for such a simulator and how it was to develop for.

The findings show that the application works great for teaching and demonstrating the *SPGblock* procedure. On the other hand, it lacks some aspects in order to be used for training. One of the main aspects being the lack of haptic feedback, the other being that the quality of the anatomy was too low. The findings were revealed through observations and user tests, followed by interviews with neurosurgeons and neurologists at St. Olavs. Further work should look into better ways of incorporating haptic feedback when performing the procedure, and increasing the level of detail in the anatomy of the head.

Keywords: *Augmented Reality, Neurosurgery, SPGblock, Training, Education, HoloLens, Magice Leap, Meta 2*

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List of Abbreviations

AR	Augmented Reality
MR	Mixed Reality
VR	Virtual Reality
HMD	Head Mounted Display
FOV	Field of View
FPS	Frames per Second
UC	Unity Collaborate
DoF	Degrees of Freedom
WEKIT	Wearable Experience for Knowledge Intensive Training
MRTK	Mixed Reality Tool Kit
API	Application Programming Interface

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1 Introduction

1.1 Motivation

The recent developments in Augmented Reality (AR), has opened up new possibilities in many research fields. Several companies have released AR Head-Mounted-Displays (HMD), and AR for mobile is growing at a fast rate. Examples of AR HMDs are the HoloLens developed by Microsoft, Meta 2 developed by Meta, and Magic Leap One developed by Magic Leap. Later this year Microsoft is also releasing a new version of the HoloLens called the HoloLens 2. As this new technology becomes available for commercial use, researchers look for new ways to take advantage of it. One field that shows much potential in this regard is medicine[1].

Training surgeons is a complex and expensive process[2]. The way it is done today is mostly through manual training where an apprentice observes a surgeon perform the procedure and later the apprentice trying to mimic the steps as good as possible. No doubt this is time-consuming, and it also has challenges. It is often difficult to learn from experts. The reason being that experts might overlook important details when explaining what to do to the apprentice. For these reasons, AR training is thought to be effective, because it captures a rich picture of the performance, and might add details that the expert deems as less important, but in fact, is important[3].

Consequently, there might be a place for training physicians using AR systems. Many surgical simulators have been built in VR and AR to fill this need. Examples include Perkstation[4] and ImmersiveTouch[5], further explained in Chapter 3. However, as the procedures vary quite a bit, it is hard to create one system that satisfies a large number of procedures. For this reason, there is a need for custom solutions for different procedures.

1.2 Context

SPGblock is a procedure developed at the Department of Neurosurgery at St. Olavs Hospital in Trondheim, Norway[6]. The goal of the procedure is to treat chronic migraine and cluster headaches. The procedure consists of injecting a neurotoxin called onabotulinumtoxinA, to the sphenopalatine-ganglion-nerve (SPG). For injecting the toxin, surgeons at St. Olavs developed a new clinical tool called the Multiguide. For further explanation, see Section 2.5.1.

The SphenoBlock AR system was created in 2017 as a master thesis at NTNU in collaboration with St. Olavs. The system was designed for the Microsoft HoloLens to train new surgeons in performing the SPGblock procedure. Even though the system was a step in the right direction, it was still an early prototype and the surgeons at St. Olavs wished to develop it further. This is why NTNU presented continuing the development of the project as a new master thesis.

Improvements to investigate included testing the system on other AR HMDs such as the META 2 and the Magic Leap One. Enhancing the quality of the models and increasing stability. Another thing that NTNU wished to look into was implementing Wearable Experience for Knowledge Intensive Training (WEKIT) [7], which is a European research project involving training apprentices using the HoloLens. Furthermore, there were some suggestions for improvements in the previous Sphenoblock AR [8] thesis that we wanted to investigate.

This master thesis was developed by two students enrolled in the master's degree programme in Informatics, interaction design, game, and learning technology, at NTNU Trondheim from 2017-2019.

1.3 Research questions

The goal of this research is to see how AR technology can improve understanding for physicians and surgeons in the SPGblock procedure. This will be achieved by further developing a prototype called SPGblock AR (the further developed version of SphenoBlock AR, see Section 2.6). This application will be developed for three different HMDs: Microsoft's HoloLens, Meta's Meta 2 and Magic Leap's Magic Leap One. Through observations and interviews, further explained in Section 1.4, with neurosurgeons and physicians, the development will get feedback and choose which HMD is most suited for further development.

The Research Questions (RQs) for this project consist of one main question with four sub-questions.

Main RQ: *How can AR technology enhance understanding of the SPGblock procedure?*

- **RQ 1:** *In what areas of training, education and demonstration is this application of AR technology useful?*
- **RQ 2:** *What are enhancements that are required before it could be used in all these three areas?*

As stated in the motivation section, there is a need to optimize the process of learning the SPGblock procedure. To do this, there is a need for finding new methods of enhancing the understanding of the procedure. Therefore we want to identify which of the areas of education, demonstration and training, is the most beneficial to enhance using AR, as well as mapping out what is needed for the application to succeed in these areas.

- **RQ 3:** Which of the AR HMDs; Hololens, Magic Leap One and Meta 2, is most suited for use in medical injection training/demonstration?
- **RQ 4:** What are the challenges and benefits when developing a SPGblock training application for the different AR HMDs; Hololens, Magic Leap One and Meta 2?

This project has access to three AR HMD devices; Hololens, Magic Leap One, and Meta 2. This provides a unique opportunity to test out which AR HMDs are most suitable for medical training. Testing which HMD is most suited includes comparing quantitative properties such as Field-Of-View, Hardware properties such as processing power and RAM, and battery lifetime. It also includes qualitative features such as; How comfortable are the HMDs to wear, how does having a motion controller affect the experience, how good is the quality of the models, and similar.

By developing for three different devices, we also got the possibility to look closer at how it is to develop for the different AR HMDs. How is the developer community around the devices? How is the documentation for each device? How is it to test and debug the different devices?

1.4 Research method

The main focus in this project was to develop an AR solution for the SPGblock procedure and see how it could be used in training, education, and demonstration. Therefore we used the *Design and Creation* strategy as presented in Oates's "Researching Information Systems and Computing"[9]. With the Design and Creation strategy, the focus was on developing an IT artifact, a prototype of an HMD AR educational and training system for neurology. This was done following a process of the five steps described in Oates[9, p 112]:

- **Awareness**
At the beginning of the project, we started with reviewing the Sphenoblock AR application, existing literature and other similar projects, see Section 4.2 and Chapter 2 and 3. Additionally, we talked with the experts and surgeons at St. Olavs to define the scope of the project and got an introduction to the SPGblock procedure, see Section 4.2.
- **Suggestion**
Together with the surgeons at St. Olavs, we created some early requirements, see Section 4.2
- **Development**
During this project, three AR prototypes were developed, using an iterative development process, for three different HMDs. In Section 1.5 the development process is presented and in Chapter 4 we describe the implementation for each iteration.
- **Evaluation**
The final evaluation of the artifact was done by conducting interviews and user tests with neurosurgeons and neurologists. During development, meetings with the staff at St. Olavs was

conducted to test and get feedback after each iteration. For testing and results see Chapter 5 and 6.

- **Conclusion**

Finally we discuss and conclude the results in Chapter 7 and 8.

1.4.1 Data generation method

For data generation, we used observation and interviews to generate qualitative data. Since the target group was not readily available, the aim was to conduct two to five semi-structured interviews conducted after a user test of the final prototype. Interviews were used since it can provide more information from each participant than for example questionnaires. This allowed us to ask more open-ended questions as well as asking follow-up questions. We also gathered data by observing the users while they conducted the user tests.

1.4.2 Data analysis method

Of the qualitative data generated, from observations during the user tests and the interviews, we did a thematic analysis of the data. This was done after transcribing the audio recorded during the interviews and notes taken during the observations of the user tests. The themes were structured after the research questions described in Section 1.3.

1.4.3 Consent form

All participants in the evaluation of this project signed a consent form based on an agreement with NTNU and NSD - The Norwegian Centre for Research Data AS. The complete form can be found in Appendix A.1.

1.5 Development method

We were two students working on this thesis. To divide and structure the work we used a Kanban board, which is an agile project management tool[10]. As for the development method, we used a human-centered design process, shown in Figure 1. The goal with this approach is to include the end users in the development. It is an iterative process where the developer iterates through four steps. First, analyzing the context of use and then secondly designing and specifying requirements. The third step is to implement a solution to meet these requirements and then finally evaluate the prototype. If the solution does not meet the requirements or the requirements have changed, a new iteration should be started.

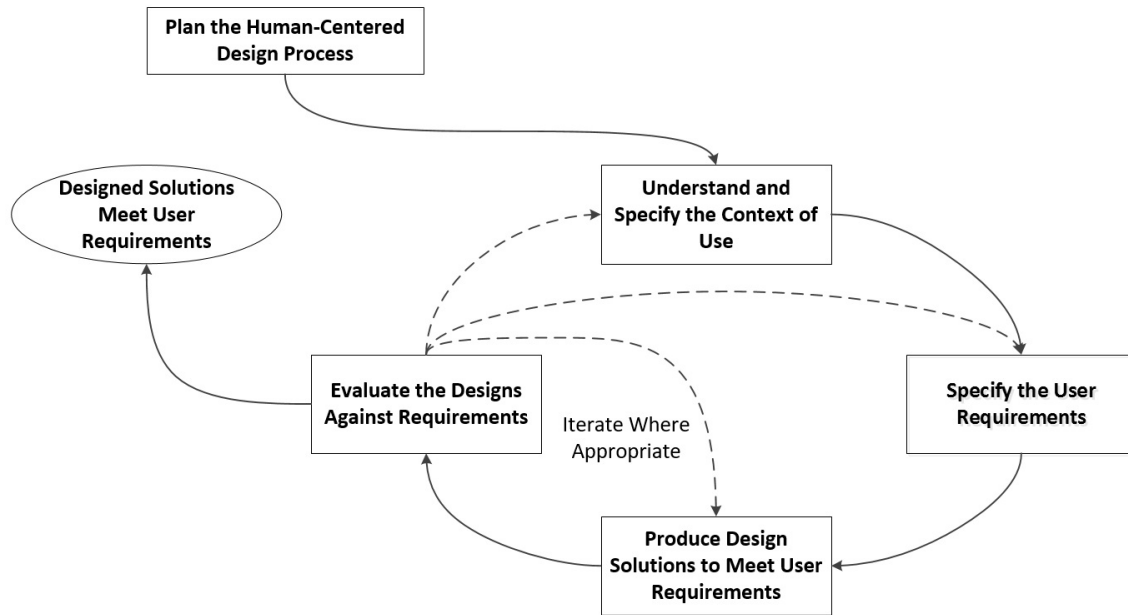


Figure 1: Human centered design process

1.6 Report outline

The rest of this report is structured as follows:

Chapter 2 presents background theory and covers the functional and non-functional requirements of the project

Chapter 3 presents related academic and proprietary work

Chapter 4 explains our implementation phase, and what kinds of functionality we implemented and why

Chapter 5 describes the testing method and testing procedure

Chapter 6 explains the results we gathered throughout the project

Chapter 7 discusses the results presented in Chapter 6, as well as future work

Chapter 8 concludes the project

2 Background

2.1 Augmented Reality

Ronald T. Azuma defines Augmented Reality (AR) as "An environment in which 3D virtual objects integrate into a real 3D environment in real time"[11]. One way to achieve this is by looking through a screen that projects the 3D models on top of the real environment. Either in HMDs or through a mobile or screen.

2.1.1 Augmented Reality vs. Mixed Reality

There has been some confusion about what the difference between AR and Mixed Reality (MR) is, as many different definitions exist.

According to Fink[12, p 19], Mixed Reality is "An experience that always gives the user a view of their real surroundings, but uses a headset to overlay graphics that are interactive with actual reality (augmented reality), and/or incorporates elements from actual reality into a virtual environment (augmented virtuality)." Augmented Reality, on the other hand, is "Overlaying or mixing simulated digital imagery with the real world as seen through a camera and on a screen. Graphics can interact with real surroundings (often controlled by users)."[12, p 18].

As seen here, there are no universally agreed upon definition of AR and MR. Stephanie Llamas makes an argument for the Metaverse definitions. She states that it is essential to separate between smartphones/screens, and HMDs as it may damage the sales of HMDs to use the same term for both. Her example is that you do not call a cinema for a TV. However, there is much confusion regarding the MR term. Many articles use this definition for both VR and AR, while others use it as a common word for both. In addition to this, Microsoft has created confusion by labeling both their Virtual Reality (VR) headsets and their Hololenses as MR headsets. This, in our opinion, makes it more confusing to use the term MR. So in this report, Azuma's definition will be used.

2.1.2 Differences from Virtual Reality

Virtual Reality (VR) is where users become fully immersed in a virtual world. AR is that virtual elements are "augmented" into the real world, see Figure 2. AR and VR are often mentioned in the same breath and is by many people regarded as the same thing. This is not correct, as the two have

entirely different goals. While VR's goal is for the user to escape Reality, the purpose of AR is to enhance reality[12, p 22].



Figure 2: The difference between AR (left) and VR (right)

2.1.3 Video-based and see-through based AR systems

AR technology divides into two categories, video-based and see-through based AR systems. One example of Augmented Reality using a video display is the smartphone, where objects can be planted "on top of the real world." The most famous example of this is the "Pokemon Go" game, where the user can see the Pokemon appearing over the real world when trying to catch them[13]. On the other hand, there are the See-through systems. See-through systems are what the HMDs typically use as it gives the best "Realspace-Imaging" as it is "minimal delay"[11]. It also has the advantage that the display only needs to project one video stream to the user[11].

2.2 AR Head-Mounted-Displays

This section describes the different AR HMDs that we worked with during this project. All HMDs are See-through based HMDs.

2.2.1 Microsoft's Hololens



Figure 3: Hololens

The Hololens, Figure 3, was released in 2016 by Microsoft. It is the most established of the HMDs with over 50,000 copies sold as of 2018[14]. It supports four infrared cameras for spatial mapping[15], which means that the Hololens has an understanding of its position relative to the world around it. It also tracks its orientation using a gyroscope, similar to what smartphones do. These things combined make it so that the Hololens can project holograms that are stationary in space and orientation with little drift.

The holograms rendered by the Hololens renders at a maximum of 60 FPS, which is the recommended FPS to have in applications by Microsoft[16]. The way the user interacts with the Holograms is through hand gestures, voice control, and gaze.

The Hololens is all-inclusive, meaning that all you need to use it is the HMD itself. There is no need for a controller or an external computer. It has a field-of-view (FOV) of 30 * 17 degrees (width * height) [17][18]. For more information about the hardware, see 2.2.4.

2.2.2 Magic Leap's Magic Leap One



Figure 4: Magic Leap One

The Magic Leap Company developed the Magic Leap One, see Figure 4, which was released in November 2018. In a similar fashion to the HoloLens, it offers the ability to have stationary holograms with little drift.

However, there are some differences. While the HoloLens uses gestures and eye-gaze for user interaction, the Magic Leap One offers a motion controller, in addition to hand gestures and voice input. The Magic Leap consists of the glasses itself, called "lightwear" and the "lightpack." The lightpack is a computer that you can wear with a shoulder strap or attach to your pockets. The lightpack and the glasses are tethered. The Magic Leap One supports a FOV of 40 * 30 degrees[19][20]. For more information about the hardware, see 2.2.4.

The Magic Leap controller, shown in Figure 5, is tracked in 6DoF (Degrees-of-freedom)[21]. It offers several buttons, including the trigger button, the bumper button, the home button, and a touchpad.

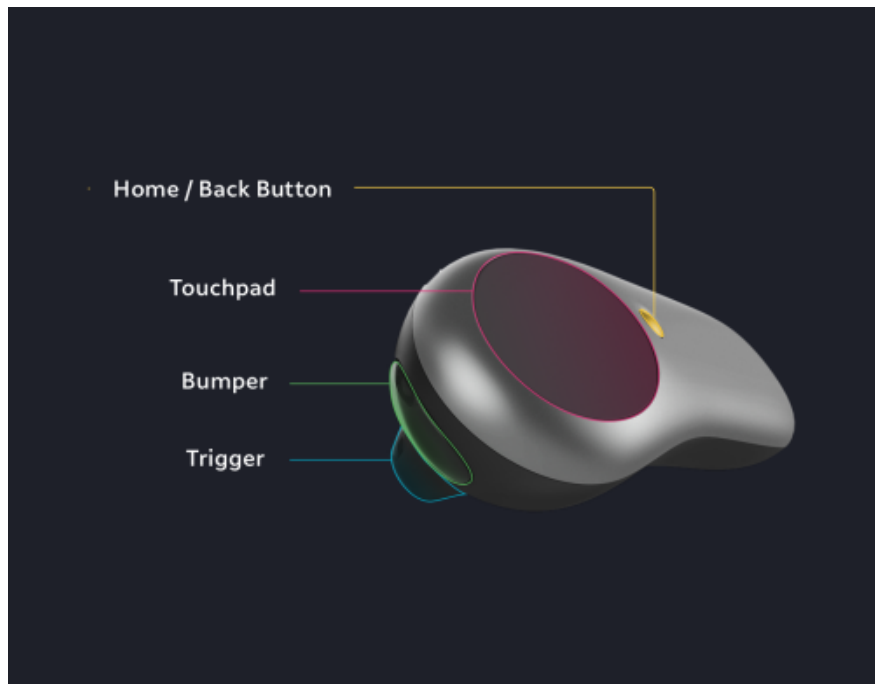


Figure 5: Magic Leap Controller

2.2.3 Meta's Meta 2



Figure 6: Meta 2

Meta 2, shown in Figure 6, was released in 2016 by Meta and stands out from the other two devices with that it needs an external computer to function. It is therefore tethered. The vision of Meta was to release a HMD that replaced monitors and screens at work. With this device, the user can have as many virtual monitors as they wish. Therefore mobility was not as much of a priority for the developers as for the other two devices.

Like the Hololens, the interaction is done with hand gestures, but instead of a "gaze and click" approach, it has a more physical approach with a "grab and drag" interaction. The design centers around a workplace setting and it is possible to connect an external mouse and keyboard using Bluetooth.

The Meta 2 tracks its environment by four cameras, making it possible to place out holograms stationary in the room. It has a 90 top/80 bottom * 50 degrees FOV. For more information about the hardware, see Section 2.2.4.

2.2.4 Hardware specifications

Device	Hololens[22]	Magic Leap One[23][24]	Meta 2[25]
CPU	Intel 32 bit architecture	NVIDIA® Parker SOC; 2 Denver 2.0 64-bit cores + 4 ARM Cortex A57 64-bit cores (2 A57's and 1 Denver accessible to applications)	External
GPU	Custom-built Microsoft Holographic Processing Unit (HPU 1.0)	NVIDIA Pascal™, 256 CUDA cores	External
Resolution	1268 x 720	1280 x 960	2560 x 1440
RAM	2 GB	8 GB	External
Storage Capacity	64 GB Flash	128 GB (actual available storage capacity 95GB)	External
Weight	579 grams	345 grams (Not counting the lightpack)	500 grams
Power	Hololens lasts 2.5 hours during intensive use and 5.5 hours during regular use.	The battery is a built-in rechargeable lithiumion battery and lasts 3 hours of regular use (this might vary).	Gets power from the computer
Audio	Spatial sounds coming from two speakers above the ears. Audio 3.5mm jack.	Built-in speaker with support for spatial audio. 3.5mm jack with audio spatialization processing.	4 Surround speakers and 3 microphones
Connectivity	Wi-Fi 802.11ac, Micro USB 2.0, Bluetooth 4.1 LE	USB-C, Bluetooth 4.2 and Wifi 802.11ac/b/g/n.	Connected to the computer using a USB-3 and an HDMI cable.

Table 1: Hardware specifications of the AR HMDs

2.3 AR use in industry

Many industries have adopted AR as a tool for enhancing their workplace. Some industries include; Energy, military, manufacturing, construction, health-care, and education.

Having the opportunity to augment virtual content onto the real world creates some compelling new use cases. One company that has taken advantage of this potential is Equinor ASA (former Statoil), which is a Norwegian energy company[26]. Equinor has used the Microsoft HoloLens to optimize maintenance work by letting mechanics "see through walls" for finding machinery quicker. They have created 3D models of the oil platforms which they have placed on top of the regular oil platforms to detect deviations from the blueprints and showing the path to specific components[27].

Another institution that has embraced this new technology is the US army, which in November 2018 landed a contract with Microsoft worth \$479 million[28], eventually rolling out 100,000 HoloLenses to the military. The military will get a particular version of the HoloLens 2 which they call "IVAS," which stands for the Integrated Visual Augmentation System[29].

The goal is that these HoloLenses will provide the soldiers in the field with extra information, formerly only seen in first-person-shooter games. Examples include the exact position of yourself and your colleagues on the battlefield, thermal night vision, enhanced aim, and sharing your situation with operators, not on the field. For a full report of what the US army wants to achieve, it exists a public document that states the objectives of the program[30][31][32].

2.4 Enhancing Learning with AR

One field where AR is shown to offer many advantages is in education[33]. The possibility to add virtual content to the real world creates opportunities that have never been seen before. One of the reasons being that "AR facilitates the observation of events which is not easy to observe with the naked eye"[34] as expressed by Akcayir[33]. AR is also shown to enhance motivation and enjoyment among students[35][36].

2.4.1 Possible opportunities of AR in education

Some examples of opportunities by using AR in education are described in the paper "A survey of Augmented Reality" by Ronald T. Azuma[11]. One of the examples he gives is teaching complex machinery maintenance by overlaying information on top of the engine while also providing step-by-step guidelines on what to do.

One application that is trying to achieve something similar to this is the WEKIT system[7]. WEKIT is a training application where a tutor can record a sequence of actions, such as speech, hand gestures, and movement. Moreover, the trainee can replay the steps and try to follow them for themselves.

Another thing that Azuma mentions is the possibility to see inside patients using AR. This could potentially be used to create a better understanding of the surgery for students or help surgeons better understand what is going on when performing minimally invasive surgery. It has been shown that AR applications are good for enhancing spatial abilities[37]. Additionally, Chien[38] express that using AR might be a powerful tool for learning about human anatomy. It has also been shown that 3D visualization is good for getting spatial and factual understanding when learning about anatomy[39][40].

2.4.2 Possible challenges using AR for education

Although AR is interesting for teaching, there are some challenges to address. The most common challenge is that AR is a new technology and that students find it challenging to use[33], which suggests that it is extra important to focus on usability[41] when developing AR applications. Cheng and Tsai[42] also suggests that usability issues should be in focus when developing AR applications because AR applications involve extensive user interaction. There are also problems with the technology; some studies show that students find AR challenging to use due to technical difficulties or limitations[33]. Another challenge that must be addressed is that using AR technology might seriously increase errors when doing high-precision manual tasks[43].

2.5 Sphenopalatine Ganglion Injection

Sphenopalatine Ganglion (SPG) is a nerve bundle localized in the sphenopalatine fossa, behind the sinuses (see Figure 7)[44]. "Neural activity through SPG is involved in the pathophysiology of migraine and cluster headache"[45]. The pathophysiology of migraine is dependent on the release of acetylcholine (ACh). By injecting a botulinum toxin, normally done intranasally, it can block the release of ACh[45]. A team of surgeons at St. Olavs University Hospital in Trondheim, has developed a new procedure to inject onabotulinumtoxinA, more commonly known as Botox, into the SPG with a newly developed tool called Multiguide. They call this procedure SPGblock (previously called SphenoBlock), and it can block the SPG for three to twelve months[6].

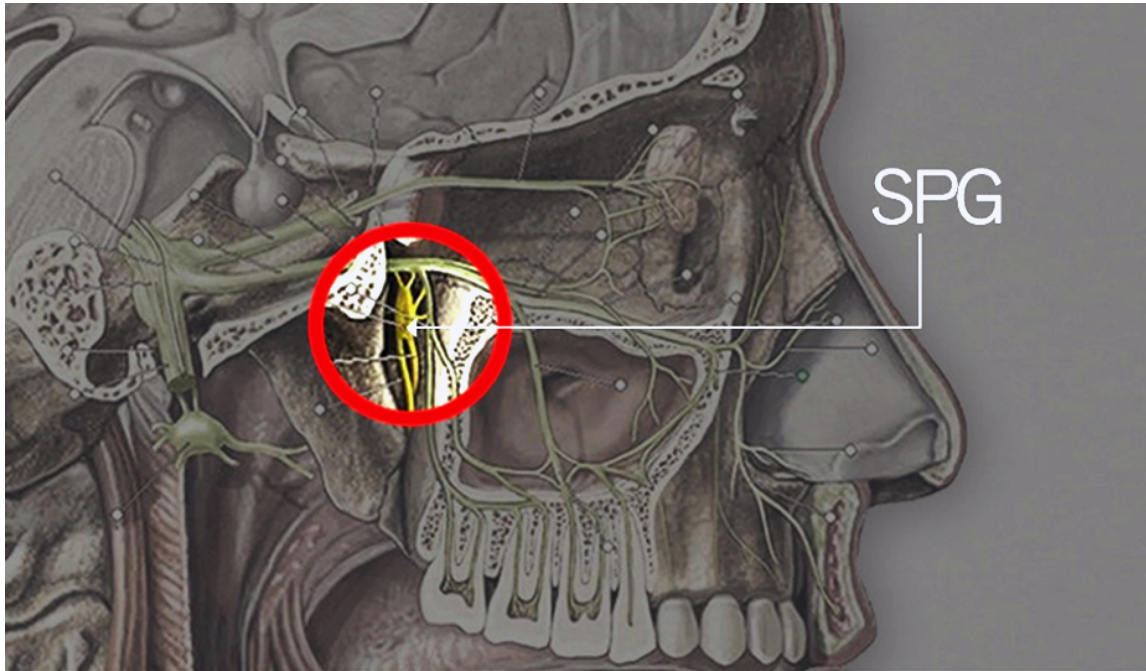


Figure 7: SPG location

2.5.1 SPGblock procedure

The SPGblock procedure is developed to be performed in an outpatient office-based setting with the patient in a supine position. Instead of doing the injection transnasal and with general anesthesia, it is done lateral and with local anesthesia[6].

The SPG is located on both sides, and the procedure is done bilaterally on some patients. If the patient suffers from cluster headache, the procedure would generally be performed on just one side. Patients with chronic migraine will have treatment on both sides.

Pre-treatment, the patient's head is CT and MRI scanned. During the procedure, these images are used in a surgical navigation system by Brainlab[46]. As illustrated in Figure 8, the images are displayed on a screen in front of the surgeon and uses an optical camera (Polaris[47]) to track the patient's head and the Multiguide.



Figure 8: An illustration of SPGblock procedure

2.5.2 Multiguide

Multiguide, Figure 9, is the clinical tool used to perform the procedure. It is developed by the same team that is behind SPGblock.

The pistol like injection tool consists of an injection/aspiration module (syringe) and an end piece. The end piece has two needles, one outer needle, constructed to penetrate the skin and muscles by 4-5 cm into the skull, and an inner needle. The inner needle is advanced forward 15mm from the SPG and used to inject the Botox with precision into SPG.



Figure 9: The newest version of the Multiguide as of 2019

2.6 Sphenoblock AR

This project is a further developed version off a former master students' project[8]. It consisted of a Unity project for the Microsoft Hololens. The Unity project included a 3D model of a skull with the SPG nerve visible, a 3D model of the training mannequin and a "Multiguide" represented by a skeleton of circles and line, as shown in Figure 10.

For placing the skull, an image recognition library called Vuforia was used to move the Multiguide. This library is used to recognize images and find their position and orientation in real-world space. Upon detection, the images would be represented as game objects in the Unity hierarchy with the position and orientation being the same as those from the real images. Then by adding a child game object to this game object, you can place objects "on top" of the images. Also included was functionality for drawing a line between the tip of the Multiguide and the SPG. This line would

be red if the path was blocked by bones, and green if it was not. Also, if hitting bones, a negative sound would play. When you came in a 15mm range of the SPG and had a clear path to it, a positive sound would play.

Also included in the project was a physical mannequin. Using image tracking to position the virtual skull, it was possible to align it with the virtual skull, thus having a way to provide haptic feedback. The image used for tracking the Multiguide would also be attached to the real Multiguide giving this a physical appearance as well.

Nystadnes had some suggestions for further work. The most important recommendation was to improve the tracking of the Multiguide, as this was very inaccurate. One way he proposed to do this was to get tracking data from Brainlab (see Section 3.1) over Wi-Fi.

Further, he suggested to implement WEKIT into the application, and finally add support for more procedures.



Figure 10: SphenoBlockAR

2.6.1 AR vs. VR in the SPGblock procedure

Some questions that have erupted is whether it would have been better to implement the system in Virtual Reality (VR) rather than in Augmented Reality (AR).

Arguments for implementing the system in VR include having more processing power, thus having the opportunity to have better 3D models. Another argument is having better controls, as the motion controllers provided by VR headsets such as HTC Vive are well established.

On the other hand, arguments against VR is that VR requires more setup and more space. The reason for needing more space is that the user cannot see the real world while inside the application. Some VR HMDs like the HTC Vive also use base stations to get a better synchronization of the room. It also requires having a powerful computer to render the virtual space needed. We would also have had to design and implement an environment in which to perform the surgery. In addition, the users would have to be tethered to a computer.

Another point is that when developing a collaborative mode, we would have to implement avatars for the users, and there would be hard to implement tools to show how to use the Multiguide. AR has the benefit of the collaborators being able to see each other in real-life as well. This opens up for using body language, voice, and other regular forms of human interaction[48]. This logic assumes that the users are in the same physical location.

Finally, the original project was developed in Unity for the Hololens, in other words, for AR. This does not necessarily mean that we would have had to continue developing the system for AR, as both VR and AR applications can use Unity for development and it likely would not have been too much work porting it for VR.

In our opinion, implementing the system in VR would put more constraints on the users because of the challenges as mentioned above. Because of these reasons, we decided that implementing the system in AR was the best solution.

2.7 Requirements

This section will start by explaining who the target group is, and then list the final requirements. The requirements are a result of several meetings with surgeons at the hospital. Each meeting is further described in chapter 4. We divide the requirements into functional and non-functional requirements.

2.7.1 Target group

The target group for our application is neurologists and neurosurgeons. The target group is divided. On one side, we have those that are going to start doing the procedure themselves or are thinking about starting to do the procedure. On the other hand, we have those that shall teach or explain the procedure to other physicians.

2.7.2 Functional requirements

1. **Implement the application on HoloLens, Meta 2 and Magic Leap One**
The surgeons wished to explore which glasses to work on further
2. **Improve the tracking of the Multiguide**
In the earlier version of the project, controlling the Multiguide with image tracking felt rough. The surgeons wanted a more precise way to control the Multiguide in the application.
3. **Replace the Multiguide with a more detailed version**
The surgeons wanted to implement a better version of the Multiguide in the application
4. **The user should be able to toggle anatomy on and off on the head**
This requirement helps to teach apprentices about the anatomy surrounding the SPG
5. **Having the ability to scale, rotate and move the skull freely to analyze anatomy**
During our meetings with the hospital, it was agreed that it would be nice to examine the anatomy surrounding the SPG in more detail.
6. **Collaboration between two or more people in the devices**
Since it was hard to keep up with what was happening in the device, if you did not wear it, the surgeons wanted some way of sharing your view with another device.
7. **There should be a way to view the procedure in a step-by-step manner**
The doctors wanted to have a good way of demonstrating the procedure.
8. **Add more visual feedback**
One thing the surgeons wanted to have was better visual feedback when doing something wrong, or right.

2.7.3 Non-functional requirements

1. **Someone who has never used the application before should be able to navigate it themselves**
As the idea is to save time for the surgeons, it is essential that users can use the application without needing training in using it from someone external. This requires that the navigating of the app is intuitive and follows best-practices in AR design.
2. **The holograms must stay in their initial position with minimal drift unless moved by the user**
There is not a need for millimeter precision as the application will have more focus on demonstration than on training. However, the holograms should stay in the positions that they are given (not drift).
3. **The glasses must last for a minimum of two hours before being depleted of energy**
The HMD must be able to last for the duration of a demonstration session without being depleted of energy.
4. **The models must be realistic and anatomically correct**
The models must be realistic enough that the user can recognize the anatomy and the Multi-

guide.

5. **The holograms must be projected without deteriorating them**

The holograms must be realistic enough that the user can recognize the anatomy and the Multiguide.

6. **The glasses must be able to maintain 60 fps while rendering the 3d model of the skull and the Multiguide**

The surgeons have stated that high fps is crucial for them. Sixty fps is the recommended fps for Hololens applications set by Microsoft[16].

7. **The hardware must be available for purchase**

If the surgeons were to buy more of these HMDs and put more work into the application, they must be confident that they can get hold of new hardware.

8. **The operating system of the device must be regularly updated to stay compatible with the latest development platforms**

For it to be realistic to continue developing for the HMD, the software must be regularly updated and be up-to-date with standard development platforms such as Unity.

3 Related Work

Medicine is one area where AR is thought to have a significant impact in the future. This is due to the ever-increasing power of computational resources that have made it possible to fuse images with reality in real-time[49]. Barsom states that AR could play a role in the training of medical personnel[50]. One of the reasons for this is that some medical exercises is not feasible to perform in real-life[51].

Recent studies have shown that VR and AR surgical simulators have helped increase surgical skills[52]. Because of this, several surgical simulators have been developed for VR and AR. We list some of them in this chapter.

3.1 Brainlab Magic Leap Partnership

Brainlab[46] is a company that creates medical technological products for advanced health care. They have created several products for medical use. One example includes software for "Image-guided surgery," which is what the real Multiguide uses along with Polaris[47] to track its position, as mentioned in Section 2.5.1.

Brainlab recently formed a partnership with the Magic Leap company to use the Magic Leap One for their applications and make use of the Magic Leap One's spatial mapping functionality[53], Figure 11. Additionally, the Brainlab team will create an open developer API.



Figure 11: Magic Leap Brainlab

3.2 FundamentalVR

One system that exists for surgical training in VR and AR is the FundamentalVR[54]. FundamentalVR is a system where users can simulate surgeries by using VR or HoloLens. The VR application offers support for four procedures: Spinal Pedicle Screw, Total Knee Arthroplasty, and Total Hip Arthroplasty (Posterior and Anterior). It supports the most common VR HMDs, including HTC Vive, Windows MR headsets, and the Oculus Rift.

Haptic feedback is essential as studies have shown that the validity of VR simulators is dependent on providing realistic haptic feedback[55].

The HoloLens, and the VR applications, supports haptic feedback using the "Geomagic Touch" haptic arms[56][57] that simulate resistance to give haptic feedback that is aligned with the visuals of the

virtual content, see Figure 12. The Hololens also offers a step-by-step walk-through on how to perform specific procedures. It also provides the ability for users to collaborate by connecting the Hololenses over a network.



Figure 12: FundamentalVR

3.3 ImmersiveTouch

ImmersiveTouch is another VR/AR system for doing surgical planning, training, and teaching[5]. It is probably the most established system with over 20 years of experience in simulation[58]. It consists of several VR and AR apps, along with actual physical devices for accompanying the training. Their AR app uses a Hololens, according to their website[5]. Their VR application supports the most common VR HMDs such as the HTC Vive, Windows MR HMD, and the Oculus Rift, see Figure 13.

An example of using a physical device is that their AR application "Utilize a hand-held robotic stylus that mimics the use of relevant surgical tools and enables the appropriate haptic feedback"[59]. It

is not mentioned on the website, but it looks like what they use is the "Geomagic Touch" haptic arms, similarly to FundamentalVR as mentioned in Section 3.2. Their VR applications also offer similar devices to mimic haptic feedback. They provide apps that supports Cardiothoracic Surgery, Neurosurgery, Spine Surgery, ENT surgery, and CMF surgery.

There have been numerous studies conducted on the ImmersiveTouch system. One example is using their system for simulating ventriculostomy, which is a "neurosurgical procedure that consists of the insertion of a catheter into the ventricles of the brain for relieving the intracranial pressure"[60]. Where it showed to increase students' success rate at performing the procedure[60].

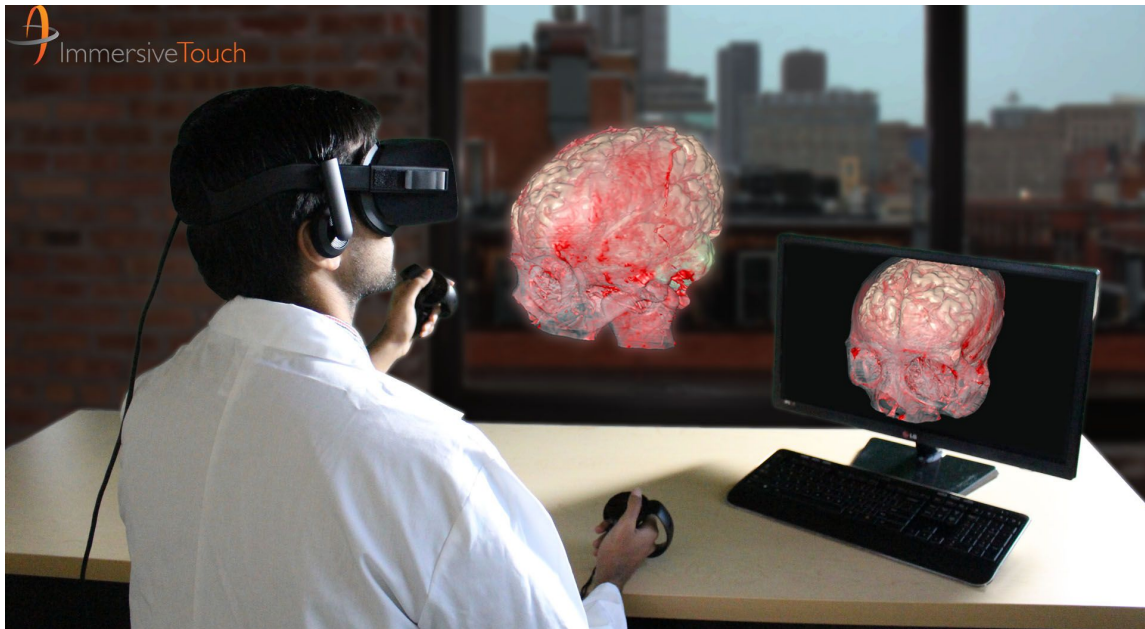


Figure 13: ImmersiveTouch

3.4 PerkStation

PerkStation is a system for training surgeons in AR[4]. The PerkStation is a training platform for image-guided surgery that measures time inside the patient, potential tissue damage, path length, and other metrics while training on a mannequin. The information is presented to the user on an LCD screen, Figure 14.



Figure 14: PerkStation

3.5 ProMIS AR simulator

Another example of an AR system that uses a screen to add digital information is the laparoscopic system ProMIS AR simulator[61], see Figure 15. This system uses three camera's to capture x, y and z positions of the instrument in 30 FPS, which is in turn used to evaluate performance when doing a procedure on a mannequin by measuring time inside the patient, instrument path length and smoothness of movement. It also includes functionality for recording and watching back the procedures after training.



Figure 15: ProMIS AR simulator

3.6 Comparison

As seen, there exist several systems for doing surgical training in AR. These systems have used different approaches. This probably has to do with the technology that was available at the time, but also what the systems try to achieve.

For instance, the ProMIS AR simulator and the PerkStation both have a focus on evaluating the users' skill during the procedure, as well as training them. ImmersiveTouch and FundamentalVR have more focus on only teaching how to perform procedures and how they work, rather than evaluating the participants.

PerkStation and ProMIS did also use screens for augmenting the digital imagery, rather than HMDs as ImmersiveTouch and FundamentalVR. The reason for this probably has to do with what technology was available at the time of development, as the PerkStation came around 2009 and the ProMIS has been around since at least 2005. ImmersiveTouch has been around for quite some

time, and used to feature screens as well; however, as of lately, they have moved over to HMDs. FundamentalVR came out in 2018.

All applications have support for haptic feedback. ImmersiveTouch and FundamentalVR solve this by using "Geomagic Touch" haptic arms[56]. ProMIS and PerkStation both offer a mannequin for providing the haptic feedback.

As seen in this section, there are several approaches one could take when developing an AR app for surgical simulation.

4 Implementation

This chapter will be structured as follows: First, we will explain the tools used and for what we have used them. The next sections will explain our development process. During development, we had three meetings with experts at the hospital before the final evaluation. The rest of the chapter will, therefore, divide into three sections, one for each phase.

4.1 Tools

4.1.1 Unity

For all three devices, all the applications were developed in Unity, Figure 16. Unity is a cross-platform game engine supporting 27 different platforms for both 2D and 3D [62]. Unity is the most used game engine in the world, with over 24 billion downloads in the last year[62]. Unity is also the most used platform for developing VR and AR content. As of 2018, Unity stands for 70% of AR and VR content developed[12, p 58].

When developing the applications, we used mostly the newest Unity version for the HoloLens app. For the Magic Leap app, we used a particular version of Unity made for Magic Leap development, namely Unity 2018.1.9f2-MLTP10 (64-bit). This version had built in the Magic Leap SDK, along with options such as "Zero Iteration" which meant we could debug the application directly from Unity. For Meta 2, we used Unity version 2018.3.1f1.

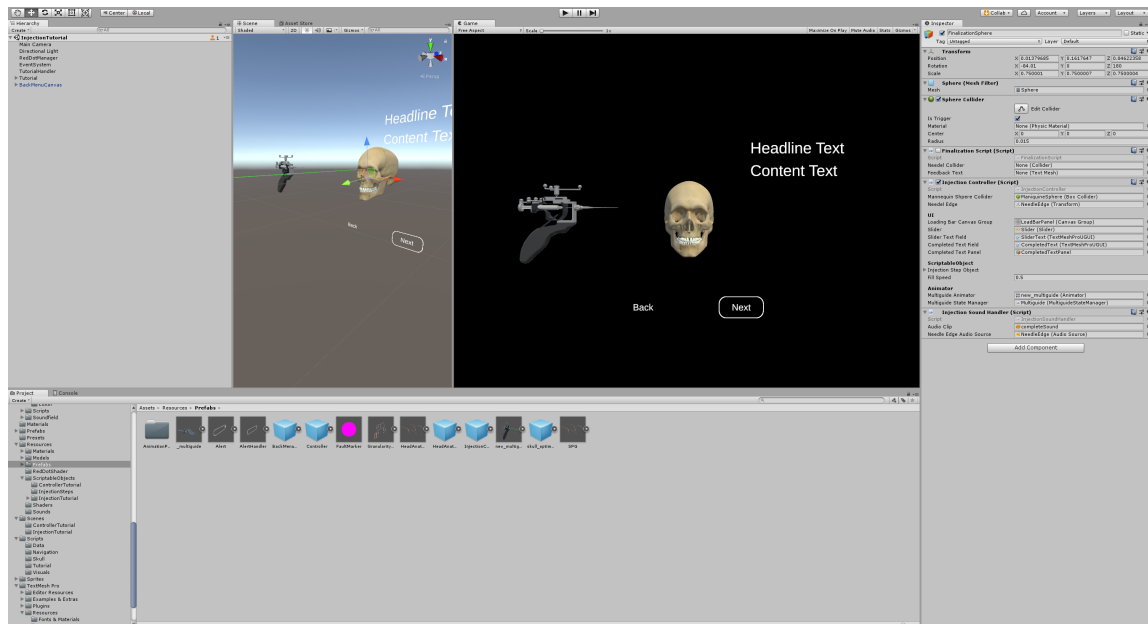


Figure 16: Unity user interface

In Unity, we also made use of the Unity Collaborate (UC) as a version control system. UC is free for up to three users, and has a project size limit of 1GB, and provides an easy way to store and share Unity projects. The reason for going with UC over something like Git is that UC provides functionality for dealing with the file structure of Unity projects in a clean way, instead of having to deal with Git ignoring a lot of different file types. This is especially true when using multiple third-party libraries as we did.

4.1.2 Blender

Blender, see Figure 17, is an open source 3D modeling software that supports a large number of tools needed for 3D modeling, animation, and rendering. It also supports video editing and game development. Through a Python API Blender allows its users to create functionality. It is one of the most used 3D graphics software and has a large and active community. In this project, Blender was used to manipulate models and for creating models and graphical content.

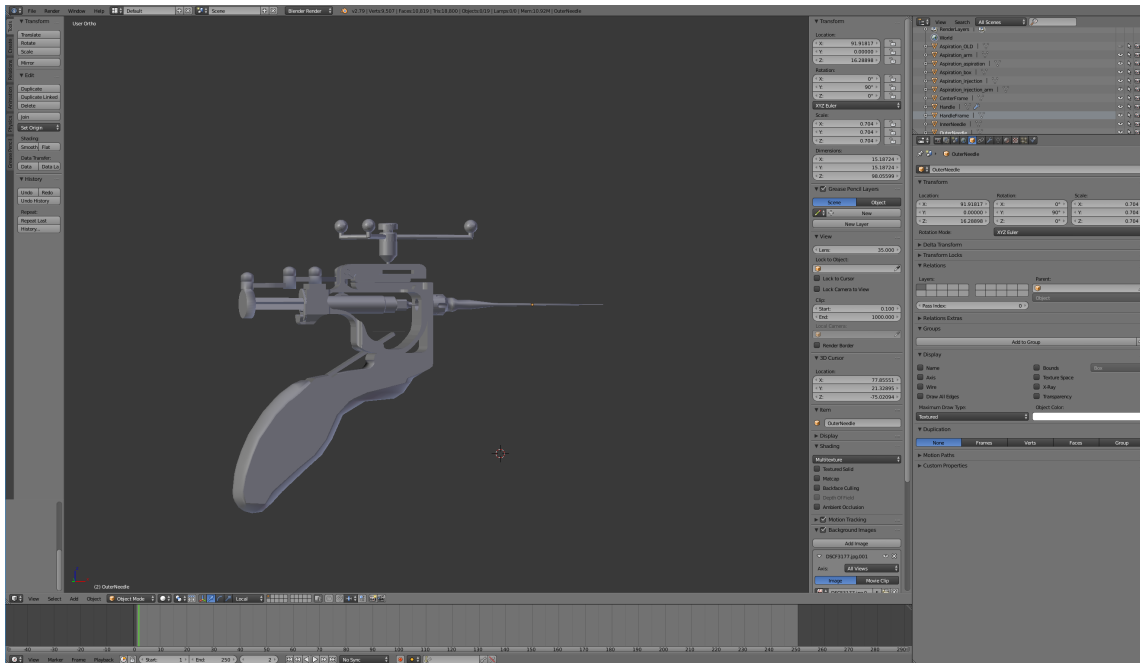


Figure 17: Blender user interface

4.1.3 Vuforia

Vuforia is an image and object recognition engine[63], supported by several platforms, including Unity. Vuforia supports several AR HMDs, as well as Android and IOS users. In this project, Vuforia was used for recognizing images, for placing the skull, and for moving the Multiguide in the applications for Hololens and Meta 2.

4.1.4 Magic Leap SDK

The Magic Leap SDK offers an API that we used to create the Magic Leap application[64]. This includes functionality for accurately tracking, and retrieving the position and orientation of the controller. Other things we used the API for include adding haptic feedback to the controller, and Magic Leap's built-in image tracking functionality. This image tracking functionality works similarly to Vuforia.

4.1.5 Mixed Reality Toolkit

MixedRealityToolkit is a library that helps with dealing with input in Hololens. It also provides functions such as a keyboard that can be used to retrieve text input from the user and functionality

for spatial mapping. Spatial mapping is the concept of mapping the room. This mapping can be retrieved in the code as a 3D mesh of the environment surrounding the user. Using this spatial map, the user can "anchor" objects to the real world. This is done by scanning the mesh and placing out objects at specific points in it. This functionality is further extended to include sharing anchors between devices in order to synchronize objects between Hololenses. We used this functionality to create the "Observer mode," see Section 4.4.3, where an expert can watch an apprentice perform the procedure in AR.

4.2 Initialization phase

In the initial meeting with the team at St. Olavs, we got an introduction to the procedure and discussed the target group. We concluded that the target group was doctors and surgeons and not medical students as the target group had been with SphenoBlock AR[8]. This was due to the procedure not being relevant to the curriculum of the medical students. We also discussed possible paths that our project could take. Ideas that came up during this phase was (with the corresponding requirement from Section 2.7):

- **Improving tracking of the Multiguide (FR2)**
Look for better ways to track the Multiguide as it was too unstable, resulting in the Multiguide jumping too much.
- **Adding more anatomy (FR4)**
Include more information about the anatomical structures around SPG.
- **Adding CT scans to the application (Ended up not being a requirement)**
As for now, the surgeon has to look at external screens, see Section 2.5.1, to navigate the Multiguide. This means that the surgeon has to look away from the patient during the procedure. Therefore there was a wish to look at ways to implement this information into the AR application. So the surgeon can focus on the patient without the need to look away to see the medical data.
- **Implement WEKIT (Ended up not being a requirement)**
Look at ways WEKIT could be used to record and visualize an expert performing the procedure and a task system for each step of the procedure.
- **Implement the existing application for the Meta 2 (FR1)**

4.2.1 Implementation of the existing project in the Hololens

Before we could start looking at new functionality, we had to get the existing project up and running. We spent some time understanding how the original project worked. This was mostly due to that the Unity version used for the project, version 2017.1.2.1f, was outdated. A vital part of this project had changed in the newer versions. Vuforia was now built-in in Unity, rather than a stand-

alone library as in the Sphenoblock AR project[8]. This meant that we had to reverse engineer the project to work with the new version of Unity (2018.3), as the old one was not supported. To complicate matters further, Vuforia was not compatible with "Remote debugging" offered by Unity. With "Remote debugging," the developer can run the application on the Hololens without the need of building it each time there was a change. This was not mentioned anywhere by Vuforia. All this culminated in us not being sure whether it was our implementation, Vuforia, or the project settings that were the issue. We had tried to build the project early on, but with the wrong project settings, thus this was falsely ruled out as a solution. It took several weeks to get the project running on the Hololens. Mostly due to time used figuring out that "Remote debugging" was not compatible with Vuforia as both make use of Hololens' camera.

4.2.2 FPS optimizations in the Hololens

When we got the project running the models were jumping and shaking. One solution suggested online was adding a world anchor, we tried this, but it did not change anything. After some trial and error, we figured out that the problem was low frames-per-second (FPS). Initially, we were at about 20 FPS. As a consequence, we conducted several optimization's in order to try and get back to the 60 FPS recommended by Microsoft [16].

The first thing we did was to remove the directional light component in Unity. This increased the FPS up to around 30-40. Further on, we changed the quality settings to be as low as possible and experimented with all possible optimization settings in Unity. As a result, the application was now running at approximately 50 FPS. We then started looking through the code and components and realized that some components were active while not doing anything. When disabling these components, we achieved the goal of 60 FPS.

4.2.3 Implementing WEKIT

It was discussed to use Wearable Experience for Knowledge Intensive Training (WEKIT)[7] in this project. WEKIT lets an expert record him-/herself perform a task, using the Hololens, so an apprentice can view it as if the expert was present. It can record voice, video instructions, and simple hand gestures and position tracking. It also provides a task system the apprentice can follow.

We did have a workshop testing out WEKIT, but since we were not able to get the source code for the project or any way implementing it in our project, we decided to not go any further with WEKIT.

4.2.4 Implementing the existing application for the Meta 2

Vuforia does not officially support Meta 2, but since it has a camera rig of four cameras, it is possible to use one of them as a camera for Vuforia. Therefore, the injection mode is the same as the Hololens

version (using image targets to do the injection), with the only difference being a button to get back to the main menu instead of voice commands.

Meta 2 interaction

The interaction in Meta 2 is more "physical" than the other HMDs we tested. With no controllers or point and click options, the user interacts with the device through grabbing/pressing digital holographic objects. Therefore it is essential to always have interactable objects within an arm's length from the user. This is especially important for the Meta 2, as it is wired and therefore, does not let the user move as freely around as the other AR HMDs.

For all the buttons, the user can "click" it by moving their hand within a collider/area of the button. No additional gestures are needed; therefore, Meta 2 does not have a defined click gesture. To prevent "miss clicks," meaning that the user accidentally touched one of the objects, we added a loading mechanism. To press a button, the user needs to hold their hand on the button for a short duration before it triggers. While the hand is within the range of the button, the color of the button changes over time and "fills" up before it triggers, see Figure 18.

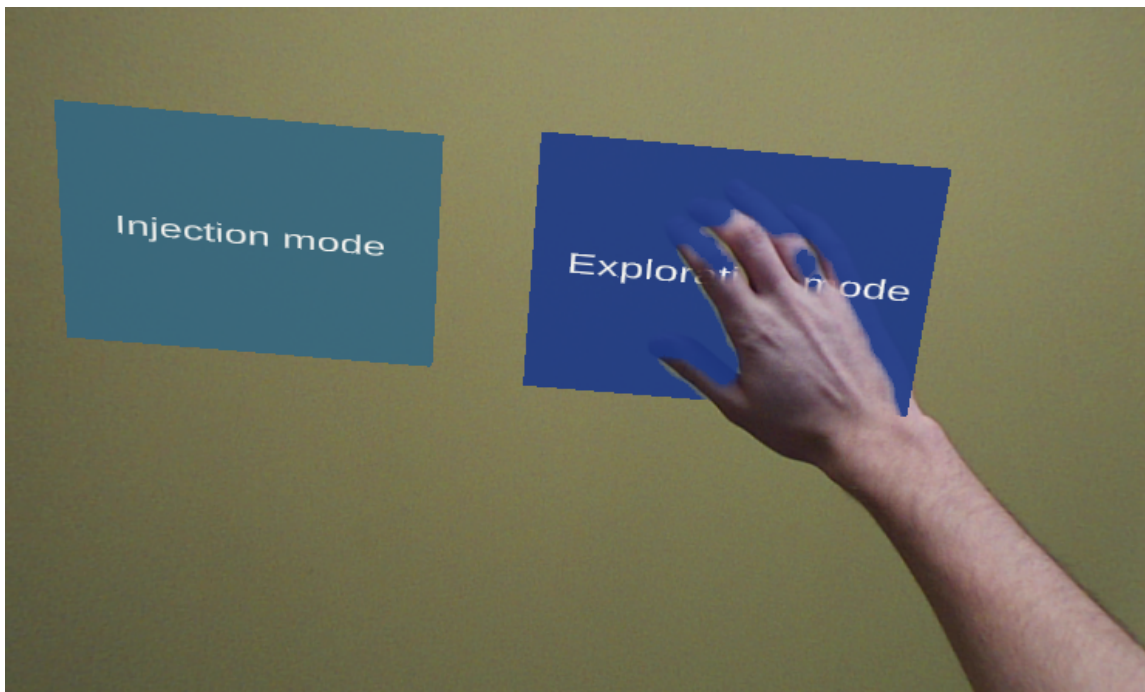


Figure 18: The interaction with the menu

Following the same interaction principles and example code as one of the demo applications for the

Meta 2, Workspace[65], the exploration mode did not need any additional tools to interact with the skull. By using one and two hands, the user could move, rotate, and scale the skull. The move and scale gestures felt natural and intuitive for most of the users, but they struggled more with the rotation gesture. This gesture is made by using two hands, Figure 19, and rotate, and the object rotates in relation to both. This took some time getting used to, but most of the users got the hang of it eventually.



Figure 19: The interaction with objects

4.3 Phase two

At the second meeting we had with the team at the hospital, we showed them the Hololens application and the Meta 2 prototype. When testing the applications, the hospital noted that the models were floating a bit in the Meta 2. Other feedback in this meeting was that it was nice that the Meta 2 offered the possibility for the user to use glasses.

The doctors were satisfied with the Hololens version but asked if we could enhance the quality of the models. When we explained that the FPS would go down if we added more detailed 3D models, they said that it was more important to maintain high FPS than having better models.

Other things mentioned was the ability to see CT-images in the Hololens, and having an ability to

see the optimal path into the skull.

After testing the applications, the hospital came up with some suggestions for further work:

- **Improve injection mode (FR8)**
Include more feedback when performing the injection, both textual and visual, to help the user understand what to do. This included steps for interacting with the Multiguide, how to advance (optimal path), and feedback when the procedure was completed.
- **Learning mode (FR5)**
Have functionality to rotate, scale/zoom and toggle on and off anatomy for getting a better understanding of the area around the SPG, and also include instructions on how to perform the procedure.
- **60 FPS requirement (NFR7)**
The surgeons decided that the applications must run at 60 FPS.
- **Implement the application for Magic Leap (FR1)**
Since we managed to get hold of a Magic Leap One, we decided to implement the application for it as well.

4.3.1 Improved Hololens application

Optimizing image tracking

One thing that we tried to optimize was the control of the Multiguide. The reason for doing this was to improve the tracking of the Multiguide, which was one of our requirements (FR2).

One problem with using an image as the control of the Multiguide was that it disappeared when the Hololens lost sight of it. This resulted in the Multiguide appearing and disappearing rapidly and was generally not something we wanted. We tried to enable extended tracking, but this only resulted in the Multiguide jumping a lot. One fix we tested was to have the Multiguide smoothly lerp [66] to the last position the image was spotted, and if tracking was lost, stay in that position. This worked decently well, but the procedure is quite hard, and precision is essential. Having the Multiguide "lag behind" impacted precision more than acceptable so we decided to leave it.

OpenCV for image tracking

We did look at replacing Vuforia with some other image tracking library. The most common suggestion being OpenCV. OpenCV (Open Source Computer Vision Library) is an open source computer vision and machine learning software library[67]. It has C++, Python, Java, and MATLAB interfaces and supports Windows, Linux, Android, and Mac OS. The source code is written in C++.

However, OpenCV does not contain an interface for Unity and Hololens. Meaning that if we were to implement OpenCV in Unity for the Hololens, it might take much time. It also does not support 3DoF rotation as well as Vuforia. Therefore, we decided to continue using Vuforia over OpenCV.

Alternatives to image tracking

It would have been better to avoid using an image for moving the pistol at all, and therefore, we looked for an alternative. Unfortunately, Microsoft does not provide a motion controller because it is intended that users should use their hands and voice for input[68].

Another alternative to track the Multiguide was to use the same system and equipment as the actual procedure. This would be the optical camera, Polaris, together with the tracking spheres on the Multiguide and patient's head, Figure 8. In cooperation with the doctors, we found out that we did not want to go for this solution. Without the need for the equipment, it would be easier to develop since it was no requirement to have access to the equipment at all times. It would also be easier to demonstrate without the need to bring additional equipment.

Exploration mode

The surgeons wanted a way to "explore" the anatomy for those less familiar with the anatomy of the face. This was a bit hard to see in the injection mode since the only way to move the skull was to move the images, leading Vuforia to regularly lose track of the images (when rotated out of FOV or vision of the camera). After implementing a few different solutions for this, we landed on adding a separate "exploration mode."

The exploration mode was implemented to be used for anatomical visualization of the SPG and the surrounding structures. This mode consisted of a head that you could move, rotate, and scale. The different interactions were selected by toggling between tools in a menu under the head, as shown in Figure 20.



Figure 20: Exploration mode

4.3.2 Implementing the application in Magic Leap

All though each HMD application was developed in Unity, there were some differences in the implementation for the Magic Leap. Unlike the Hololens and the Meta 2, the Magic Leap offers a six-degrees-of-freedom (6DoF) motion controller which means that it tracks the position and orientation in three dimensions. The controller is precise, and there is little lag. The controller also provides Linear Resonant Actuators (LRA) based haptic feedback[21]. Vuforia was not, as of January 14th, 2019, compatible with the Magic Leap [69][70]. That meant that we had to find some other way of placing the skull in space, as in the other versions we spawned it on top of a reference image.

We decided to implement a control system using the controller for moving and rotating the skull. After researching online, we decided that it was best to keep movement and rotation as separate modes[71]. This meant that we had to implement three different tools for the application. The regular "injection" tool where you moved the Multiguide, a "drag/move" tool where you changed the position of the skull in space, and a "rotation" tool where you rotated the skull. This raised another question as of how we should swap between the different tools while also preserving functionality.

Tool selection

We wanted to have some way to visualize which tool was currently selected. Initially, we had a symbol that stood on top of the controller and tapped the touchpad to switch to the "next" tool

in a circular fashion. For visualizing this, we added a tool menu that showcased which tool was currently selected, see Figure 21, this menu would be soft-locked to the screen meaning that it would follow the orientation and position of the user's head with some slack[72][68].

When testing, we found that it was cumbersome not to have the opportunity to switch back to the previous tool or have to go through all tools if miss-clicking the touchpad. In an attempt to fix this, we made it so that you could switch tool by swiping in either direction using the touchpad.

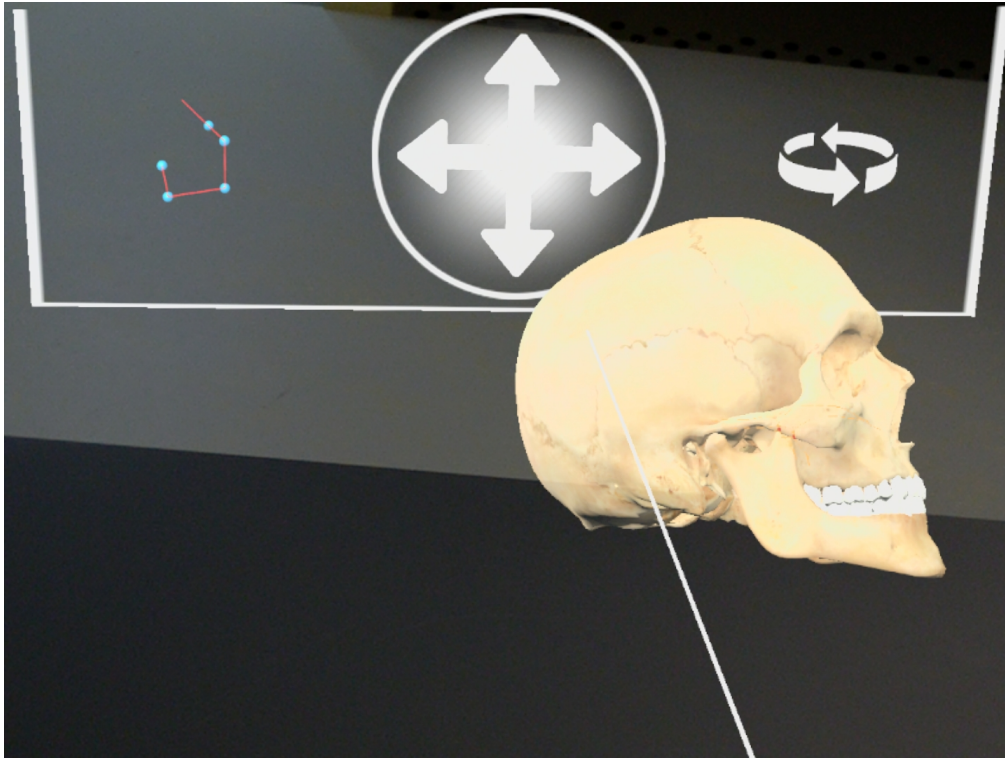


Figure 21: Magic leap mode menu, currently chosen mode is move mode

Injection tool

The primary tool of the application is the injection tool. This tool was represented by the inside/skeleton of the Multiguide, see Figure 22, and it works the same way as it does in the Hololens version, except the fact that you move it with the controller instead of images. The aforementioned tool is the tool the user uses to perform the procedure.

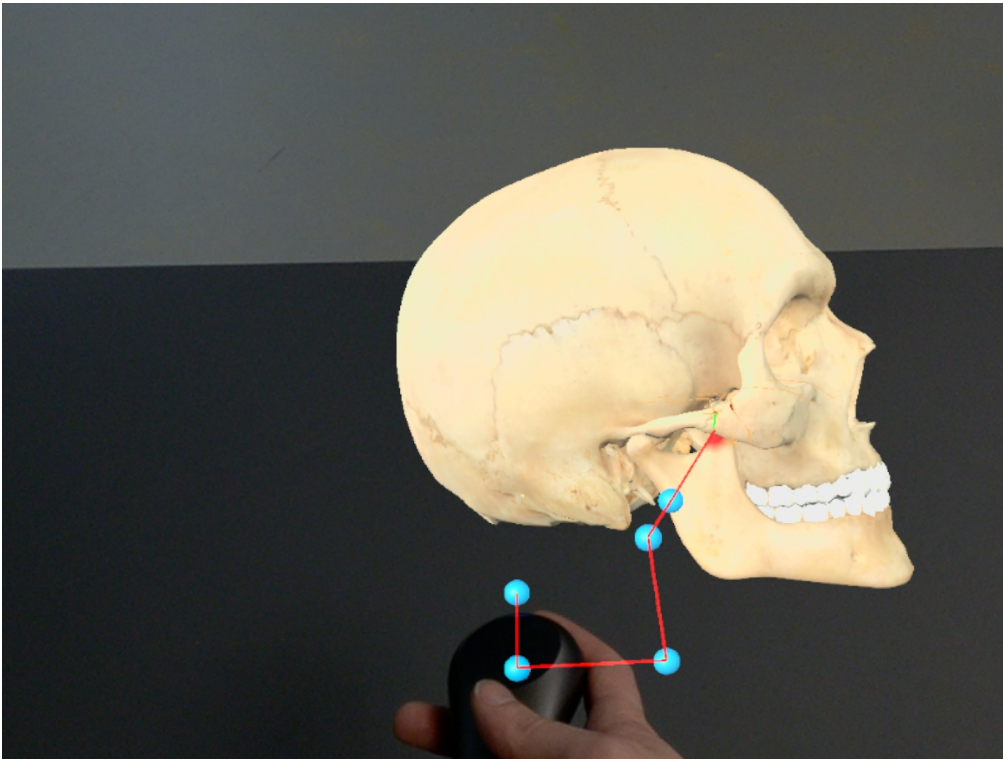


Figure 22: How the injection mode looked with the old Multiguide

Move tool

This tool is for moving the skull. It works by showing a pointer. If the user presses the trigger button, the skull will move to the tip of this pointer. When letting go of the trigger button, the skull stays in-place.

Rotation tool

The last tool is the rotation tool. We performed several tests to try and find the best way to implement the rotation. One method was to have the skull rotate in the direction the user moved the controller. This proved confusing. Because we could not spend too much time on this, we landed on having the skull's rotation copy the controller's rotation when pressing the trigger button, and stay where it is when letting go of the trigger button.

4.3.3 Hit mark functionality and audio feedback

One of the challenges with the procedure is to avoid hitting any bone structures. In the original project, the user would hear a negative sound when hitting bones. To give the user more precise

and visual feedback, we added a "hit marker" leaving a red mark where the user penetrates the bone, see Figure 23. We also changed the sound so it would be more distinct from the positive sound played when the user is 15mm from the SPG. This was added to both the Meta 2 application and the Hololens application.

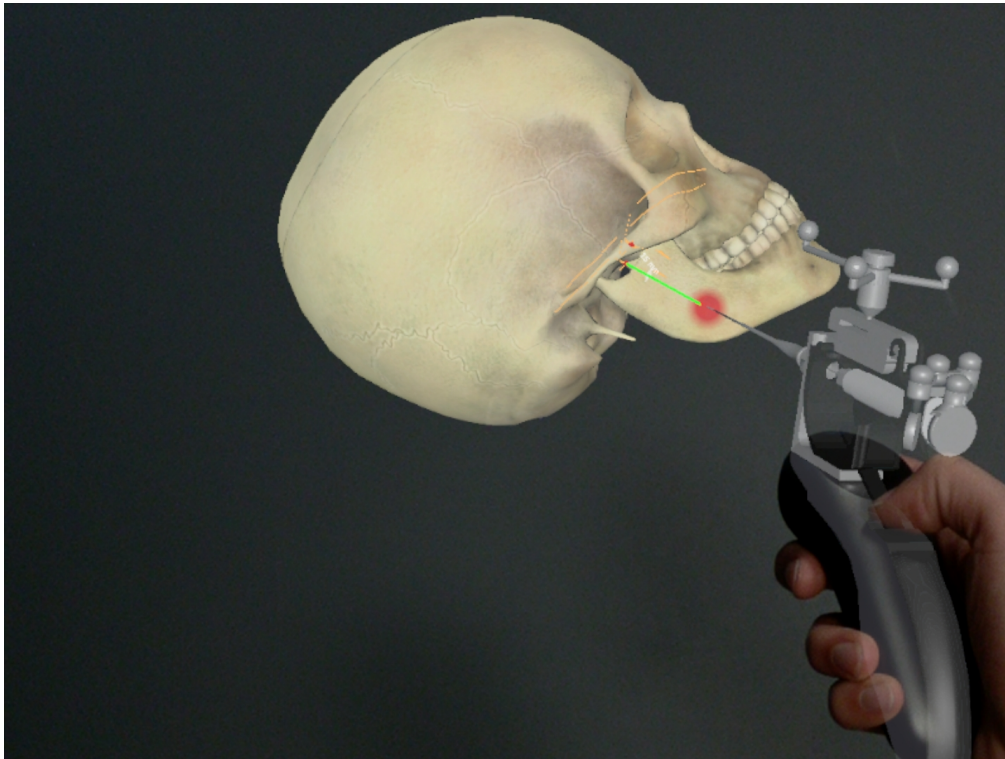


Figure 23: Hit mark when hitting bones (final version Magic Leap)

4.3.4 Loading bar functionality

The doctors wanted some way to visualize the steps of the procedure. Namely, advance inner needle, aspirate, and inject. As a way to add in these steps, we decided to add a loading bar, see Figure 24. The loading bar fills up automatically when holding the needle tip within the 15mm range of the SPG. As the loading bar progresses, animations simulating the Multiguide's steps will play, further explained in Section 4.4.1.

We looked into making the loading bar more interactive. The way we tried to do this was by having the user press and hold the trigger button on the Magic Leap controller, and then having to let go and press it again on the next step. However, when showing this to the doctors, they noted that it was hard to hold the needle still in the 15mm range, while also focusing on pressing the trigger

button. They also commented that merely pressing a button was nothing like performing the steps in the real procedure. For this reason, we decided to drop the interaction functionality.

However, the loading bars were still useful, as they act as reminders for the person learning to do the procedure.

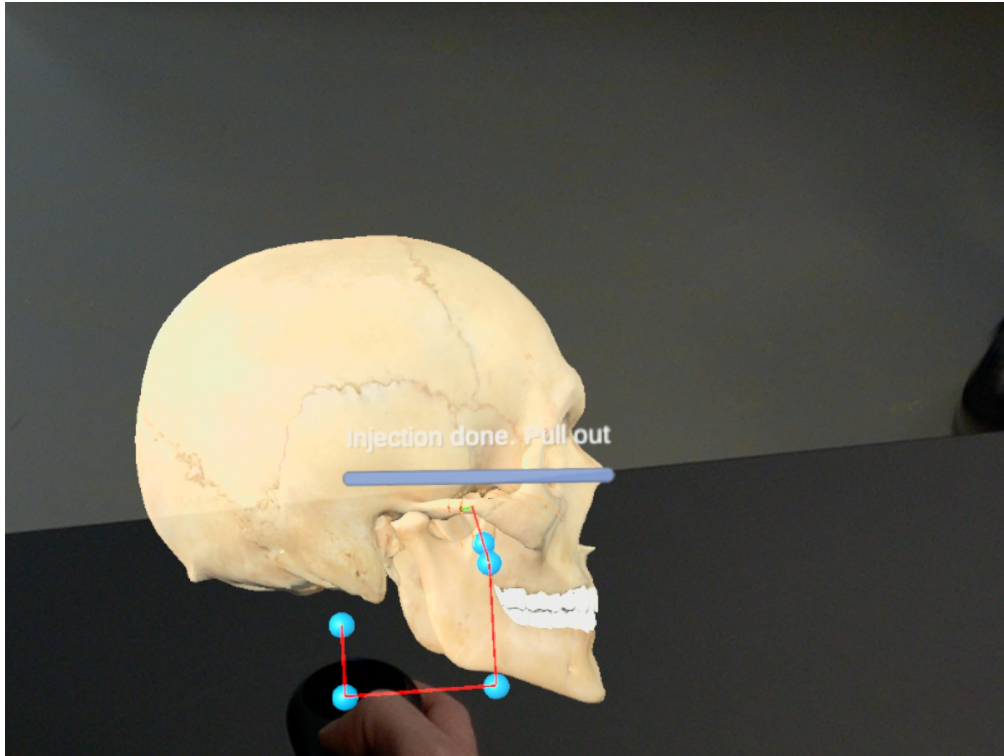


Figure 24: Loading bar with old Multiguide

4.3.5 Replaying the path taken

We started on implementing functionality for replaying the path of the Multiguide when the apprentice had finished the injection. The reason for replaying the path taken was so that the apprentice could watch a replay of their performance, and compare it to the optimal path. The way we would do this would be to record the position and rotation of the Multiguide when it entered the skull, and until the procedure was finished. After finishing the procedure, the apprentice would get a question if they would like to watch his performance back. This would be achieved by moving the Multiguide along the given coordinates over the time the apprentice used. Because of time constraints, we did not finish this functionality.

4.4 Final phase

On the third meeting, we showed what we had developed so far. This included the exploration mode and the injection mode in the HoloLens and the Meta 2 applications, and the new Magic Leap application.

The doctors liked the Magic Leap application better than the HoloLens and Meta 2 applications. The reason for this was that they felt that the increased processing power and the precision of the controller made it more user-friendly than the others. When testing the application, the doctors expressed that they thought that it could be a great way of demonstrating the procedure. So we moved away from the training focus and focused more on making the app suitable for demonstrative purposes. This includes making the application more suitable for use on conferences and exhibitions as well as phasing out the physical elements such as the mannequin.

Suggestions from the meeting for further development:

- **Model of the newest version of the Multiguide (FR3)**
Update the Multiguide 3D model to the newest version of the Multiguide.
- **More anatomical structures in the head model (FR4)**
Change the model to a model with more anatomical details, making it possible to look at different layers of anatomical structures.
- **Mirror the users view on a monitor (Ended up not being a requirement)**
For the Magic Leap, find a way to show what the user sees on an external monitor for use in conferences and presentations.
- **Add a collaborative mode where a supervisor can observe an apprentice doing the procedure (FR6)**
Check out if it is feasible to share experiences between several HMDs.

At this point, in January 2019, the Meta company went bankrupt. We decided to stop further development on the Meta 2 application. This decision was mainly made by the uncertainty of the opportunity to get hold of new Meta 2s in addition to the holograms floating and also the poor developer support.

In the earlier meetings, it was discussed to incorporate CT-images into the injection mode. After a meeting with a HoloLens team at SINTEF (*Stiftelsen for Industriell og Teknisk Forskning*), we decided to not go through with this. The reason being that they were already working on how to get medical data with CT and MRI streamed directly into the HoloLens. As SINTEF had a whole team working on this, we decided to focus on other tasks.

To formalize the requirements for the final prototype, we created a document with all the requirements for the application. These requirements are presented in Section 2.7.

The rest of this section is structured as follows; general additions, that are additions that were

implemented on both devices, and then individual additions for the Magic Leap and Hololens.

4.4.1 General additions

Implementing the Multiguide

One task we focused on after meeting with the team at the hospital was to improve the 3D models in the application. Since the Magic Leap had more processing power than was previously available with the Hololens, we were able to add more detailed models. We were given a 3D model of the actual Multiguide, used in the demonstration video the hospital had[73], see Figure 25. This model was detailed, but it had 400,000 triangles. We discovered that the modeling software, Blender, had a decimate functionality. This means that Blender automatically reduces the triangle count with the cost that the model might look worse and less detailed. However, after a couple of iterations in Blender, we managed to get the triangle count of the model down from the original 400,000 to around 35,000, meaning over a 90 percent reduction in triangles. However, the Hololens already had the maximum number of triangles to run in 60 FPS. Adding the 3D model of the Multiguide reduced the FPS to about 50. This was fixed by also going over the skull and decimating it, bringing it from around 80,000 triangles to about 30,000. This meant that we were able to add the Multiguide to both the Magic Leap and Hololens applications.

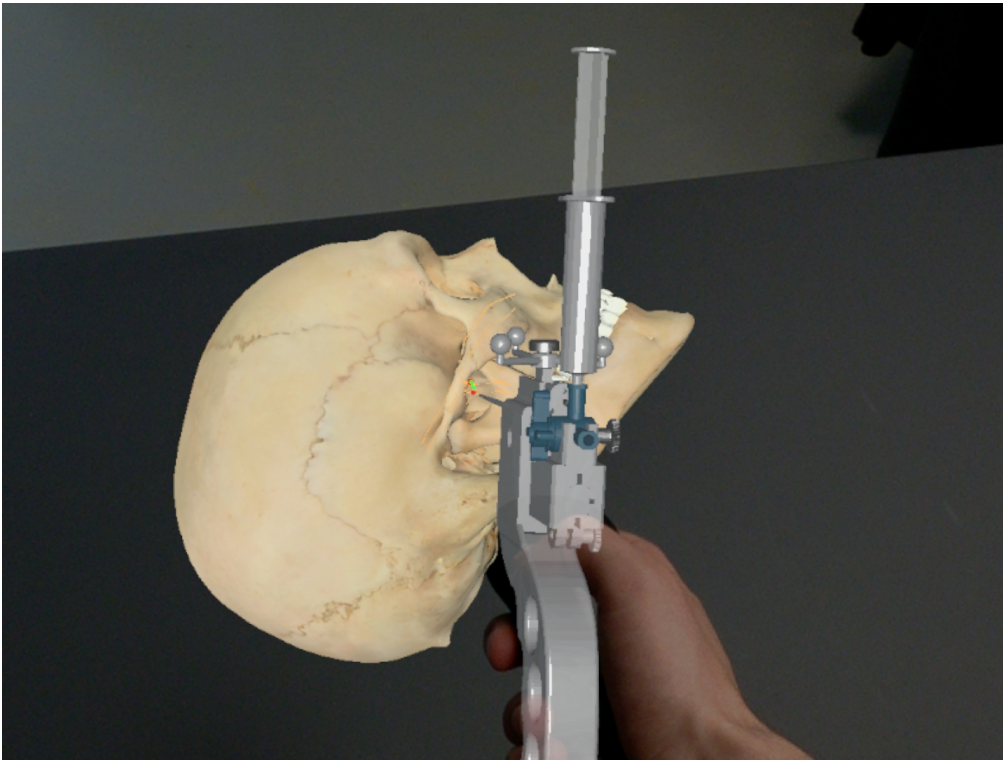


Figure 25: 3D model of the old version Multiguide

Creating a new model of the Multiguide

Even though the new Multiguide model was a step in the right direction, it was still an older version, and the Multiguide team had developed an even newer version that they were going to start using. Unfortunately, it was not possible to get the 3D model of the newest Multiguide, so we needed a way to make the model ourselves.

Since we had access to a physical version of the new Multiguide, we tried to 3D scan it with an Artec Eva handheld 3D scanner, see Figure 26. The Artec Eva uses structured light to scan objects, meaning it projects light in a pattern recognized and analyzed by a camera system[74, p 222]. Since it was an active light based scanner, it had problems scanning dark, shiny, transparent, and thin objects/surfaces. Because these surfaces reflected the light differently into the camera than expected from the light pattern. This meant that the scanner had a hard time scanning the Multiguide with its thin, metallic, and dark surfaces. We were therefore not able to get an acceptable result with the gear, time, and experience we had with the 3D scanning.



Figure 26: Attempt to 3D scan the Multiguide

As the 3D scan gave poor results, we decided to try modeling the model using an image, Figure 9, of the Multiguide as a reference along with the physical copy of the Multiguide. This resulted in an acceptable 3D replication of the Multiguide. All the measurements were not exact, but it was good enough for this use-case. By modeling it, we also got more control of the structure of the model. This made it more straightforward when later animating the Multiguide to perform the different interactions, as explained in Section 4.4.1.



Figure 27: The final result of the new Multiguide model

Animating the Multiguide

During the procedure, the surgeon performs different interactions with the Multiguide tool. In the application, these steps are simulated when the user reaches 15mm from the SPG. So there are no interactions needed from the user to perform the procedure other than advancing the Multiguide correctly and holding it in place. To give the user a perception of the interaction with the physical Multiguide, we animated the Multiguide to simulate these interactions.

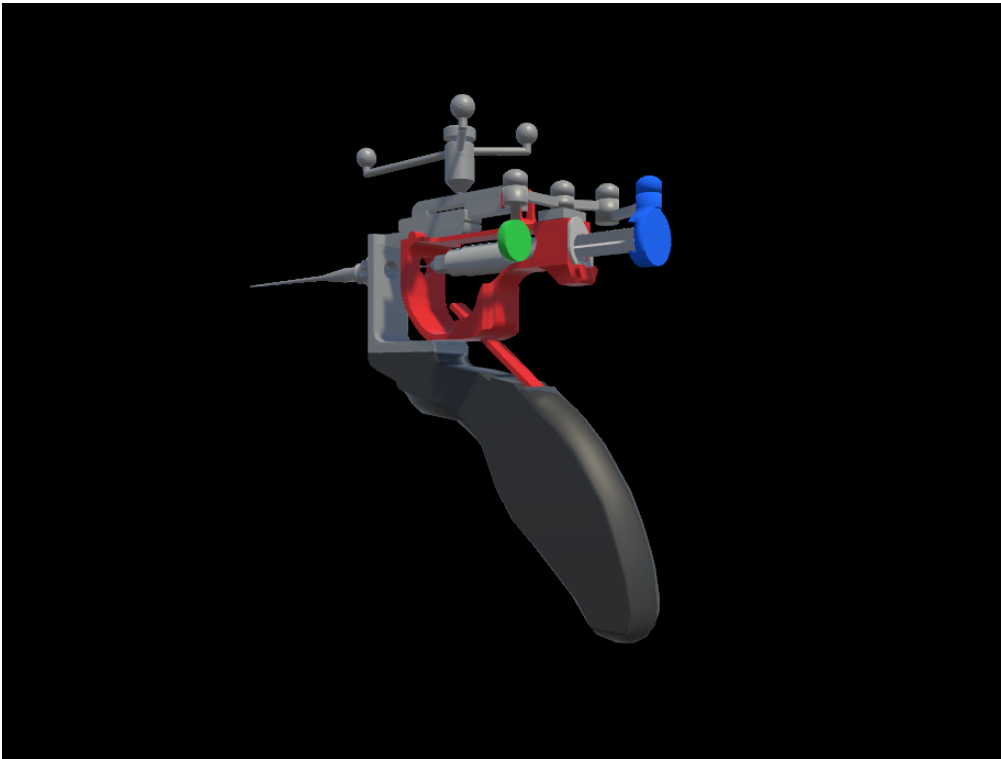


Figure 28: Highlighted areas of interaction with the Multiguide

Figure 28 shows the different parts of the Multiguide that the operator interacts with. The red area is pushed forward to advance the inner needle and to reset the Multiguide after an injection. The green button is pressed to aspirate, and the blue one is pushed to perform the injection. All of these steps are explained for the user in the injection tutorial, see Section 4.4.1.

With Blender, it is possible to rig models and define how different elements of a model can move and rotate. This technique is used to manipulate and animate the model. With limited experience with rigging and animating with Blender and limited time, we decided to do this in Unity using the editor's built-in animator. Using the animator, the developer can define the rotation, position, and scale, at different keyframes. Meaning that instead of manipulating bones and rigging within Blender, we manipulated each object of the model directly in Unity. This is usually more tedious, but was in this case, less time consuming than learning how to rig, and then animating it in Blender.

New head anatomy model

The surgeons wanted to have more anatomical structures in the application. We did not have access to any detailed models nor the skills to make them. For this reason, we went online and searched

for 3D models of head anatomy. After this, we put together a list of suggestions and sent them to our contact person at the hospital that bought the most relevant one.

Now we had to implement it into the application. The new model lacked the SPG, so we moved this nerve from the old model into the new one, placing it roughly in the same position. The skull of the new model was not as detailed as the old one, and therefore, the placement of the SPG was not exact, but it was decent enough to get a perception of its location.

The new model's anatomy roughly divided into eight sections: Muscles, skull, skin, lymphatic system, nervous system, digestive system, respiratory system, and circulatory system. After some discussion with the surgeons, we removed the less relevant anatomy sections. This includes the lymphatic-, respiratory- and the nervous system.

The doctors also wanted a way to toggle anatomy on and off at will. To achieve this, we added an anatomy toggle menu. The anatomy menu was a circular menu surrounding the head when turned on. With it, it was possible to turn on or off the four sections of anatomy, see Figure 29.

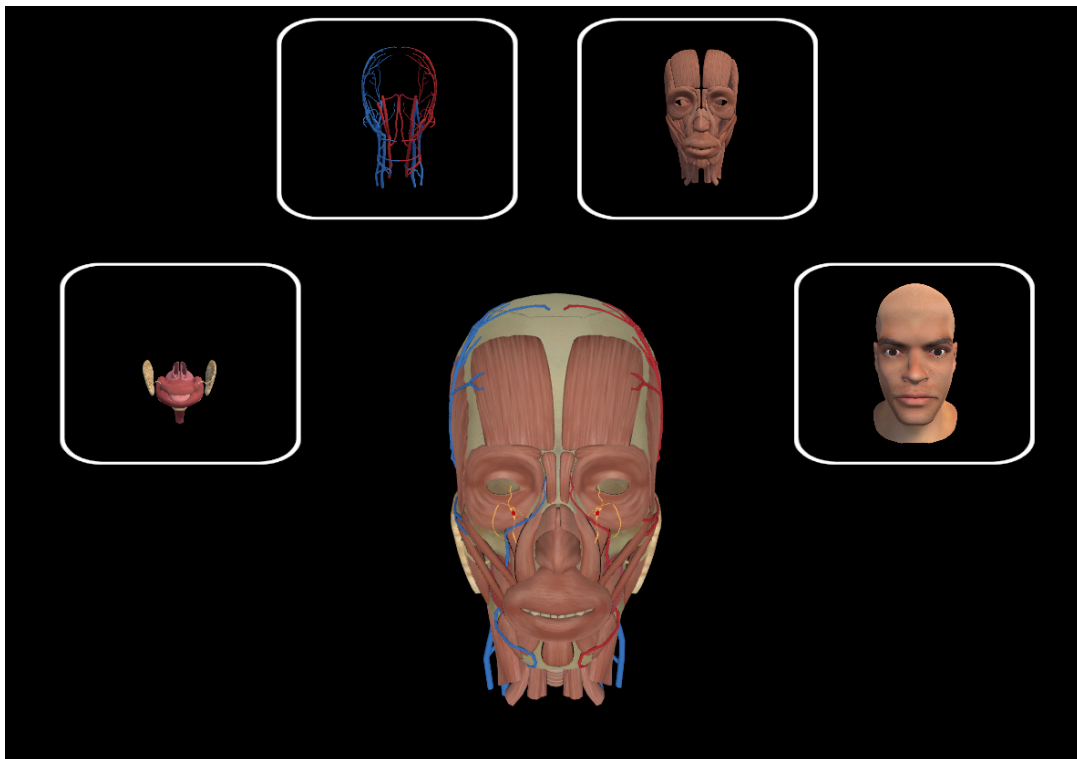


Figure 29: Head with anatomy and anatomy menu

Injection tutorial

A goal for the application was to demonstrate the procedure for users less familiar with the SPG-block procedure or similar procedures in general. Therefore, we developed a tutorial to guide the user through each step of the procedure, see Figure 30. With the tutorial, the apprentice can get an understanding of how to perform the procedure. Alternatively, an expert can use it as a visualization tool when teaching apprentices.

The tutorial shows the user the position of the SPG, the entry point in the skull and one possible path to the SPG. During the procedure, the surgeon performs different interactions with the Multiguide. The tutorial shows how to perform these actions and which part of the Multiguide to interact with. These steps consist of how to advance the inner needle, aspirate, inject, and how to reset the Multiguide.

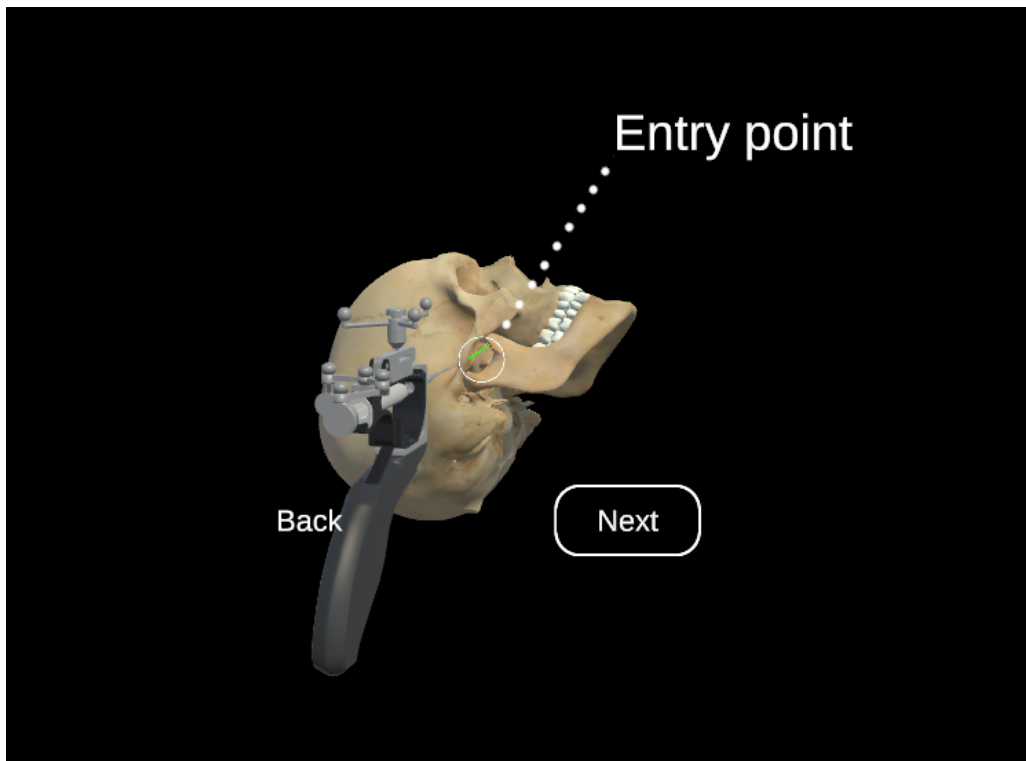


Figure 30: One of the steps from the injection tutorial in Magic Leap

Main menu and navigation

Since we added other scenes to the project, there was a need for a way to effectively swap between them. For this reason, we implemented a "main menu" that was soft-locked to the head. The imple-

mentation had to be different in the Hololens and the Magic Leap. In the Magic Leap, menu items are chosen with the controller, and in the Hololens they are chosen with gaze and airtap.

In the Hololens we added a collider to the menu that expanded over the sides. If the user looked outside this collider, the menu would come flying towards them and stop at the center of their gaze. To get back to the main menu from another scene voice recognition was implemented. By saying "back," the user would go back to the main menu.

In the Magic Leap, the menu would stay in the center of view at all times, though with a 5cm slack such that it would not shake if the user did not hold their gaze entirely still. To get back to the main menu, the user could hold the "home button" on the controller to show a home menu, where the user could choose between going back to the main menu and canceling.

Injection from both sides

In the Sphenoblock AR project, it was only possible to do the injection from one side. Some users would try to do the injection procedure on the wrong side of the head, and be confused when nothing happened. After speaking with the surgeons, they explained that the nerve is present on both sides and that it is reasonable to do the procedure bilaterally on some patients. If the patients suffered from cluster headache, they would do the injection on one side, but if the patient had chronic migraine, they performed it from both sides. For these reasons, we implemented the nerve with functionality on both sides.

4.4.2 Improved Magic Leap application

Changes to the rotation tool

Of the tools we had implemented, the rotation tool was the one that test users found the hardest to use. In an attempt to find a better solution, we tested out several different ways of using the controller to rotate the skull. Eventually, we landed on having the skull rotate by the change in rotation, rather than the raw rotation. This means that if the trigger button on the controller is pressed, and then rotated, the skull will also rotate with the same amount of degrees as the controller relative to its start position, as shown in Figure 31.

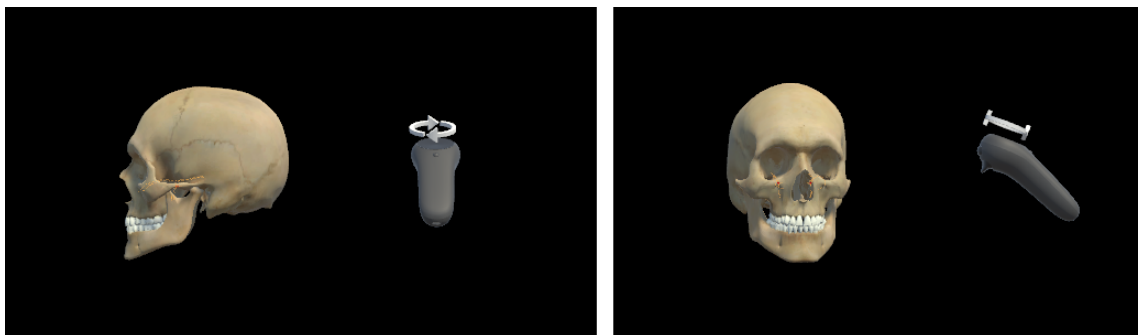


Figure 31: Figure showing how it looks to rotate the skull 90 degrees to the right

Changes to the move tool

When moving the skull, it was not obvious where the skull would go when hitting the trigger button. In an attempt to fix this we added a "ghost" skull which followed the tip of the pointer, see Figure 32. This way, the user would be able to see where the skull would go when hitting the trigger button before actually moving it.

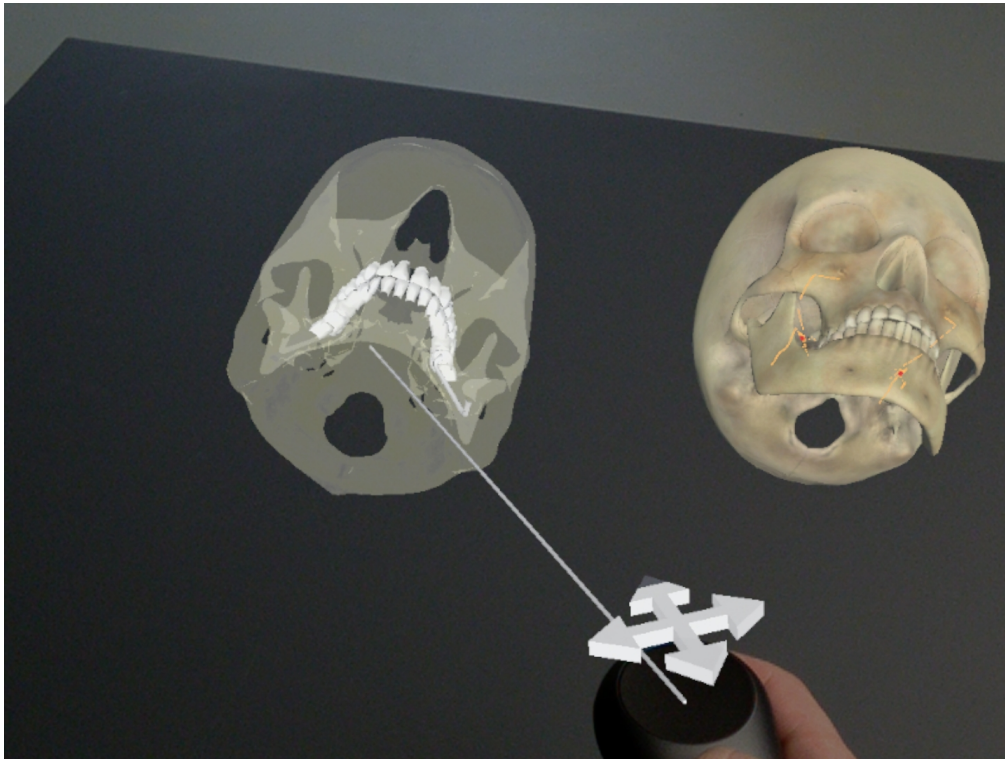


Figure 32: Move tool

Magic Leap image tracking

We experimented with using the image tracking functionality provided by the Magic Leap SDK. However, it was not as accurate as Vuforia; additionally, there had to be a head-locked camera icon visible to the user at all times. There was no way of removing the icon[75]. Because of this icon, and that the image tracking was less precise, we decided not to use it.

Adding clipping alert

In the Magic Leap, the near clipping plane is hard-locked by the developers to 37 cm. This means that when the glasses come closer than 37cm to the object, it disappears. This is intended from Magic Leap's side, as they claim that having objects closer than this can cause disorientation.

The surgeons expressed concerns about this limitation. To account for this, we added a warning that would show up when the controller was closer than 37 cm to the users head. This warning message would be head-locked at 37 cm away from the device in the direction the user was gazing.

Removing the tool menu

When testing with users, we found that the tool menu seemed to be more distracting than helpful. Because of this, we decided to remove the tool menu. As there was no longer a way to see the options, it was weird to have swipes to choose a tool in either direction, so we made it so that it was only possible to change the tool in one direction in a circular queue using the bumper button.

For visualizing which tool was currently active, we found universal symbols for rotation and movement and placed these on top of the controller when using these tools.

15mm mark

When having a meeting with the lead surgeon, he missed a way to identify how far away from the point 15mm was. To fix this, a rectangle with text saying "15mm" was added, that would float at the line between the needle edge and the SPG. This marker would stay locked at a point 15mm away from the SPG. This rectangle disappears when the needle edge comes closer than 15mm to the nerve.

Haptic feedback

The Magic Leap controller provides the opportunity to give haptic feedback. When talking to the surgeons, they said that the biggest problem with the injection procedure in the application was the lack of haptic feedback. In the real world, there would be much resistance to the needle when doing the injection. So to try and make this a little better, we added haptic feedback when hitting bones. This meant that the controller would vibrate when hitting bones.

Controller tutorial

Since few had tried the Magic Leap or similar technology before we needed a way to introduce the controller to the user, we decided to add a controller tutorial to show how the controller is used in our application, see Figure 33. By teaching the user the name of each button, it was more convenient during demonstrations to help the user if they had problems navigating the application. The tutorial also goes through the different tools and how to use them in the injection mode.

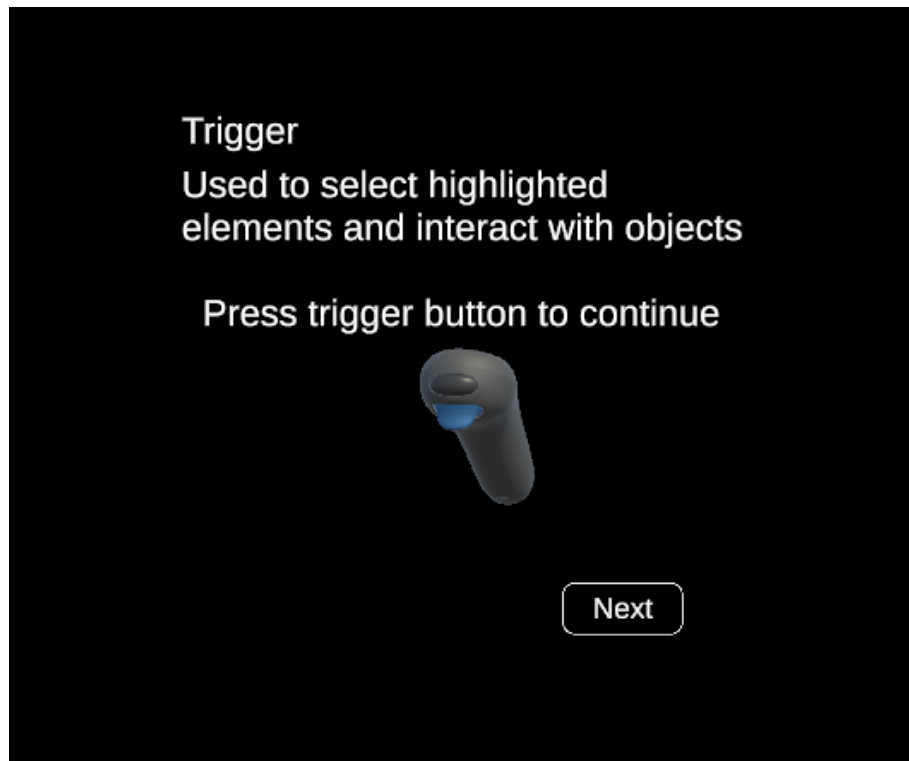


Figure 33: One of the steps in controller tutorial

Controller help interface

The controller help interface was built to help the user to remember the name and functionalities of the buttons. The names of the buttons were attached and followed the movement and rotation of the controller, Figure 34. The user could look at the controller and see the names. In a demonstration setting, this could make it easier to help the user if they got stuck.

This was not implemented in the final version as the precision of the arrows was not mapped good enough over the controller and that it required other GUI objects/interactions to hide and show the help interface.

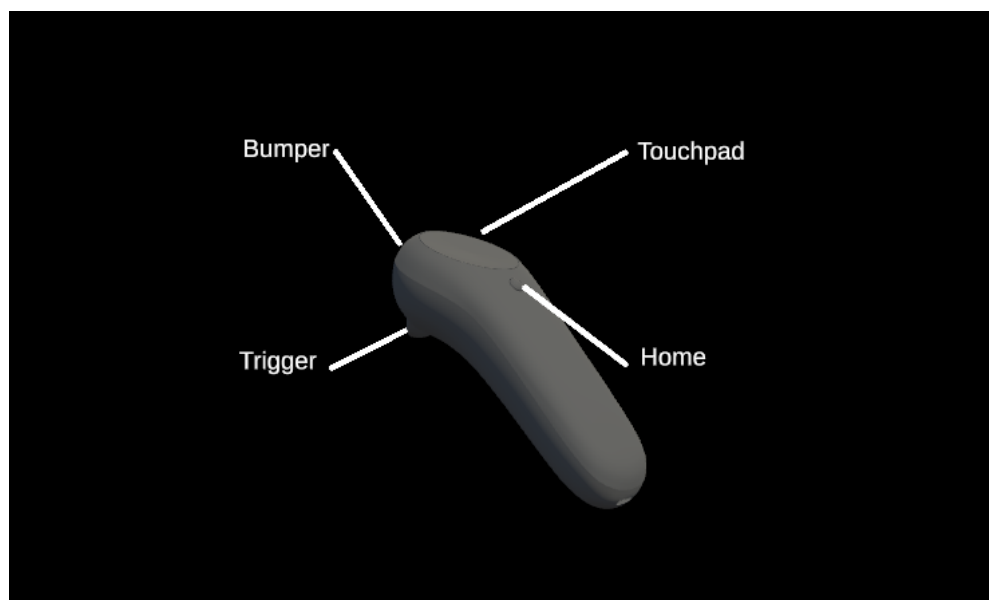


Figure 34: Reminder of the names and functionality to the buttons on the controller

4.4.3 Improved Hololens application

Observer mode

One problem that the doctors pointed out was that it was hard to see if the students performed the injection correctly, as there was no way to see what they were doing. It was also hard to use the application as a demonstration tool if there were no way to observe someone do the injection in the application.

To cope with this, we implemented a prototype of an observer mode in the Hololens app, see Figure 35. The observer mode worked by having one user "host" a session. This user would then have to give the other user their IP address, which was shown in the application. The other user, the "observer," would then type this IP address into a text field and connect to the host.

When connected, the host could perform the injection regularly, and the observer would be able to see what the host was doing. The observer, however, would not be able to do anything other than watching. The application used a peer-to-peer connection, meaning that there was no external server implemented.

The application worked by having the host create and attach a world anchor to the scene, and this world anchor would then be sent over Wi-Fi to the observer when he connected. The observer app would then try to map the world anchor to their environment, creating a common reference point for both applications. After this, positional and rotational data relative to the reference point would

be passed over from the host to the observer. Consequently, the host and the observer would see the models at the same position in space. The host could also toggle different anatomy as in the injection mode.

We were only able to send data, approximately 15 times each second from Hololens to Hololens without it failing to process it all in time. It is unclear if this is due to our implementation, Unity networking, or the Hololens' hardware being too bad. To try and remedy this we did interpolate[76] the movement as well as we could, but this was not perfected due to time limitations.



Figure 35: An illustration of observer mode

5 Testing

In this chapter, we will go through how we evaluated and tested our applications. First, we will go through testing during development and then how we evaluated the final prototype. Finally, we tested the applications on an external AR user interface expert as described in Section 5.3.

5.1 Testing during development

During the development of the applications, we had three meetings with members of the team behind the procedure at the St. Olavs. These meetings are the ones referred to in the implementation chapter, Chapter 4. We had the initial meeting in September and then a meeting in November and January, before a demo in May. During these meetings, we demonstrated the new functionality and improvements we had done since the last meeting. We would then discuss the changes with the surgeons and made a plan for further development.

The structure of these meetings was different from the structure of the final tests, as described in Section 5.2. They were more focused on the improvements and newly developed functionality of the applications and aimed at getting gather feedback for further development. The reason for not conducting full-scale user tests was that the experts of the procedure did not have time to participate.

Some feedback on the usability, was also gathered from people visiting the VR lab at NTNU, however this was not structured and they had no experience with the SPGblock procedure.

5.2 Testing of final prototype

In this section, we will explain the evaluation of the final prototype.

5.2.1 Method

We performed user tests where the participants tested both the Magic Leap and Hololens applications. After testing, we had a semi-structured interview with the participant. The reason for doing interviews rather than questionnaires was because of the low amount of participants. Interviews

are likely to give more information than questionnaires, as discussed in Section 1.4.1. After getting consent from the participants, the interview and user test was audio recorded and later transcribed.

5.2.2 Participants

We tested the applications on five participants with different experience with the SPGblock procedure, all from the Department of Neuroscience NTNU at St. Olavs. Three of them were neurosurgeons that had previously performed the procedure on patients and two neurologists that had little or no experience with the procedure.

Participant 1 (P1) and participant 2 (P2), both neurosurgeons, had taken part in the development of the procedure and the Multiguide. They have performed the procedure on multiple patients and are taking part in training new surgeons to perform the procedure. P2 had taken part in earlier meetings and had seen the application in earlier versions before the test. Participant 3 (P3) is also a neurosurgeon and had performed the procedure on a handful of patients, but said he was under training and not yet confident enough to perform the procedure alone. P1 and P2 had tried out the Hololens before, with the original project, but had never tried the Magic Leap. P3 had never used any AR HMDs.

Participant 4 (P4) and participant 5 (P5) were both neurologists. P4 had been working with the Multiguide team and the studies conducted in conjunction with the use of the SPGblock procedure on patients. P4 has never performed this procedure but has been teaching and working with other injections. P5 had done injections of Botox in other procedures, but besides from this never studied the SPGblock procedure. None of the neurologists had used AR HMDs before.

5.2.3 Test equipment

Figure 36 shows the equipment used during the test. It consisted of two Hololenses with the ImageTarget-images and the Magic Leap One with the controller.



Figure 36: The equipment used during the test

5.2.4 Test context

P1 was tested in a complex office environment. P2-P5 was all tested in the same meeting room at the hospital. The test with P1 was used to check the correctness of the application. The feedback from this session was later used to improve the application before further testing. Since P1 also checked the correctness of the application, this test took two hours. All the other tests took around one hour each.

5.2.5 Testing steps

Introduction

We started by asking the participants about their prior experience with the procedure. Then we proceeded with explaining our project, and what the goal of the user test was. We made sure to ensure them that we tested the application and not the participant.

Testing the Magic Leap application

When the participant tested the Magic Leap application, we first had them do the controller tutorial to learn the controls. They then proceeded to do the injection tutorial to get an introduction to the

procedure and how to perform it in the application. Finally, we asked the participants to try out the injection mode.

Follow-up questions to the Magic Leap test

To gather data about the experience while it was still fresh in their minds, we asked some questions about the Magic Leap application.

1. How did the tools work to place the skull/patient in the right position?
2. How did it work to do the injection in AR?
3. Did the 37 cm limit in Magic Leap distract you when doing the injection?
4. Can the physical design of the Magic Leap, that it is tethered and has darker lenses, have an impact of the use of the HMD in a medical setting?
5. Did the tutorial help when later performing the procedure in the application?

Testing the Hololens application

Because of time constraints, we only had the participants test the exploration and the observer mode.

1. How was it to perform the procedure in the Hololens? (Planned, but not conducted)
2. How was it to use images to track the skull and the Multiguide? (Planned, but not conducted)
3. How did the exploration mode work?
4. Can the exploration mode be useful to learn about the anatomy around SPG?
5. How can the observer mode be useful?
6. Can the observer mode with the exploration mode functionality be used in an educational setting?

Semi-structured interview

After testing all the functionality, we asked some questions in a loose-styled interview.

General questions

1. How do you train and educate apprentices today?
2. Could this application be used to explain and demonstrate the SPGblock procedure?
3. Would you have used this application to learn the procedure?
4. How correct is the application (anatomy, procedure)?
5. Do you have any suggestions for further work?
6. Any thoughts on having the tutorial as a separate application to be used in education?

Magic Leap vs Hololens

1. Was it any variety in the FOV between the two devices?
2. Was there differences in the quality of the holograms?
3. Which of the HMDs do you think is the most suited for medical use?

5.3 Testing with AR user interface expert

At the end of the project, we had the opportunity to test our application with an expert in AR user interfaces. During this session, we demonstrated the application on Magic Leap and Hololens with the focus on the user interface. The participant did not have any medical training or experience with injections nor the procedure.

6 Results

This chapter explains the results, structured as explained in Chapter 5.

6.1 Expert evaluation by Neurosurgeon (P1)

6.1.1 Magic Leap application

Controller tutorial

P1 noted that the content was too big for the field-of-view. We noted that P1 had some problems finding the bumper button. They found the other buttons with no problems.

Injection tutorial

When looking at the simulated injection in the tutorial, P1 noted that it could be ambiguous that the red dot was the SPG because that the white marker in the tutorial highlighted a larger area of the skull. When looking at the injection in the tutorial, P1 tried to walk around and look more closely and was bothered that the view would follow the head. P1 also noted that the "Check" step, the step to check that all liquid has been injected, was excessive because any doctor would do this by default. It was discussed if the "Check" step could be moved to after the "Aspirate" step to remind the user to check for any blood in the syringe. However, since we had not implemented any fluid simulations, we decided to remove the "Check" step.

P1 said that when looking at the animations of the Multiguide steps, it could be hard to see what was happening if the user had the wrong angle. We had added a highlight color to the moving component, but P1 said that it might be hard to see. They also informed us about some textual errors (see 6.1.6).

Injection procedure

P1 started by trying to move and rotate the skull to the right position. P1 noticed that the controller would disappear when closer than 37 cm to the HMD. They expressed that this created an unnatural and tiring work position, as the user would have to keep their arm too far from the body.

We noted that it seemed hard to understand how to change tools, even after completing the tutorial.

P1 also had some problems navigating the anatomy menu, as clockwise-swipe functionality was hard to understand.

When leaving the 15mm sphere around the SPG, the state would not reset. P1 commented that it would be better to reset the Multiguide state and the loading bar state upon leaving the 15mm sphere.

When looking through the anatomy provided by the application, P1 noted some flaws. Firstly, P1 said that the lymphatic system was excessive as it was not relevant to the procedure. Second, the blood vessel called "maxillary artery" was placed in the wrong spot, namely right in front of the SPG. The SPG was also not at the correct spot. P1 noted that this could cause users of the application to believe that they risked hitting this vessel and that it was dangerous to perform the procedure when, in fact, the vessel was far away from the SPG.

Follow-up questions about the Magic Leap application

After doing the test of the application, we asked P1 what they thought about it. They noted that they believed it could have been hard to use the application if they was alone, but that after understanding how it worked, it was intuitive. When doing the injection, P1 said that it was too much happening too quickly, with the loading bars filling up way to fast and sounds playing to fast. To remedy this, P1 suggested slowing down the loading bars and having to press some button to trigger each new action.

P1 also called for some way of knowing when they were 15mm from the SPG. In general, P1 expressed that using a motion controller for controlling the Multiguide felt natural.

In order to increase the effectiveness of the application, P1 suggested integrating the injection tutorial into the injection part, thus creating a more step-by-step approach where the user has to perform each step to advance.

6.1.2 HoloLens application

Exploration mode

P1 toggled anatomy on and off and moved the head around a bit. Then stating that there was little benefit from this mode. The reason for this was that the quality of the models was too low and that it was not detailed enough to get a good enough understanding of the anatomy. P1 had some trouble performing the "airtap" gesture. This was amplified by the models' instability caused by low FPS.¹

¹Note that we asked the expert to ignore these technical issues during testing.

Observer mode

We did not manage to sync the HoloLenses correctly for this test. This meant that there was an offset of the reference point between the two HoloLenses. The offset was about 1.5 meters. The probable reason was that space was complicated, and the HoloLenses struggled to map the environment. However, P1 understood how it was supposed to work, and noted that being able to see the same things in the HMDs would be useful for educational purposes.

6.1.3 Post-test interview

When asked about their opinion of the applications, P1 explained there was little benefit of training on the procedure with the application. The reason being that haptic resistance was significant in order to get an understanding of how it is to perform the procedure.

P1 liked the injection tutorial for demonstrating the procedure, as AR technology helps to give a better 3D understanding. They also said that the model of the Multiguide and the animations were impressive. P1 expressed that the Multiguide was scaled correctly relative to the skull. However, they had mixed feelings about the head anatomy, claiming that it was not very realistic, but that it was good enough for this use-case. They claimed that with some minor polishing, such as having the objects stay still and changing some sentences, it could be used for explaining the procedure to doctors.

P1 was not very fond of the exploration mode, expressing that the resolution, along with the quality and instability of the models, made the mode almost unusable. They liked the observation mode and explained that being able to share holograms between devices could be very useful for teaching.

6.1.4 Magic Leap vs HoloLens

When asked about if they preferred the Magic Leap or the HoloLens P1 said that the Magic Leap was much better than the HoloLens for medical use. The main reason being that the superior processing power of the Magic Leap made the experience much smoother and that the increased quality of the models was helpful. P1 also said that the increased FOV enhanced the experience. They also preferred using the controller over hand gestures.

P1 expressed that the dark lenses of the Magic Leap were not a problem, as the users could add more light. They did not find the "lightpack" to be a problem either and compared it to wearing head-lamps connected to battery packs worn on the hip.

P1 noted that the HoloLens was substantial and that it would be tough to wear it for a more extended period.

6.1.5 Suggestions for future work

We also asked what direction P1 thought the project should take next. They said that, especially in the observer mode, it would be nice if the observer could communicate with the apprentice. P1 then suggested letting the observer highlight elements of the head or removing them temporarily, so that the observer could explain anatomy to the apprentice more easily.

Something that was mentioned by P1 was the ability to get haptic feedback. It felt very unnatural to advance with no resistance, so they suggested re-adding the mannequin from Nystadsnes's project[8] or adding some other way of simulating it.

Another suggestion from P1 was to either create a controller shaped like the Multiguide, or more realistically, to 3D print one, and put the Magic Leap controller[21] inside.

P1 also lacked something to aim at while doing the injection. They suggested adding a predefined path that the user could use for guidance as they do when performing on a patient.

6.1.6 Updating text

As we were fortunate enough to have one of the leading experts of the procedure testing the application, we also wanted to get feedback on the correctness of the application. Under is a summary of textual errors that erupted from the test of P1.

- Change the name of the procedure from "Sphenoblock procedure" to "SPGblock procedure"
- Entry point, not entrance point
- Advance the needle, not inject
- Calling the anatomy menu something else than "Granularity menu" preferably "Anatomy menu"
- Call granularity something else, for instance, layers

6.2 Evaluation by Neurosurgeons (P2 and P3)

In this section we present the results from P2 and P3, as they are grouped together as neurosurgeons.

6.2.1 Participant 2

Magic Leap application

Controller tutorial

P2 went through the controller tutorial without any problems.

Injection Tutorial

P2 started the tutorial when sitting down and then stood up. This led the tutorial to spawn in the wrong height. We discussed solving this by letting the user place the tutorial. For now, P2 had to go to the main menu and then go back to the tutorial to re-spawn the models in another height.

P2 tried "holding" the virtual Multiguide in the real world, to test if the entry angle and path was correct, and stated that it was good.

They also suggested that it had been better to show one SPG at a time and not both. This was to avoid confusing the user and also not clutter the scene, making it easier to focus on the task.

Injection

P2 commented that the models were good enough and that the blood vessel "maxillary artery" maybe was misplaced, but worked as a reminder that it is a vessel in the area.

Initially, P2 had some issues understanding how the tool menu worked, and also with navigating the anatomy menu. P2 sought more interaction during the injection and suggested using the controller buttons to initialize the next step of the procedure.

Hololens application

Exploration mode

We did not test the exploration mode, as P2 already had tried it on an earlier occasion.

Observer mode

P2 commented that the Multiguide was lagging behind the actual movement of the ImageTarget.

Post-test interview

P2 was satisfied with the application, especially as a tool for learning about the anatomy around SPG for people not so familiar with the area. P2 suggested that the application could be a good tool for introducing people to the procedure before they observed a surgeon performing it on a patient.

Magic Leap vs Hololens

When asked about which HMDs they liked the most, P2 answered that the Magic Leap was the preferred one. This was due to it being easier and more comfortable on the head than the Hololens, and also its better graphics. P2 noted that the glasses were a bit dark. They noted that this was better on the Hololens where the glasses are more transparent and also have a larger perspective. The Magic Leap is designed to have a smaller side vision to make the appearance of the FOV larger.

P2 pointed out that it could be hard to use their regular glasses when using the two HMDs. They also noted some vibrations in the models and that the models became blurry when gazing at them at the edge of the FOV.

Suggestions for future work

P2 wanted a better response time when using the controller. They also asked if it would be possible to edit the controller to look like a Multiguide. They also sought more haptic feedback and blurring the line between reality and digital holograms.

6.2.2 Participant 3

Magic Leap application

Controller tutorial

During the controller tutorial, we had to explain to P3 how to navigate using the trigger and what we meant by highlighted elements. After figuring out how the navigation worked, P3 had no issues using it later on. They commented that the tutorial sometimes went out of the FOV because it was too big.

Injection

After doing the injection tutorial, without any comments, P3 tried to do the injection. P3 did not remember how to navigate the tool menu. They had also forgotten how to use the rotation tool and the anatomy menu.

P3 commented that it was no visualization of the entry point or path in the injection. P3 explained that they, before performing the procedure, usually plan where to go in and then draw the path on the CT images. This path would later be used to navigate the Multiguide when performing the procedure on a patient. We explained that this did not exist in the application, but that we use the trajectory between the Multiguide needle edge and the SPG to show the path.

P3 proposed that some sort of interaction when doing the aspiration and injection parts of the procedure would be helpful.

Hololens application

Exploration mode

While testing the exploration mode, P3 said it took some time getting used to the gestures and interactions with the Hololens. Therefore it was hard to use the different tools in the beginning. P3 noted that there is potential in using the mode to study anatomy.

Observer mode

P3 said the "observer mode" could have many use-cases and that it could be useful in the future if the models could show more detailed anatomy. Especially for showing microanatomy. However, for now, it did not give any more benefit than training on the doll with an expert present.

Post-test interview

When discussing the target group for the application, P3 suggested maybe using it to show the procedure to curious patients. Some patients want to know how the surgeons work and what they are about to do with them.

When asked about how it was to perform the procedure in AR, P3 answered that it needs to have physical resistance and haptic feedback. They thought that the mannequin is the closest it is possible to get to a real patient. With the mannequin, the apprentice would also get more stability and resistance than when doing the procedure on digital holograms.

P3 noted that it was possible to complete the procedure even if they advanced the needle through bones or cranial structures. On a real patient or the mannequin, there would not be possible to change the direction and rotation of the Multiguide after starting the advancement. P3 commented that the weight of the Magic Leap controller was lighter than the physical Multiguide and therefore made the experience even more different from performing the procedure in real-life.

P3 thought that the application could be used as an educational tool, but for getting an understanding of the procedure rather than learning to perform it. In the process of teaching people the procedure, P3 meant that after observing an expert perform the procedure on 2-3 patients, the application could be used as a repetition tool to see if the user had understood the procedure.

P3 also thought it could be used to introduce the procedure to neurologists and show that it is safe to perform the procedure, which means that there are no critical structures that can be destroyed thereby convincing them to learn the procedure.

Magic Leap vs Hololens

P3 saw no bigger variations in the quality of the holograms. They also had no issues that the Magic Leap is tethered and has darker lenses than the Hololens. Moreover, they liked the Magic Leap controller for having something physical to hold when doing the injection and navigating the application.

P3 did not think the FOV of any of the HMDs was a problem, but pointed out that the user needs to figure out how to place the models themselves to get the best view.

Suggestions for future work

P3 said that if the application were to be used for training, there would have to be more physical resistance. Also suggesting that trying to map it to a mannequin could make it better for training.

6.3 Evaluation by Neurologists (P4 and P5)

The last group we interviewed was neurologists. These had theoretical knowledge of the procedure but had not done any injections themselves.

6.3.1 Participant 4

Magic Leap

Controller tutorial

P4 went through the controller tutorial without problems.

Injection tutorial

When doing the injection procedure, P4 noted that it is important to hold the needle still around 3 seconds before pulling it out when the injection is finished. This is to ensure that all the botox flows out before pulling out.

Injection procedure

Initially, P4 had problems understanding the circular queue system for changing tools, but after a short while, they understood it. P4 did not understand how to rotate the skull initially. They tried to move the controller instead of rotating it.

Also, they commented on having to hold the controller 37 cm from the head, saying that the position felt unnatural.

Hololens

Exploration mode

When testing out the exploration mode, P4 expressed that it was hard to use the controls. Particularly that the rotation tool felt weird to use.

Observer mode

P4 tested out watching one of us doing an injection in the Hololens using the observer mode. They expressed that this was a good way of discussing between teacher and apprentice.

Post-test interview

How was it to do the procedure in AR?

P4 had many thoughts about how it was to do the procedure in AR. They started with the positives, expressing that this was a great way to visualize anatomy. Continuing down that lane, P4 also noted that visualization is a powerful way of learning compared to just reading.

P4 noted that, if the study they participated in would be successful, this procedure would soon be rolled out to a broad audience. Therefore, having more ways to teach the procedure would be

necessary.

P4 noted that the application could be useful for neurologists and doctors that will have to learn to do the procedure but are not that used to the anatomy in the face. They also explained that getting some understanding of where the SPG is, and what the surrounding anatomy is, could be useful information to possess before going to train on real patients.

On the negative, P4 said that doing the procedure in AR was unrealistic and that having the haptic feedback is crucial if this tool were ever to be used for practicing the procedure. Especially the aspiration part, where the loading bar fills up, felt abstract, and almost unnecessary.

They also noted that there were several gestures to perform on the Multiguide, which meant that only having to press the trigger between the steps would not be enough. To make it suitable for training, they noted that there would have to be haptic feedback and some way of simulating the gestures performed on the Multiguide.

Magic Leap vs Hololens

P4 said that the Hololens was uncomfortable on the nose. They also said that the Magic Leap was very user-friendly, but that it took some training to get used to. Another thing we mentioned was that it might be easier to learn the controls if the user is familiar with the HMDs already. P4 agreed with this. They also noted that they had little experience with gaming and that if they had, it might have been easier.

Suggestions for further work by P4

P4 had many ideas for upgrades and further development. Their first suggestion was tweaking the observation mode, adding several skulls, as the skull is very different from person to person. The teacher and the apprentice could then discuss and plan the paths through a variety of skulls, helping the apprentice get training on deciding the path. P4 also suggested generating the skulls out of CT-images, so that the skulls would be as realistic as possible.

As a vital part of performing the procedure is performing the tasks on the Multiguide, P4 suggested adding mechanisms to simulate these gestures in order to make the experience more natural. One of the ways to do this was to 3D print a Multiguide, and attach it to the Magic Leap controller.

Another suggestion P4 made, which was not as relevant for the SPGblock procedure, was to better visualize the nerve networks from the brain, as these are complex and hard to learn for students.

6.3.2 Participant 5

Magic Leap

Controller tutorial

When doing the controller tutorial P5 noted that they expected something to happen when pressing

the buttons that were explained in the tutorial.

Injection tutorial

When moving from the controller tutorial to the injection tutorial P5 noted that the main menu was too large for the FOV.

P5 also tried to interact with the skull during the tutorial and noted that they expected some interaction.

P5 noted that the marking of the SPG was fitting and that it was no problems seeing where it was and was surprised to see that it was supposed to be done from the side, and not the front of the head. However, they mentioned that the anatomy surrounding the SPG was not accurate enough to be trusted.

Injection procedure

When trying to do the injection, we noted that P5 had trouble understanding that they needed to hold the pistol 37 cm from the head. When they understood it, they said that it felt very unnatural.

P5 had no problems switching between the tools. They also understood how to use the move tool instantly. They found the rotation tool hard to understand. When trying to navigate the anatomy menu, they noted that the touchpad was unresponsive.

As P5 was doing the injection, they noted that it was hard to hold the pistol still inside the 15 mm mark, because of the lack of resistance.

Hololens

Exploration mode

P5 had no problems moving and scaling the skull. They also managed to rotate the skull, all though it was a little hard they noted. The anatomy menu was also intuitive, and they found it easier to use the look and "airtap" than the touchpad in the Magic Leap.

Observation mode

P5 tested out being the observer in observer mode. They noted that the Multiguide was jumping a lot. We explained that this was because of the image tracking sometimes losing track.

Magic Leap vs Hololens

P5 liked the Magic Leap better. It was lighter and felt better to have on the head they added. They did not see too much difference between the models, but they noted that the lighting was better in the Hololens.

They also noted that doing the procedure with the controller seemed much better than doing it with images.

When comparing the tools used for maneuvering the skull, P5 noted that it was easier to move and rotate the skull using the controller.

They also expressed that they did not find the limited FOV as a problem, as their focus was on the skull.

P5 noted that the glasses were a bit warm after using them for some time, but that this was not something they had thought about while wearing them.

What did you think of doing the procedure in AR?

P5 started by noting that this application could not replace actual training with the supervisor on patients, but that it might be useful for introducing the procedure to neurologists with little experience with the procedure, or patients with particular interest. P5 also stated that it could also be useful for understanding why the surgeon supervisor does the steps they do when performing the procedure.

The lack of physical resistance was also something that P5 was missing. They proclaimed that without physical resistance, there was no way that this could be used for actual training.

On the more positive side, P5 explained that they thought this could be a helpful way to explain where the SPG was. If the anatomy was more detailed, they could also see this technology being better for learning about anatomy than using an anatomy atlas. Tying up to this, they added that the observation mode, along with more detailed anatomy, could be perfect for teaching and explaining the procedure and the surrounding anatomy. They also noted that they thought using an application like this would be a more powerful learning tool than reading about the procedure or watching a Youtube video.

P5 also jokingly said that it could be a potent PR tool for the procedure, sparking interest.

Further work suggestions by P5

P5 said that they thought it would be wise to re-add the mannequin again or having some other way of simulating physical resistance. They also repeat that the anatomy was not detailed enough to be relied upon and that this would have to be addressed.

6.4 Expert evaluation by AR user interface expert

6.4.1 Magic Leap

After testing the application on the Magic Leap, they suggested merging the tutorials into the injection mode. Where the user first will be presented how to perform a step (move/rotate the skull,

use the anatomy menu, perform the injection), and then perform it themselves, before advancing to the next step.

They also noted that it was hard to know why the loading bar, the simulation of the Multiguide interactions, stopped loading. They missed some feedback telling on what to do with the Multiguide to continue the procedure. It is necessary to inform that the participant depended on using glasses and might not have seen the 15mm mark hovering on the trajectory between SPG and the needle edge of the Multiguide. One suggestion to improve on this was to use voice to tell the user what to do. Another suggestion was to colorize the sphere around SPG, making it easier to see where to advance the Multiguide.

The expert proposed adding "ghost-tracking" the Multiguide. Meaning to have a Multiguide perform the procedure without the interaction from the user. For instance, having the steps from the injection tutorial be played if the user needs a hint. The suggestion was to trigger these events after X amount of time the user had been outside the SPG sphere (after triggering the loading steps).

6.4.2 Hololens

After testing the Hololens, they stated that the menus work better on the Hololens than on the Magic Leap. Emphasizing that it was easier to "gaze and click," than using the touchpad on the Magic Leap controller. We debated if it would have been better to use a "point and click" method, with a pointer/ray cast from the Magic Leap controller. This is what many VR applications use, and also some Magic Leap applications. For now, the menus and navigation in the Magic Leap application are designed from the design principles of the Magic Leap OS, as seen in Figure 37.

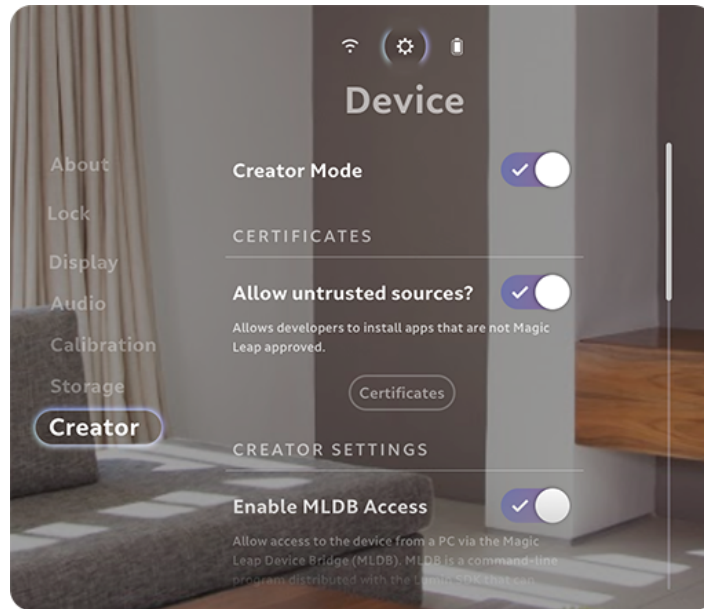


Figure 37: Magic Leap settings menu

They also stated that it was better to do the interaction with the Magic Leap controller rather than using the images for doing the procedure. A suggestion was to make a custom device to simulate different medical tools. In this case a replica of the Multiguide with accelerator and other sensors to track it, where the user also got the possibility to physically press the advancement of the inner needle and perform the aspiration, and injection.

6.5 Our evaluation of the HMDs

We wanted to compare the HMDs for use in medical training. After discussing with the surgeons, we came up with the most important non-functional requirements for the devices to be useful in a medical setting. The requirements are described in 2.7.

In order to answer some of the requirements that are not explicitly answered in the implementation chapter, we decided to make this table that explains how well the different HMDs solve each task.

The degree in which they solve the task ranges from not at all too poorly to good to very good. The results are based upon our evaluation of HMDs in relation to the requirements.

Device	Hololens	Magic Leap	Meta 2
The holograms must stay their initial position with minimal drift unless moved by the user (NFR3).	Very good	Very good	Poorly
The glasses must last a minimum of two hours before being depleted of energy (NFR4).	Very good	Good	Very good
The holograms must be projected without deteriorating them (NFR5).	Good	Very good	Poorly
The hardware must be available for purchase (NFR8).	Very good	Good	Not at all
The operating system of the device must be regularly updated to stay compatible with the latest development platforms (NFR9).	Very good	Very good	Not at all
The glasses must be able to maintain 60 FPS while rendering the 3D model of the skull and the Multiguide (NFR7).	Poorly	Very good	Very good

Table 2: Our evaluation of the HMDs

7 Discussion

We start this chapter by discussing the different HMDs, laying the foundation for the comparison. We then discuss the results presented in Chapter 6 before we present our contributions and the limitations of the project.

7.1 Discussion of different HMDs

In this section we discuss the three HMDs we worked with and discuss their advantages and disadvantages.

7.1.1 Hololens

That the Hololens is all inclusive, as explained in Section 2.2.1, is a two-edged sword, no motion controller means that all input happens through hand gestures and voice input. This might feel imprecise at times and cause frustration for the users.

Hololens having all hardware embedded in the HMD, puts constraints on the processing power. This is because of weight and space limitations. Therefore Hololens is capped to rendering in 60 FPS. If one is to maintain this FPS, there should not be more than 100k triangles rendered at all times[77]. This puts constraints on developers who have to optimize their applications if they want to have complicated or detailed content with many triangles. As a result, we had to decimate the 3D models for the Hololens, meaning that the quality of the models was lowered. If the quality of the models is low, this might also lead to inaccuracy when performing tasks. This could be an issue for this application, as the precision is essential concerning the small scale of the SPG.

Purely technically, the Hololens scans the room automatically, and the holograms stays in place with little drift, which is important for our application. However, we noted some drift in the Observer mode. This might be due to the Hololenses having issues mapping the environment, as mentioned by Evans[78]. Having the holograms drift could possibly affect the experts evaluation of the apprentice. The reason being that the expert might misunderstand what the apprentice means or does as their experience is not fully synchronized.

Using image tracking for controlling the Multiguide is not the best, as when the camera lost tracking, the Multiguide would disappear and appear rapidly or start shaking. This is a challenge, as precise

control of the Multiguide is vital for the user experience.

We tried to find alternatives to tracking the images. Alternatives that came up was using Polaris[47] or some Microsoft motion controller. Unfortunately, we were not able to find a motion controller. Adding the Polaris to our project had some practical challenges, as we did not have a Polaris and would have needed to borrow one from the hospital. Also since there was no API readily available for the Hololens, we would have to implement the communication from scratch, which might have taken much time. Additionally, the doctors wanted the system to be lightweight and easy to set up — the reason being that this would be more effective for exhibitions and conferences.

The limited FOV at only 30 * 17 degrees imposes usability issues, as it is hard to keep track of the holograms around the user. During the tests, it came up that this was less of a concern than initially assumed. The test participants said that their focus was on the single hologram and that the limited FOV was not an issue.

The tight space between the user's head and the display of the glasses means that it is hard to wear regular glasses while using the HMD. This might be a problem, as many doctors wear glasses. However, even though the HMD is not designed for users wearing regular glasses, we have seen examples of users managing to do it.

7.1.2 Magic Leap

Compared to the Hololens, the Magic Leap offers the same levels of stability of the holograms, but with a broader field of view, see Section 2.2.2. It has more processing power, see Section 2.2.4. Therefore, we can have 3D models with larger amounts of triangles.

The 6DoF controller provided by Magic Leap One is accurate, and the test participants found it easier to use than the gesture system of the Hololens. In addition, the Magic Leap also supports voice input and hand gestures, just as the Hololens does.

Since the computing power of the Magic Leap is carried in a lightpack, it makes the actual HMD much lighter than the Hololens. Thus it is more relaxing on the head. However, the lightpack needs to be worn on the hip or over the shoulder, meaning that it is a bit more restrictive than the Hololens.

The Magic Leap does not provide the opportunity to wear glasses when worn. This is an issue, as many are dependent on their glasses. As a solution, Magic Leap has started a partnership with Framesdirect to provide "Prescription Inserts" lenses for the Magic Leap One[79]. This solves the problem for individual owners, but since this application will mainly be used in education, it is not to be expected that the institution can provide such lenses for all.

One problem with the Magic Leap is the capped "Near clipping plane," which means that holograms will disappear when coming closer to the camera than 37 cm compared to the regular Unity limit of 1 cm, which can also be worked around to be even lower. The reason for this is that Magic

Leap means the holograms might strain the user's eyes if coming closer than this. It is a problem in applications such as this as the users might want to take a closer look at the anatomy. The 37 cm limit is currently an issue for many developers and is one of the most debated topics on the Magic Leap Developer Forum[80].

Another thing that might be a challenge for some applications is that the lenses are dark. This makes the real world less present and the virtual objects more clear. However, this did not turn out to be a problem in our application. The participants expressed that this is not a problem generally for the medical setting, when it is resolved by simply adding more light in the operating room.

7.1.3 Meta 2

The Meta 2 has the largest field of view of the three HMDs allowing having more sophisticated user interfaces with more elements. The Meta 2 is tethered, needing to be connected with a computer to work. As a result, the computing power is not limited to the device itself, but rather to the computer. This means that Meta 2 can render and compute complex tasks and detailed models without dropping in FPS. As the device is tethered, it does not give the possibility to walk around freely. For the SPGblock application, this is not an issue since the user does not need to move around during the procedure, but it can limit the user when exploring the anatomy of the head.

Meta 2 scans the user's surroundings using cameras around the front of the device. For each new scene loaded, the user needs to look around and scan the area around them. Magic Leap and Hololens scan the surroundings more thoroughly, which results in the position of the holograms being stable. For this application, Meta 2 did not provide holograms that was stable enough, as they were drifting more than on the other devices.

Vuforia does not officially support Meta 2 and requires to find workaround solutions to get it to work. This caused problems when trying to control the Multiguide. We tried using Meta 2's built-in grab and move functionality, but since this did not provide rotation, we could not use it for this project.

The Meta 2 is larger than the Hololens and Magic Leap. Because of the size and design of the device, it is possible for the user to wear glasses. It had roughly the same weight as the Hololens, but it feels more unbalanced on the head. The cooling system makes more noise, making it louder than the other HMDs we tested.

In January 2019, the Meta company was declared bankrupt[81]. Shortly after, it was revealed that an anonymous buyer had bought the Meta assets and intellectual properties. In May 2019 it was announced that the buyer was Olive Tree Ventures. Together with investments from BNSG Capital, they started the new company Meta View Inc. with Jay Wright, co-founder of Vuforia, as CEO[82]. They stated that they will support all sold devices, but that there will no longer be possible to purchase new Meta 2s.

7.2 Discussion of development

In this section, we discuss how it was to develop for the different devices, explaining strengths and limitations.

7.2.1 Developing for the Hololens

The Hololens is the most established AR HMD there is, as mentioned in Section 2.2.1. Therefore, it also has the most user-generated content and the most prominent online community. Microsoft offers a library for Hololens development called Mixed Reality Toolkit (MRTK), which was explained in Section 4.1.5. Unlike the Magic Leap API, MRTK is open-source.

It was hard to work with the MRTK. Several versions were floating the web, and there was hard to understand which version one is supposed to use. This also created confusion regarding what documentation belonging to what version. It was also quite hard to merge Vuforia behavior (image tracking) with the MRTK behavior (gestures and voice input), as both depend on the camera object in Unity.

We had some issues getting started developing for the Hololens. The reason for this was that the remote debugging functionality was not compatible with Vuforia, as explained in Section 4.2.1. It is, in our opinion, a problem that such a well established third-party library cannot run together with the "remote debugging" functionality. This resulted in having to build the project every time we wanted to test new code. Each build took around five minutes. No doubt, this was unnecessarily time-consuming.

7.2.2 Developing for the Magic Leap

It was easy to get started developing for the Magic Leap One. This was because their website provided many tutorials and guides for getting started with the basics. These basics include setting up the developer environment, how to build the application and how to use their API.

Their developer forum was very active, and the Magic Leap company offers many video resources that talk about and discuss several relevant topics. These topics includes best practices of how to handle input and user interfaces.

One of the biggest strengths in terms of developer support by the Magic Leap was its "Zero iteration" functionality. This functionality made it possible to develop and run the code on the Magic Leap without building. This made it as easy to test the code for the Magic Leap as for a mobile device.

That the Magic Leap provided a particular version of Unity was in our opinion a strength. It made it much easier to get started, and it was helpful not to have to worry about installing all the right libraries and changing all the project settings. The only negative thing about it was that it was

harder to share assets between the Magic Leap and the HoloLens applications. This resulted in us having to setup components in Unity twice. Once for the HoloLens and once for the Magic Leap.

The simplicity of the Magic Leap API was a two-edged sword. The API is straight forward and easy to get started with, but the developer is limited to using the API calls as they are, and cannot tweak them. The reason for this is that the Magic Leap API is proprietary, and not open source. This, combined with its simplicity, makes it less versatile. The lack of versatility became a problem for us when we implemented the swipe-functionality. Some users found that they had to press hard when swiping. This was strange as in the main menu of the OS, there was no need of swiping as hard. When we tried to analyze the source code to understand if we had implemented something wrong, we found that it was locked. The same situation occurred when we tried to remove the camera icon that was locked to the screen when using image tracking in the Magic Leap API.

7.2.3 Developing for the Meta 2

The developer support for the Meta 2 was not great. There were some video resources online, introducing some fundamental functionality, and "getting started" guides. It also had a small community forum. It was easy to get started with good tutorials for simple implementation. However, their developer forum, "developer center", was down for most of our development time and as of January 2019 only linked to the main web page. Most of the resources given by the Meta company was of spatial interface design and user interface guidelines. To find developer resources, we had to rely on external forums and articles.

During development for the Meta 2, the Meta 2 and Unity crashed multiple times. After running the application from the Unity editor (play mode), the editor would crash if you tried to compile any scripts. The Meta 2 did also freeze randomly either saying that it was unplugged (error 127) or that it did not manage to read the calibration data from the headset (error 4031). This also happened when the Meta 2 was correctly plugged in and worked again after resetting the headset and Unity editor.

7.3 Discussion of research question results

In this section, we discuss the answers to the research question. The answers are derived from the interviews as well as observations of the participants. The exception is RQ 4, which is solely based on our evaluation.

Main RQ: How can AR technology enhance understanding of the SPGblock procedure?

To answer this question we have to answer each of the four sub-questions.

RQ 1: In what areas of training, education, and demonstration are this application of AR technology useful?

To answer this question we will separate the three parts training, education and demonstration, and then summarize in the end of the section.

Training

All the participants in the final evaluation agreed that performing the procedure in the application gave little value in terms of practicing the procedure. The reason for this was that everyone felt that doing the procedure without physical resistance felt very unnatural. That haptic feedback is important is also in-line with the literature, as previously mentioned in Section 3.6. That the participants felt this way might have been amplified by that it is hard to get a precise spatial understanding of the position of the holograms, as this has been shown to be an issue with the Hololens[43].

The application in its current form is not well suited for practicing for performing the procedure. Some suggestions on how to remedy this are given in Section 8.2.

Education

There were mixed opinions on how well the application would perform in an educational setting.

In both the expert evaluation (P1) and the evaluation of one of the neurologists (P5), it came up that the anatomy was not detailed enough to be trusted to replace traditional ways of learning about anatomy. P1 was concerned about a blood vessel that was placed in the wrong spot, giving the impression that there was a risk hitting this vessel when performing the procedure. They also noted that the quality of the holograms was too low to give an accurate representation of the head. Especially, the holograms in the Hololens was of such low quality that he failed to recognize some structures. P5 meant that the quality of the anatomy was not good enough to replace other learning material. However, the other participants stated that the model was realistic enough to give a good impression of the anatomy surrounding the SPG and where to advance during the procedure. This ties nicely up to what Dunser said about AR enhancing spatial understanding[37].

P1 expressed that the injection tutorial part of the application could be used for education if some minor changes were done. These minor changes included changing some colors and correcting some text. Using a step-by-step approach for teaching how to do specific procedures is not something new, and has been done successfully in other domains. One example is when teaching sophisticated machinery, as mentioned in Section 2.4.

P4 stated that they meant the nature of the Hololens, as well as the ability to collaborate over several HMDs, made it a powerful tool for learning about anatomy. This is consistent with what Chien said about AR being useful for learning human anatomy[38]. The reason for this might be what Akcayir said about AR being able to facilitate events that cannot easily be seen with the naked eye, such as internal anatomy[33], which again ties up to that it has been shown that 3D visualization is essential for learning about anatomy[39][40].

P4 also thought that seeing the Multiguide perform the procedure, together with the functionality for toggling anatomy, could make this an excellent tool for learning the basics of the procedure before proceeding onto the observation. This could potentially decrease the time needed between surgeon and apprentice.

P5 noted that they thought the application was a better tool for learning about the procedure, than using a video or a book. Moreover, they stated that it could decrease the preparation time needed for the apprentice before going to do the observation.

P3 noted that they thought the application could be used as a repetition tool after observing a surgeon perform the procedure on a patient. This might help the apprentice understanding what the surgeon did by looking at the anatomy around the injection area to understand why the surgeon chose that path. It might also help refreshing memories of how to perform the procedure for the apprentice.

This suggests that the application could play a role in the education of an apprentice, especially if the anatomy were further upgraded. How this could be implemented is explored in Section 8.2.2.

Demonstration

All the participants thought that the application was fascinating to use. P4 said that the application would be great for demonstrating the application to the general public. P3 said if the goal was to impress, we had succeeded. This goes in hand-in-hand with that AR enhances enjoyment and motivation, as stated in Section 2.4.

P3 suggested using the application for explaining the procedure to the patient that was getting the treatment. When we presented this idea to P4 and P5, they thought it would be a good idea, but that it would depend on how much the patient wished to know.

As it seems, the application would be useful for demonstrating the procedure for people that is in the start phase of learning about the procedure. Examples include new neurologists that are going to start doing the procedure, and also maybe patients that are interested in what is going to happen to them. P3 also stated that it could be used for recruiting new surgeons to learn the procedure.

Summary

To summarize, we believe that the application could be used for demonstration and for education, but not so much for training.

RQ 2: What are enhancements that are required before it could be used in all these three areas?

From the final evaluation, it was two enhancements that stuck out for this application to be used for training and education mainly. If the application were to be used for teaching apprentices about the anatomy, the detail of the anatomy surrounding the SPG would have to be increased. For it to be used for training, haptic feedback would have to be simulated.

For more information on how this could be achieved, see Section 8.2.

RQ 3: Which of the AR HMDs; Hololens, Magic Leap One and Meta 2, is most suited for use in medical injection training/demonstration?

As the Meta 2 company went bankrupt, we decided to drop these glasses early on, as explained in Section 7.1.3.

All of the participants agreed that the Magic Leap One was the better device for this use-case. The reason being its superior processing power, FOV, and stability of the holograms as discussed in Section 7.1.

That the Magic Leap is tethered to the lightpack was not a problem, as the surgeons are used to having battery packs connected to their headlamps, see Section 6.1.4. That the lenses are dark is not an issue either, as a solution is to add more light. The participants preferred the motion controller of Magic Leap One over using image tracking when performing the procedure. This was because it was more precise, and that the participants felt it was more natural to hold than using holding an image. They also liked using it for navigating the user interface more than using gestures. The only exception being the anatomy toggle menu, where they preferred the Hololens airtap gesture over the circular-swipe.

The users also had initial problems finding the bumper button. However, after using it a few times it was fine. This might be because of the unfamiliarity with the technology as described in Section 7.5.

The only thing that the participants found frustrating was the inability to wear glasses with the Magic Leap. There exist prescription lenses designed for the Magic Leap, as mentioned in Section 7.1.2, but these do not solve the problem as multiple doctors need to use the HMD, and it is hard to have lenses for all.

Most test participants found the Hololens to be easy to use. However, some of the test participants found it difficult to only navigate using voice input and gestures. This might be because they lacked experience using this kind of interaction, as described in Section 7.5. Some of the test participants noted that the quality of the models was lowed in the Hololens than in the Magic Leap One. The reason is explained in Section 7.1.1.

The Magic Leap has built-up sides acting as "blinkers" and darker lenses. This makes the holograms appear sharper than in the other HMDs. It also takes the focus away from the relatively small FOV. Hololens, on the other hand, has more open sides, which makes it more apparent that the FOV is small. However, two of the test participants noted that the real world was brighter in the Hololens, and that combined with the broader view of the real world, the holograms blends better in with the environment.

It should be mentioned that the Hololens is from 2016 and that Microsoft, in February 2019, re-

leased the sequel to HoloLens, namely the HoloLens 2[83]. The HoloLens 2 has more processing power, a larger FOV, and many new features such as eye-tracking that can be used for scrolling, and a portable forehead gasket. Microsoft also recently made a deal with the US military, as mentioned in Section 2.3, where 100,000 HoloLens 2's will be rolled out to them. That is more than twice the amount of HoloLenses sold as of 2015[14]. This might impact the future of HoloLens 2. Unfortunately, as it was released so late into this project, and the practical challenges with getting it to Norway, did result in us not being able to test this device in this project.

RQ 4: How is it to develop a SPGblock training application for the different AR HMDs; HoloLens, Magic Leap One and Meta 2?

As described in Section 7.2, the Magic Leap was the easiest to get started with and also the easiest to debug while developing. However, there were some problems customizing the functionality offered by their API. The HoloLens was complex to get started with but provided us with much control over the code. The HoloLens also offered the most notable community and the most online content. The Meta 2 was easy to get started with, but it was hard to develop anything beside basic functionality. The reason for this was that it lacked a good development community and documentation.

It is our opinion that the Magic Leap is the best device to develop for, as it was much quicker to debug. This was because there was no need to build each time we did a change, and also that the API was well documented and easy to use. It should be mentioned that it might have been easier to develop for the HoloLens if we did not use Vuforia. However, Vuforia is such a well-established third-party platform, and that the remote debugging fails when using Vuforia is not a good sign regarding the stability of the remote debugging. The MixedRealityToolkit was usable, but it was complex, and quite hard to get into.

7.4 Contributions

The first section compares our project to the related work mentioned in Chapter 3. We then present our contributions to the field.

7.4.1 Comparison of related work and SPGblock AR

The most apparent difference between our application and the other applications is that we not only have created a version for the HoloLens, but also for the Magic Leap and the Meta 2. None of the applications mentioned in related work has tested and developed their applications for several AR HMDs.

Our applications are more similar to ImmersiveTouch and FundamentalVR than the ProMIS AR and PerkStation. This is mostly because our applications make use of AR HMDs rather than screens. Also, our applications have more focus on demonstration and explanation, and less focus on evaluating

the users' performance, as is very much the case in ProMIS and PerkStation as explained in Section 3.6.

One difference between our applications and the other applications is that they are more focused on having as realistic simulations as possible, rather than the visual demonstration. All the AR applications offer haptic feedback, either by using a mannequin or by utilizing "Geomagic Touch" haptic arms[56][57].

There are some similarities between the related work and our application. For instance, FundamentalVR offers step-by-step walk-through's of specific procedures; the example on their website is "Total Knee Arthroplasty." This closely resembles our "injection tutorial," where the user can go back and forth, watching each step in the procedure. Both our Hololens application, and FundamentalVR's Hololens application offers a collaboration mode. In our "Observer mode," one user can watch another user performing the procedure in real-time. In FundamentalVR, up to twenty students can see the same model.

One difference between our application and the related works is that our application focuses on one procedure, while the other ones support several procedures. This is probably because of the differences in resources available for our project and their projects, but it also gives our project the benefit that it can optimize all interaction and features for this one procedure.

7.4.2 List of contributions

Under we list what we see as our contributions to the field.

- Three AR applications for teaching and learning about the SPGblock procedure, one for the Hololens, one for Magic Leap One and one for Meta 2
- A comparison on how it was to develop for three different AR HMDs
- Which device, of the three AR HMDs, is most suited for neurosurgical applications
- Insight into the strengths and weaknesses of using AR in neurosurgical simulation
- Insight into what neurologists and neurosurgeons think about using the most sophisticated AR HMDs available as of 2018, to teach and learn about the SPGblock procedure
- Insight into what neurologists and neurosurgeons think about learning the SPGblock procedure in a collaborative AR application

7.5 Limitations

7.5.1 Sample size

Due to having a specific target group, and the time of the year, getting participants to test the prototype was challenging. Therefore we had five participants. The participants consisted of neurologists

and neurosurgeons with various experience with the SPGblock procedure. This helped in providing a diverse range of opinions from different points of view.

However, a larger sample size could have helped to uncover more aspects of the application. Especially having more participants with less knowledge about the procedure could have proved useful for getting a more diverse view from this group. Mainly because that there might be important details that the experts deem as less important[3] as stated in Section 1.1.

Also, if we had many participants, we could have divided the participants into two groups. The first group could have gotten to use our application and the other group some traditional learning tools such as a YouTube video or book. After, we could have compared the two groups to see whether our application was better for learning or not.

7.5.2 Uncertainty of the User Experience

When the participants performed the tests, except for the observer mode, we were not able to see what they were experiencing. This meant that it could be hard to know what the participant was doing in their augmented world. If the users did not speak out loud what they were doing, it might have resulted in us missing valuable feedback due to the participant not pointing it out. The reason for this was that, in the Hololens, Vuforia uses the web camera for image recognition. Consequently, we could not use the web camera for the live-preview functionality offered by Microsoft[84].

The Magic Leap does offer functionality for running the application directly from Unity and thus making us partly able to see what is going on. However, image from the camera is not transferred, meaning that we would only see the objects on a black surface. Also, using this functionality for running the application negatively affects performance, and the FPS drops significantly. Lastly, the device would have to be tethered to the computer, putting constraints on the user experience with the application. As of May 2019, functionality for broadcasting the augmented view of the user on to a computer is under development by the Magic Leap team[85].

7.5.3 Previous experience with similar technology

We are under the impression that having previous experience with the technology or with technology that uses similar interaction techniques, such as VR and video games, might affect the perception of the application.

Many of the testers had a hard time with essential interaction with the technology, mainly the use of gestures in the Hololens. This might have affected how well they liked the applications.

We observed that the participants had a more positive attitude towards the applications when they figured out how to navigate the applications. This usually took some minutes for the participants that had never tried the AR HMDs before. This challenge also ties up to that students can find AR challenging to use, as mentioned by Akcayir[33] and described in Section 2.4.

More focus on the Magic Leap during the interviews

There was more focus on the Magic Leap application during the interviews. The main reason for this was that some of the surgeons already had tested the Hololens application. This occurred during our meetings throughout the semester.

These surgeons were under the impression that the Magic Leap application was better than the Hololens application when it came to doing the procedure — explaining that they found it very cumbersome to use image tracking for controlling the Multiguide. Therefore, we mainly focused on testing doing the procedure with the Magic Leap.

Personal involvement in the project

Some of the participants of this study might financially profit on the success of this project. They are also part of the Multiguide team, and thus might be biased in their reviews of the application.

7.5.4 Lack of anatomical knowledge

One limitation that we had in this project was that we lacked anatomical knowledge. Thus, we were dependent on the doctors on the hospital to evaluate the correctness of the 3D models we used.

The way we solved this is by us going online and searching for models. Here we searched a lot on commercial 3D modeling markets, mainly Turbosquid[86] and Sketchfab[87]. One issue with these markets is that they intend on providing 3D models for games, and the models might not be accurate enough for anatomical learning.

7.5.5 No experience with AR development

When starting this project, we had some experience with Unity development, but no experience in developing AR applications for HMDs. Because of this, we probably used more time on developing than someone with more experience in the field would have used.

8 Conclusions and further work

8.1 Conclusion

In this project, we wanted to explore how to use AR technology to enhance training, education, and demonstration for new apprentices looking to learn the SPGblock procedure. We wanted to take a look at which of the three HMDs we possessed, namely the Hololens, the Magic Leap One and the Meta 2, was the most suited for medical training applications. Finally, we wanted to see which HMD was the easiest to develop such an application for.

Throughout the project, three applications were created — one for each of the HMDs. The Meta 2 application was scrapped before the final evaluation as it did not meet the neurologists' criteria. The ways the applications tried to achieve the goals mentioned above were by further developing the Sphenoblock AR application. This was done by porting the application to the Magic Leap and Meta 2. In all applications, except the Meta 2, we added better 3D models, more anatomy and better visual feedback. The injection tutorial was added to both the Magic Leap and Hololens applications, showing the procedure done step-by-step. In the Hololens we added the exploration mode, for exploring the anatomy around the SPG, and the Observation mode, which lets one user perform the procedure while another user observes. In the Magic Leap we added functionality for controlling the Multiguide with the motion controller. During development we found that the Magic Leap was the easiest device to develop for, and also the most suited HMD for the SPGblock AR application.

The application was developed in collaboration with neurosurgeons at St. Olavs University Hospital in Trondheim, where we had three meetings to gather feedback and further outline the requirements. At the end of the project duration, we had evaluations by three neurosurgeons and two neurologists. This was done by user tests, followed by semi-structured interviews. Several findings were made during these interviews, the most crucial being that the lack of haptic feedback made the application less suited for practicing performing the procedure. However, most participants agreed that the application is, or could be, useful for demonstrating the procedure and teaching the procedure to apprentices. It is useful because that the 3D nature of the application gives a good sense of where the SPG is located and the surrounding anatomy, and the step-by-step tutorial helps the apprentices understand the necessary steps involved in the procedure.

Hopefully, this project has contributed to the field of medical AR applications, and help inspire

others to continue work in this exciting field.

8.2 Suggestions for Future Work

8.2.1 Adding haptic feedback

As explained in Section 7.3, we found that we could not use the application as a training tool in its current form. The reason being the lack of haptic feedback. One way to solve this is by re-introducing the training mannequin from the original Sphenoblock AR project, as explained in Section 2.6. The image targets could be used to align the mannequin with the virtual head. Another, more sophisticated way, could be to implement the Brainlab and Polaris tracking into the HMDs. If it were possible to get the positional and rotational data into the HMDs, there would be possible to track the real Multiguide and the mannequin and overlay virtual information on those with millimeter precision. This would be especially feasible with the Magic Leap, if Brainlab launches its Magic Leap developer API, as mentioned in Section 3.1.

Other options include connecting the Multiguide to a haptic arm that could add physical resistance by command of the HMD. This is what several surgical simulators, including FundamentalVR and ImmersiveTouch, has done. This was explained in Section 3.

8.2.2 Improving anatomical details

As stated in Section 7.3, some of the participants meant that the anatomy in the model was not realistic enough. One solution for this issue is to get a new, more detailed model of the head and its anatomy. This is also what we tried to do as explained in Section 4.4.1. The practical challenge we faced was that it is not easy to get hold of an anatomically correct, detailed 3D model of a head with the correct dimensions. The reason for this being that the anatomy is extremely complex, and creating such a model requires a very high level of competence in multiple fields. Namely human anatomy on several levels, as well as in 3D modeling.

Another challenge regarding the detail of the 3D models is the quality of the models when rendered in the HMDs. It came up during the expert evaluation, see Section 6.1, that the resolution was not good enough for letting the anatomy paint a realistic picture of how the anatomy looks. This was, according to the expert, especially true for the Hololens.

8.2.3 Adding a mode for pre-planning the path in several different skull structures

One suggestion that came up during the interviews was to add a mode where the user could get practice planning which path to take to get to the skull. This could be done by having several skulls

with slight anatomical variations, and having the user pick one of several paths through each skull. If an apprentice and an expert could synchronize their Hologlasses, they could also possibly discuss different skulls, and what paths that would be most beneficial to consider in the different situations.

8.2.4 Simulating the Multiguide inputs

In our application, the Multiguide steps are simulated by animations that trigger when the user enters the 15mm sphere around the SPG. When having the final evaluation, one suggestion that came up was to find some way to have the user perform the Multiguide input steps. One possible way to achieve this was to add some 3D printed structures to the Magic Leap controller and have some physical mechanisms that the user would trigger in-order to trigger the events in the application. Another way to achieve this could be to create a unique controller for the HMDs, imitating the Multiguide.

8.2.5 Porting the application to the Hologlass 2

Another thing that could be done is to port the application to the Hologlass 2, or other new AR HMDs, released in the future.

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A Appendix

A.1 Consent form

Taking part in the research project

” Immersive Technologies for Learning and Training ”

This is an inquiry about participation in a research project where the main purpose is to explore the potentials and limitations of Immersive Technologies (virtual/mixed/augmented reality, VR/MR/AR) for learning and training in different areas, as a part of master student projects at Innovative Technologies for Learning (IMTEL) VR lab. To conduct this research, we will need to investigate the development and use of immersive technologies for learning and training in various contexts, including learning of language and mathematics, visualization of climate change, immersive exploration of historical manuscripts, workplace training and visualization of medical procedures. In this letter we will give you information about the purpose of the project and what your participation will involve.

Purpose of the project

To conduct this research, we will need to analyze the use immersive technologies for learning and training in various contexts, including learning of language and mathematics, visualization of climate change, immersive exploration of historical manuscripts, workplace training and visualization of medical procedures. The goal is to develop innovative learning methods and tools using immersive technologies.

Who is responsible for the research project?

NTNU, Department of Education and Lifelong learning is the institution responsible for the project.

Why are you being asked to participate?

You are asked to participate because you are a potential user of educational applications developed as a part of this project and have visited our lab/expressed interest in immersive technologies. Your feedback is important for develop innovative learning methods and tools.

What does participation involve for you?

You will be ask to test immersive applications for learning and training purposes and then give feedbacks in the form of questionnaires and interviews/group interviews.

Participation is voluntary

Participation in the project is voluntary. If you chose to participate, you can withdraw your consent at any time without giving a reason. All information about you will then be made anonymous. There will be no negative consequences for you if you chose not to participate or later decide to withdraw.

Your personal privacy – how we will store and use your personal data

We will only use your personal data for the purpose(s) specified in this information letter. We will process your personal data confidentially and in accordance with data protection legislation (the General Data Protection Regulation and Personal Data Act). Any data that can be traced to individual participants will be kept confidential and anonymized before being used for research purposes. Parts of the sound recordings will be transcribed (written down) and stored electronically. All source data will be handled and stored in accordance with the existing regulations by NTNU as the responsible institution and only persons associated with the project (IMTEL VR lab research personnel and master students) will have access to them.

What will happen to your personal data at the end of the research project?

The project is scheduled to end 31.12.2019. All data will be anonymized at the end of the project, e.g. audio and video will be deleted when transcripts and analysis of data are completed, except for selected video and photo material to be used for research purpose. These and anonymized recordings from the inside of the virtual environments may be used for demonstrations in research context in such a way that no information will be linked to individuals. Scientific reports and presentations from this study might contain recordings from the VR/MR/AR sessions, questionnaire results, anonymized photos/videos from the sessions and anonymized citations from the interviews.

Your rights

So long as you can be identified in the collected data, you have the right to:

- access the personal data that is being processed about you
- request that your personal data is deleted
- request that incorrect personal data about you is corrected/rectified
- receive a copy of your personal data (data portability), and
- send a complaint to the Data Protection Officer or The Norwegian Data Protection Authority regarding the processing of your personal data

What gives us the right to process your personal data?

We will process your personal data based on your consent.

Based on an agreement with NTNU, NSD – The Norwegian Centre for Research Data AS has assessed that the processing of personal data in this project is in accordance with data protection legislation.

Where can I find out more?

If you have questions about the project, or want to exercise your rights, contact:

- Ekaterina Prasolova-Førland (Department of Education and Lifelong Learning, NTNU)
- phone: +47 99 44 08 61, email: ekaterip@ntnu.no
- NSD – The Norwegian Centre for Research Data AS, by email: (personvertjenester@nsd.no) or by telephone: +47 55 58 21 17.

Consent form

I have received and understood information about the project **Immersive Technologies for Learning and Training** and have been given the opportunity to ask questions. I hereby declare my consent that my data in relation to Immersive Technologies for Learning and Training may be stored, documented and used for research and educational purposes as described above. I give consent for my personal data to be processed until the end date of the project, approx. 31.12.2019

(Signed by participant, date)

