Asbjørn Fiksdal Kallestad and Maria Lande

Use of Augmented Reality to Enhance Learning and Collaboration for Students in Neuroscience

Master's thesis in Computer Science
Supervisor: Gabriel Kiss
Co-supervisor: Ekaterina Prasolova-Førland
June 2023

Master's thesis

NTNU
Norwegian University of Science and Technology
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Preface

With this Master's thesis, our five-year journey as computer science students end. This thesis marks our finishing project at Norwegian Science and Technology University. It has been a time filled with joy, struggle, ups and downs.

Working with augmented reality and HoloLens was a new experience for us. Through this project, we experienced a steep learning curve. The process has been time-consuming, but in the end, we acquired a new skill set within the field of augmented reality development. We feel honoured to be able to take part in a up-and-coming technology, and we can't wait to discover what the future might hold for AR. After reading this thesis, we hope you are just as excited as we are.

This section of the thesis may be the first you read, but for us, it was the last; before leaving the halls of campus for the last time. In a way, we are left feeling wistful; eighteen years of school suddenly comes to an end. However, we are ready to embark on new challenges and all the exciting adventures we may be part of.

"*Computers themselves, and software yet to be developed, will revolutionize the way we learn.*" - Steve Jobs

Acknowledgement

We thank our Supervisors Gabriel Kiss and Ekaterina Prasolova-Førland for their support and guidance throughout this master's thesis. We would also like to thank Mikhail Fominykh for the informative Lectures about academic writing he held for the master student writing for IMTEL. It was a huge help.

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Your support made this project a thrilling learning experience. Thank you.

Abstract

This thesis presents the design and development of an educational Augmented Reality (AR) application on a Head Mounted Display (HMD) for collaborative anatomy learning. The primary objective of this research was to investigate how the application could facilitate both remote and collocated Collaborative learning (CL). The study focused on implementing various features to enhance user collaboration, engagement, and communication.

Throughout the research process, several features were incorporated into the application. This included finger tracking, gestures, avatar representation, chat functionality, Azure spatial anchor, and machine learning. Finger tracking allowed users to point at specific anatomical structures, facilitating remote collaboration. Gestures, such as waving, thumbs-up, and thumbs-down, provided expressive communication options for users to engage with one another. The user avatar contributes to a stronger sense of working together. The chat functionality was a helpful tool for note-taking during sessions, although limitations of the HoloLens keyboard were acknowledged. Text chat was suggested as an alternative for more effective communication, particularly in noisy environments.

The Azure spatial anchor is a good feature to improve presence in an AR application. Machine Learning (ML) techniques were also found to work on HoloLens and achieve high prediction accuracy, although inference times were slower than traditional computer setups. ML ran only on a bare-bone application, not a complex system like Nevrolens. Optimisation of ML models, including exploring alternative backbone architectures, was recommended for improved performance on the HoloLens.

The project's findings indicate that integrating collaborative features, interaction techniques, and communication functionalities into the AR application has positively impacted engagement and communication. This might contribute to enhanced learning.

Sammendrag

Denne avhandlingen presenterer design og utvikling av en utdanningsrettet "utvidet virkelighet" applikasjon, på en hodemontert skjerm, for samarbeidsbasert læring av anatomi. Hovedmålet med denne forskningen var å undersøke hvordan applikasjonen kunne legge til rette for både fjern- og samlokaliserte samarbeidslæring. Studien fokuserte på implementering av ulike funksjoner for å forbedre brukernes samarbeid, engasjement og kommunikasjon.

Gjennom forskningsprosessen ble det inkorporerte flere funksjoner i applikasjonen. Dette inkluderte fingertracking, gestikulering, avatar representasjon, chat funksjonalitet, Azure Spatial Anchor og maskinlæring. Fingertracking tillot brukere å peke på spesifikke anatomiske strukturer, noe som muliggjorde fjernsamarbeid. Gestikulering, som vinking, tommel opp og tommel ned, ga uttrykksfulle kommunikasjonsalternativer. Brukeravatar bidrar til en sterkere følelse av samarbeid. Chat-funksjonaliteten var et nyttig verktøy for notater under øktene, selv om begrensninger med HoloLens-tastaturet ble erkjent. Tekstchat ble foreslått som et alternativ for mer effektiv kommunikasjon, spesielt i støyende omgivelser.

Azure Spatial Anchor fungerte bra som en funksjon for å forbedre tilstedeværelsen i en "utvidet virkelighet" applikasjon. Maskinlæringsteknikker ble også funnet å fungere på HoloLens, med en høy prediksjonsnøyaktighet, selv om prediksjonstiden var lengre enn på en tradisjonelt datamaskin. Maskinlæring kjørte bare på en grunnleggende applikasjon, ikke et komplekst system som Nevrolens. Optimalisering av Maskinlæringsmodeller, inkludert utforsking av alternative arkitekturer, ble anbefalt for forbedret ytelse på HoloLens.

Prosjektets funn indikerer at integrering av funksjoner for samarbeid, teknikker for interaksjon og funksjoner for kommunikasjon har hatt en positiv innvirkning på engasjement og kommunikasjon i den utvidet virkelighet applikasjonen. Brukt i utdanning vil dette kunne føre til bedre læring.

Contents

Figures

Tables

Acronyms

2D Two dimensional. 9, 12, 21, 38, 47

3D Three dimensional. xv, 1, 5, 8–13, 15, 19–21, 38, 47

AI Artificial Intelligence. 11

AR Augmented Reality. vii, xi, xv, 1–3, 5–19, 21–23, 26, 29, 32, 39, 66, 67, 71–78

CL Collaborative learning. vii, xi, 2, 3, 14–19, 23, 24, 26, 32, 41, 67–69, 71, 73, 78

CSCL Computer-supported collaborative learning. 14, 16

CT Computer Tomography. 19, 20

FR Functional requirements. xvii, 41, 42, 48

HD Handheld Display. 7

HMD Head Mounted Display. vii, 2, 3, 5, 7, 8, 10, 18, 22, 39, 66, 73, 77, 78

IBL Inquiry-based learning. 12

IT Information Technology. 31

ML Machine Learning. vii, xiii, 40, 49, 53, 57, 58, 69, 70, 79

MR Mixed Reality. 6, 15, 18, 39

MRI Magnetic Resonance Imaging. 21

MRTK 2 Mixed Reality Toolkit 2. xii, 39, 44, 45

NFR Non-Functional Requirements. 41–43

RQ Research questions. xi, xvii, 2, 3, 66, 69, 73, 74

SD Spatial Display. 7

SUS System Usability Scale. xiii, xv, xvii, 33–36, 62, 63, 70–72

UI User Interface. 23, 34, 61

VoIP Voice over Internet Protocol. 40

VR Virtual Reality. 5, 9, 11, 12, 15, 18, 78

WebAR Web-based Augmented Reality. 11

Glossary

Android Android OS is a Linux-based mobile operating system that primarily runs on smartphones and tablets. 22, 24, 43, 56, 77

API API stands for Application Programming Interface. An API is a set of programming code that enables data transmission between one software product and another. 38, 39, 57

CPU Central Processing Unit (CPU), the principal part of any digital computer system, generally composed of the main memory, control unit, and arithmetic-logic unit. It constitutes the physical heart of the entire computer system; it is linked various peripheral equipment, including input/output devices and auxiliary storage units. In modern computers, the CPU is contained on an integrated circuit chip called a microprocessor. (Britannica) . 7, 8, 39

Cross-platform In computing, cross-platform software (also called multi-platform software, platform-agnostic software, or platform-independent software) is computer software that is designed to work in several computing platforms. (Wikipedia). 24

FDA The Food and Drug Administration (FDA) protects public health by assuring the safety, efficacy, and security of human and veterinary drugs, biological products, medical devices, our nation's food supply, cosmetics, and products that emit radiation. 9

feature A feature is a unit of functionality of a software system (app) that satisfies a requirement, represents a design decision, and provides a potential configuration option[1]. xvii, 2, 3, 31

GPU Graphics Processing Unit (GPU) is a specialised electronic circuit designed to manipulate and alter memory to accelerate the creation of images in a frame buffer intended for output to a display device. GPUs are used in embedded systems, mobile phones, personal computers, workstations, and game consoles. (Wikipedia) . 39

hyperparameter optimisation In machine learning, hyperparameter optimisation or tuning is the problem of choosing a set of optimal hyperparameters for a learning algorithm. A hyperparameter is a parameter whose value is used to control the learning process (Wikipedia). 70, 77

ImageNet ImageNet is an image database organized according to the WordNet hierarchy, in which each node of the hierarchy is depicted by hundreds and thousands of images. The project has been instrumental in advancing computer vision and deep learning research. The data is available for free to researchers for non-commercial use. 39, 40, 49, 70

IMTEL Innovative Immersive Technologies for Learning. IMTEL research group researches innovative immersive technologies for learning in several contexts, ranging from university education to emergency and medical training and workplace training. IMTEL is located at NTNU. 24, 40, 50

inference time Inference time is the time it takes for a machine learning model to make a prediction on new data. xvi, 58, 60, 70, 77, 79

iOS iOS, an acronym for iPhone Operating System, is a Unix-derived operating system powering all of Apple's mobile devices. The name iOS was not officially applied to the software until 2008, when Apple released the iPhone software development kit, enabling any app makers to create applications for the platform. 24, 43, 77

iPEAR Inclusive Peer to Peer Learning with Augmented Reality. The iPEAR project combines collaborative expertise of technology-enhanced learning researchers, computer scientists, and educators to build a strategic partnership to streamline the adoption of Augmented Reality (AR) technology in educational practice. [2] IMTEL is a part of iPEAR project. 18

Machine learning Machine learning enables a machine to automatically learn from data, improve performance from experiences, and predict things without being explicitly programmed. xvi, 53, 59, 60, 77

mirror Mirror is a system for building multiplayer capabilities for Unity games. It is built on top of the lower level transport real-time communication layer. Mirror is focused on ease of use and iterative development and provides useful functionality for multiplayer games. 29, 40, 44

MoSCoW MoSCoW prioritisation, also known as the MoSCoW method or MoSCoW analysis, is a popular prioritisation technique for managing requirements. The acronym MoSCoW represents four categories of initiatives: must-have, should-have, could-have, won't-have, or will not have right now. Some companies also use the "W" in MoSCoW to mean "wish" [3] . 23, 41

NPS NPS stands for Net Promoter Score, a metric used in customer experience programs. NPS measures the loyalty of customers to a company. NPS scores are measured with a single-question survey and reported with a number ranging from -100 to +100. A higher score is desirable. xv, 36

NTNU Norwegian University of Science and Technology. 24, 26, 40

OpenXR OpenXR is an open-source, royalty-free standard for access to virtual reality and augmented reality platforms and devices. It is developed by a working group managed by the Khronos Group consortium. 44, 69, 78

peer learning Peer learning is an education method that helps students solidify their knowledge by teaching each other.. 18, 74

PUN Photon Unity Networking (PUN) is a Unity package for multiplayer games. Flexible matchmaking gets your players into rooms where objects can be synchronised over the network. 23

RAM Random-access memory (RAM), main computer memory in which specific contents can be accessed (read or written) directly by the central processing unit in a very short time regardless of the sequence (and hence location) in which they were recorded. (Britannica). 7, 8

Chapter 1

Introduction

1.1 Motivation

Anatomy is traditionally taught using cadavers and performing dissection. This learning method enhances the student's understanding of anatomical structures and gives a 3D perspective of structures [4]. There has, however, been a reduction in the traditional, cadaver-based anatomy teaching, with some anatomy courses not providing it at all [5, 6]. The reason being it is costly, time-consuming, and raises some ethical issues concerning the use of cadavers. This, alongside an increase in the medical curriculum, has led to dedicated research to provide alternative teaching methods that provide engaging and interactive learning based on state-of-the-art technologies [7].

One such technology is Augmented Reality (AR) which has shown promise as a learning tool for anatomy. Several applications using AR to teach anatomy have already been created and tested. Some of these will be presented in this report. These AR-based applications allow the user to see virtual objects in a physical space, which allows for more realistic experiences in medical learning situations. Studies have shown that AR-based anatomy learning tools increase engagement, have a positive impact on motivation, and increase the student's spatial understanding and 3D comprehension of anatomical structures [8–10]. The studies of AR anatomy learning applications also found no significant difference in how well the students learned using an AR application versus the traditional learning methods. It is important to note that an anatomy AR application is intended to supplement the current solution rather than replace it, where, especially dissection, is irreplaceable due to the physical feedback. [7, 10, 11]

Online classes and remote collaboration have become increasingly prominent in recent years. The most common format is online video meetings and lectures. This format of teaching does not support an in-person teaching method like dissection. Alternative methods that still provide the students with benefits similar to dissection would be beneficial for teaching anatomy. AR applications made for mobile phones could provide this and be an accessible tool for students to use for self-study. Such a tool would benefit from a collaborative feature that allows for a visual aid in an online lecture and a collaborative study tool for students.

Collaborative learning (CL) has been shown to improve engagement, dedication, and overall knowledge compared to self-study [8]. Facilitating collaboration by researching what collaborative features to implement in AR solutions has great potential for AR applications for anatomy learning [7, 10–12]. There is still a need for AR technology research and further improvements to make it a good tool in the educational sector. Most of the AR applications presented in the literature for anatomical studies lack or have limited collaborative functionality, especially for remote collaboration. The motivation of this research project is to research these shortcomings further.

1.2 Purpose

The purpose and goal of this project are to gather insight into the state of Collaborative learning (CL) in AR, the state of the Nevrolens application and the previous work on this application. Then use the acquired insight and knowledge to identify what features should be implemented and evaluated in a collaborative AR application for collocated and remote anatomy learning.

This research project is a continuation of the research and development performed in the master thesis of Ravna (2021) [13] and Haugum and Woldseth (2022) [14]. Their work identified and implemented several features that support CL in an educational AR anatomy application. This research project will continue with the primary focus being to improve communication and interaction between the collaborators by identifying and implementing features that support this. In Haugum and Woldseth's thesis, they also concluded that there was a lack of testing of the implemented features, so these will be tested further.

1.3 Research questions

The current authors defined the Research questions (RQ) based on motivation, literature and the pre-study (See Specialisation project in section 2.7). The RQ has three sub-questions that will help to answer the main RQ. The sub-questions are numbered 1-3. This project will attempt to answer these questions and acquire helpful insight.

RQ: How can the design of an educational AR application on a Head Mounted Display (HMD) be optimised to enhance collocated and remote Collaborative learning (CL) experiences in the field of anatomy?

- RQ1: What collaborative features should be implemented to enhance the learning of anatomy?
- RQ2: What interaction and communication features should be incorporated to increase engagement in the educational AR application?
- RQ3: What interaction and communication features should be integrated to facilitate effective user communication in the educational AR application?

1.4 Contribution

This project contributes to CL by introducing various features for an AR application. The project's primary objective is to thoroughly assess the impact of these features on user collaboration and evaluate the effectiveness of using an HMD-AR headset for CL in neuroscience anatomy.

To achieve these goals, testing and evaluation were conducted to gauge the positive impact of the implemented features on CL. By carefully analysing user feedback and observations, the project aims to provide valuable insights into the efficacy of the developed features in fostering collaboration among users.

A video showcasing the application has been created to visually demonstrate the newly implemented features. This video serves as a comprehensive overview, emphasising the notable advancements made in this project.

Table 1.1: Click the link below to see this video of the new features

Link to video:	`https://clipchamp.com/watch/JA7Qx4NSqnd`

By combining theoretical knowledge and practical implementation, this research project contributes to advancing CL in the context of neuroscience. The findings and outcomes of this study pave the way for future developments in the field, enabling educators and learners to leverage AR and collaborative tools for enhanced educational experiences.

Chapter 2

Background

2.1 Augmented Reality

Augmented Reality (AR) overlays digital information onto the real-world environment to enhance user experience. This should not be confused with Virtual Reality (VR) where the user is completely immersed in the digital world. AR combines reality and digital information.

AR has convenient features for educational purposes. One of them is the ability to visualise virtual 3D objects that the user can interact with. The ability to visualise virtual 3D objects can help students better comprehend the composition of the visualised objects. AR can also allow users to collaborate and interact with the same virtual objects, which gives the students flexibility for learning a subject. Since AR can be used to visualise an object, AR can also contribute to reducing cognitive load in learning [15].

AR is not a new invention. Fighter planes used AR during World War II to display radar images on their windshield to guide the pilot [15]. Today cars can be equipped with a head-up display with AR. The display projects information for the driver, such as; the car's speed and detected traffic signs, navigation instructions and information from the assistance systems displayed in clear view for the driver. Directional arrows from the navigation system can be displayed and virtually projected onto the road up ahead [16].

Julie Carmigniani et al. published the article; "Augmented reality technologies, systems, and applications" in 2011 [17]. They point out that AR does not have to be restricted to visual information displayed at an Head Mounted Display (HMD) nor limited to the sense of sight. AR can apply to all senses, augmenting smell, touch and hearing.

Milgram and Kishino published their paper "A Taxonomy of Mixed Reality Visual Display", where they introduce the reality-virtuality continuum fig: 2.1 and the term Mixed Reality (MR) [18] [19].

Skarbez et al. [20] revisited this view on how to look at the continuum of real and virtual environments. They argue that today there are more dimensions to real and virtual than only one line. They argue that the Milgram and Kishino continuum is continuous. Hence, perfect virtuality cannot be reached. Secondly, they point out that MR is broader than previously believed and encompasses conventional virtual reality experiences. They presented their revisited reality-virtuality continuum as seen in figure 2.1. The addition to the original figure by Milgram and Kishino is the "Matrix-like" Virtual Environment.

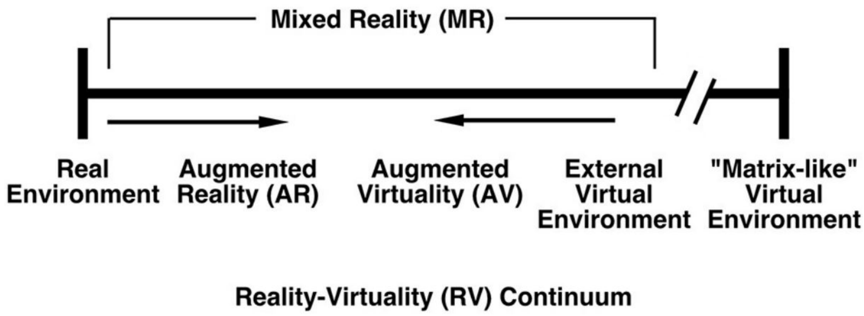


Figure 2.1: Skarbez et al. Revisited reality-virtuality continuum [20]

Qiao et al. [21] published an article about Web-based AR for mobile AR in 2019. They nicely present the history of mobile AR in the way it's known today. The historical evolution of AR is shown in figure 2.2.

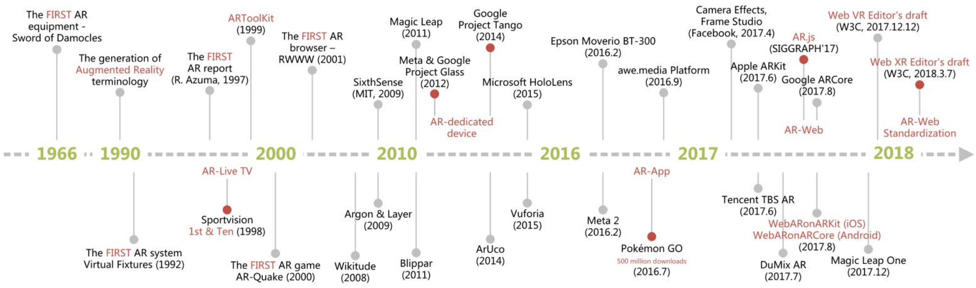


Figure 2.2: Historical evolution of AR (from Qiao et al. [21]

The article emphasises that in the years, technological advances have fuelled the research and development of AR. The core technologies are dedicated AR devices (e.g. Google Glass, Microsoft Hololens, Epson Moverio BT-300, Magic Leap, and XYZ ATOM), powerful development kits (e.g. ARCore and ARKit), improvements in the performance of mobile devices and sensor integration, and advances in computer vision technologies.

The four things all AR systems have in common are a display, input devices, tracking, and computers [17].

Display

There are three types of displays: Head Mounted Display (HMD), Handheld Display (HD) and Spatial Display (SD).

HMD is a display worn on the head or as part of a helmet and places both images of the real and virtual environment over the user's view. HMD can either be video-see-through or optical see-through. Examples of optical see-through are Microsoft HoloLens [22] and XYZ ATOM [23], while Varjo XR-3 [24] is an example of a video-see-through device.

HD are typically smartphones or tablets. They use video-see-through techniques to overlay graphics onto the real environment and employ sensors.

SD uses video projectors, optical elements, and holograms to display graphical information directly onto physical objects.

Input device

Many input devices exist, such as gloves, wristbands, pointers, hand gestures, gaze interaction, and speech recognition. In the case of a mobile phone, the phone itself can be a pointer and accept input through a touch screen or speech.

Tracking

Tracking devices are needed to put the displayed information into the correct coordinate system. A range of technologies can help to track where you are located in the real world and display the wanted information in the correct position.

Tracking devices include digital cameras, optical sensors, GPS, accelerometers, solid-state compasses, wireless sensors, mechanical devices, and more. These systems can provide different ranges, resolutions, and accuracy. GPS will give you unlimited range, but the accuracy will be within meters, while optical systems will limit the range it can provide millimetre accuracy.

Swensen [25] describe and exemplify this by dividing it into marker-less or marker-based categories. Pokémon Go is an example of marker-less since it uses GPS data to identify users' locations. Marker-based AR relies on visual markers like QR codes. This can also be called location-based and image-based AR.

Computers

AR systems require a powerful CPU and large RAM to process camera images. In 2010 they still needed a laptop in backpack configuration, while today, smartphones and tablets can offer the CPU and RAM capacity to run sophisticated AR applications.

2.2 AR in different fields

Cardoso et al. [26] published a paper in 2020 where they looked at AR within the industry. They argue that AR is a viable tool and opportunity within the fourth industrial revolution.

According to the world economic forum, the fourth industrial revolution is the cyber-physical systems evolving exponentially rather than at a linear pace. In the web article from 2016 [27], Klaus Schwab put it this way:

> “The possibilities of billions of people connected by mobile devices, with unprecedented processing power, storage capacity, and access to knowledge, are unlimited. And these possibilities will be multiplied by emerging technology breakthroughs in fields such as artificial intelligence, robotics, the Internet of Things, autonomous vehicles, 3-D printing, nanotechnology, biotechnology, materials science, energy storage, and quantum computing.”

AR technology has already been applied in many fields, including tourism, archaeology, art, commerce, industrial manufacturing, construction and restoration, education, emergency management, entertainment and leisure, medical treatment, and military operations.

In commerce, AR is developed as a decision-making tool for mobile devices. You don’t need to visit the stores to have a representation of the gods. IKEA is an example of this. You can see how furniture would look in your home without leaving the house.

Within the industry, there are many areas where real-time visual information will increase productivity. Boeing explored this already at the beginning of 90’. They created the prototype of an AR system for helping workers assemble wires and cable for an aircraft [17]. Today, there have been commercialised AR systems for the building industry with portable HMD integrated in helmets for construction teams. XYZ™ Reality market their Atom system as an engineering grad AR with millimetre-accurate AR for construction [23]. With the Atom, construction teams can view and position holograms of 3D design models to millimetre accuracy onsite. See picture 2.3.

Figure 2.3: Illustration of XYZ AR system to project 3D models onsite. [23]

In medicine, AR and VR has been developed into valuable help for especially surgeons. AR technology enables projecting 3D images or other patient information while conducting real-time surgery. This way, the doctors do not have to remove the sight from the patient and look at 2D preoperative images displayed on 2D monitors while conducting the procedure [28].

There has been an exponential growth in research articles about AR in surgery in the last few years. Barcali et al. [28] analyse the application of AR in medicine and which of its technical solutions are the most used. They reviewed articles from 2019 to 2022. AR has mainly been used in orthopaedics, maxillofacial surgery and oncology. They found that Microsoft HoloLens is the most used display device. For tracking and registration, the marker-based method remains the most used system. They conclude that AR is an innovative technology with numerous advantages, finding applications in several new surgery domains.

One example is Novared. The company was the first to receive FDA clearance for their AR surgical system using Microsoft HoloLens [29]. The system uses optical code alignment (markers), cameras, and sensors, to map both the patient and the surrounding environment from above, to the side, behind, or even underneath the patient. Figure 2.4 illustrate how it looks for the surgeon.

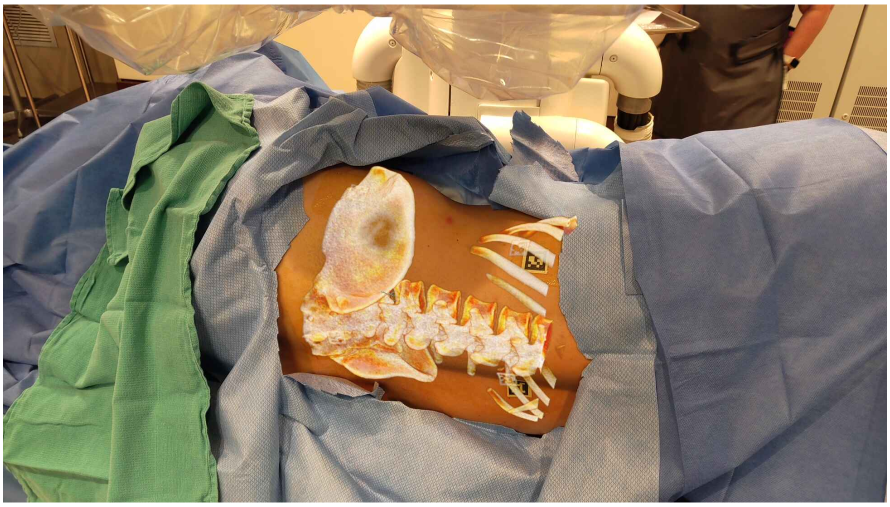


Figure 2.4: HoloLens used by OpenSight system from Novared to visualise the spinal cord on a patient during surgery. Note the markers attached to the skin for alignment of the virtual structure. [29]

2.3 AR in Education

AR has opportunities to be used both for education and training purposes. This section will describe the use of AR in education and the benefit of training on 3D models. Then a brief description of the history, but mainly the advantages of AR and the exponential growth of research papers related to AR.

Juan Garzon published in 2021 a review article in which he gave an overview of 25 years of AR in education [29]. The first AR system to be used in educational settings was a tool for teaching three-dimensional anatomy. This AR system used a HMD to visualise human bone structures. The AR system was demonstrated at the first international conference on computer vision, virtual reality, and medical robotics in 1995.

Since then, AR has been explored and implemented in various educational fields. Garzon divides the period of AR in education into three generations illustrated in figure 2.5

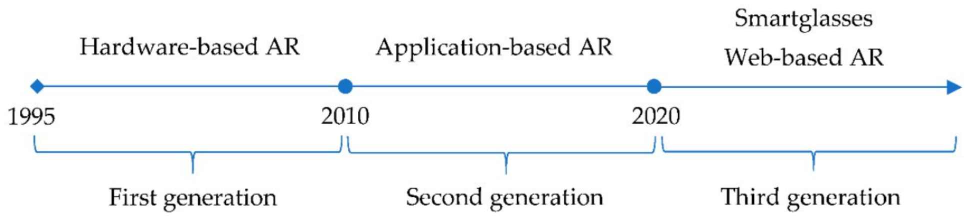


Figure 2.5: Three generations of AR in education.

The characteristics of the first generation are the expensive and complex AR systems. These systems were intended to teach subjects related to health, natural sciences, or engineering at the bachelor level. Limitations for first-generation AR were high cost and usability.

Billinghurst [30] described already in 2002 the possibilities and limitations of AR in education. It was pointed out that the opportunity lies in the seamless interaction between reality and virtuality. However, there was not much research on the real impact of learning by using AR. Motivation for students was one of the few things mentioned as an effect on learning by Dunleavy et al. in 2009 [31].

The second generation of AR, as Garzon [29] describes it, is the availability through mobile devices and the emergence of game engines. Development of AR applications becomes more manageable and available.

The third generation, according to Garzon [29], is characterised by the introduction of available smart glasses (HoloLens (AR), Oculus Rift (VR)), Web-based Augmented Reality (WebAR), and Artificial Intelligence (AI). The benefit of WebAR are that the users do not have to install specific applications on their portable devices, but access the features through web and cloud servers, made possible due to high-speed internet access through 5G technology. Thirdly AI will fuel AR to become even more realistic and provide more powerful customisation of applications.

2.3.1 Benefits of AR in education

Several studies have been conducted to reveal the benefit of implementing AR in education beyond the effect on motivation caused by curiosity and excitement of testing new “gadgets”. Chang et al. [32] published in 2022 a meta-analysis of experimental studies from 2012 to 2021 to investigate the impact of AR in education. They looked mainly at publications comparing AR with Non-AR instructions in education. Their main conclusion was that AR shows, on average, a medium effect on learning experience, a medium to a large effect on enhancing knowledge and skill, and a nearly large effect on facilitating students’ authentic performance.

One of the most used benefit of AR is to educate on 3D structures. Whenever you need to communicate 3D designs, AR technology can help to visualise this and replace the need for physical objects. Within anatomy studies, there is a need to understand how anatomical structures interact and are placed in a three-dimensional space. It is likely not by coincidence that the first educational use of AR was in the field of anatomy back in 1995 [29].

Swensen [25] presented in 2016 a conference paper describing the potential for AR in science education. In his paper, he looked at parameters that could positively affect learning outcomes in STEM education (STEM; Science, Technology, Engineering and Mathematics). He discussed four parameters; (1) Cognitive effort, (2) Motivation, (3) Situated learning, and (4) Inquiry-based learning.

By implementing AR, the cognitive effort to understand the structures will be reduced. The cognitive effort will be reduced because humans do not have to process 2D images into 3D structures in their brains, but instead get them visualised in front of them. This can also help in mathematics and physics when studying 3D graphics, as presented by Xie et al. [33]. Millais et al. [34] compared 2D to 3D visualisation of data and found that accuracy and depth of insight increased when using 3D in VR to study the data.

Peoples ability to visualise 3D structures varies, which could be a reason some people find IKEA drawings challenging to use as a guide for assembling furniture. AR can be a tool to visualise the steps in the assembling process directly when you are working with the pieces, making it unnecessary to read and interpret a 2D representation.

Motivation to learn and study can be increased with the help of AR by visualising problems and solutions in 3D. Motivation can also be increased through collaborating with other students.

Situated learning is about a sense of presence, immersion, cooperation, interaction and location. Swensen [25] found several articles mentioning the value of learning happening in an authentic context. This could lead to both increased commitment and deeper understanding.

The fourth parameter presented by Swensen was Inquiry-based learning (IBL). In contrast to deductive learning, IBL is a way to act upon students' curiosity and interest in the subject. Studies using AR in IBL have achieved better results than traditional IBL [25]. This can be explained by students being less exposed to cognitive overload when relevant information is presented in the right place at the right time during their studies.

Bölek et al. [35] conducted a systematic review and meta-analysis on the effectiveness of AR in anatomy education. Historically anatomical studies have been carried out by the use of cadavers, anatomical models and drawings in textbooks. The use of AR in anatomical education has been promoted by numerous authors, who point out the financial and ethical advantages besides the decrease in cognitive load and the students increased motivation and engagement.

From the screening of 571 publications, they focused on five studies where AR was compared with another form of anatomical learning. From this limited amount of studies, they could not find significant differences in test scores between the AR group and the control group. They did not find a significant correlation between the mean difference in test results and spatial abilities. They concluded that the studies showed insufficient evidence to state that AR significantly impacts learning outcomes or spatial skills compared to traditional learning methods.

Yammine and Violato [36] published a meta-analysis in 2014 to review the effectiveness of 3D visualisation technology in teaching and learning anatomy compared to all teaching methods. They found that 3D visualisation technology resulted in higher factual knowledge, yielded significantly better results in spatial knowledge acquisition, and produced a significant increase in user satisfaction besides the learner's perception of the effectiveness of the learning tool.

Undoubtedly, there has been exponential growth in educational publications related to AR. Garzon [29] present a search in the Web of Science database for AR in education that resulted in 2698 studies. Figure 2.6 show the exponential growth of such studies from 1996 to 2019.

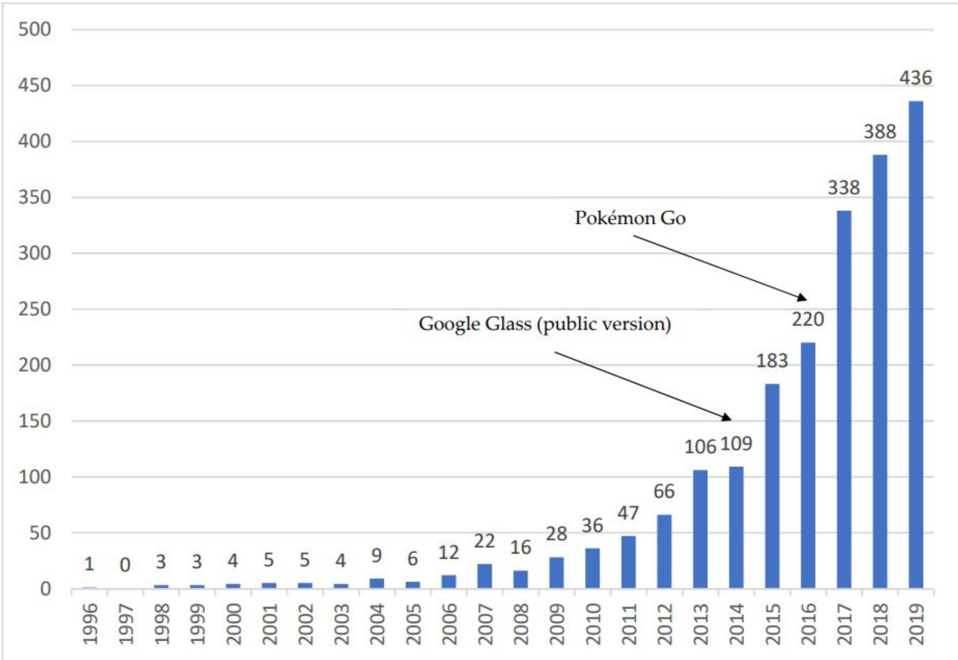


Figure 2.6: Number of studies of AR in education per year in WoS.

Even though there are different perspectives on what is the effect and benefits of AR in education, an article by Radu [37] in 2014 describes the following five learning benefits from AR:

- **Increased content understanding.** This is where the topic contains spatial understanding, for instance, geometrical shape, chemical structures, mechanical machinery, astronomy configuration or human organs.
- **Long-term memory retention.** Some studies have shown that content learned by AR experience is memorised more powerfully than through non-AR experiences.
- **Improved physical task performance.** Many studies have shown that AR is more effective than traditional media when users must train or perform

a physical task.

- **Improved collaboration.** AR makes it possible for students to observe and explore the same object, and this increases their collaboration.
- **Increased student motivation.** Motivation is fundamental for increased learning. Studies of AR in education often find that students express higher enthusiasm and report higher satisfaction, have more fun and are more willing to repeat the AR experience.

2.4 Collaborative learning

Laal and Laal presented Collaborative learning (CL) in a paper from 2012 where they define CL as an umbrella term for a variety of educational approaches involving joint intellectual effort from small group projects to the more specific form of group work known as cooperative learning [38].

In other words, learners work together in groups to achieve common goals with their commitment to the group's success.

CL has been shown to give social, psychological, and academic benefits compared to learning environments that are individual or competitive. The CL must meet some conditions to achieve these benefits. Team members should depend on and interact with each other positively. The individual group members should also feel personally invested in achieving a common team goal. With these traits, a team has a healthy, collaborative environment that fosters effective and good learning [39].

When students work together, where one explains something while another listen, all parties gain valuable knowledge through the formulation of ideas, discussion, and immediate feedback on questions. Help can be personalised, which reduces the time individuals are stuck. Work can be overwhelming or boring in demanding tasks and lectures where students must do a lot of repetition. Collaboration could make this learning process more fun and interesting. Participants are less likely to drop out when they are in a group where they can rely upon and motivate each other [39].

The concept of CL has branched out to a research topic of Computer-supported collaborative learning (CSCL). CSCL provides access to technologies supporting CL in face-to-face and distributed settings.

Jeong et al. [40] published a meta-analysis of ten years of CSCL in STEM education for 2005-2014. They state that CSCL is built on the premise that collaborative knowledge construction and problem-solving can effectively be assisted by technology. 143 studies were included, and from these, they grouped technology into six groups: Communication technologies, Dynamic technologies, Sharing and co-construction tools, Systems or environments, Hardware, and Miscellaneous software and hardware. The group of dynamic technologies contains; simulations, games, and immersive technologies (AR/VR). With statistical analysis, they found the size effect (small, moderate, or large) of the different applied technologies. Within all investigated technologies, they found that simulations gave the most positive impact, rated as a large effect. In contrast, the integrated environment was rated as medium effect and immersive technologies were rated as a small effect.

Joeng et al. performed their analysis based on research papers from 2005-2014, with limited access to AR. This can explain the lower score for immersive technologies regarding the effect on learning.

Bork et al. [10] studied more specifically the effect of collaborative AR in gross anatomy teaching and published their work in 2020. They believed that AR has the potential to serve as a complementary pedagogical tool for facilitating interactive learning. Until then, it was a lack of AR systems that enabled multiple students to engage in CL environments. Bork et al. tested their hypothesis by conducting a study where 16 first-year medical students were introduced to the VesARlius AR system for visualising anatomical structures. Bork et al. compared the results of anatomical knowledge between groups of students using anatomy atlases with students learning anatomy with the VesARlius system. The teaching time was 135 minutes for both groups. They conducted a pre-test and post-test for the two groups. They found a slightly better score for students using VesARlius. After the post-test, they swapped the learning method for both groups to experience the two methods of learning anatomy. Then they surveyed with statements for the students to rate on a scale from 0-20, completely disagree or agree.

They concluded that the VesARlius system significantly increased students' anatomy knowledge, even more than within the control group. Additionally, students highlighted other benefits, such as its potential for the 3D understanding of anatomy, increased engagement, fun, and motivation. Bork et al. state at the end of this article:

> "The results of this work provide supporting evidence that AR-based learning in teams has the potential to become an important, supplementary element in modern, multi-modal gross anatomy courses that follow the recent paradigm shift toward more active, student-centred and exploratory learning."

Baratz et al. [41] conducted a similar study as Bork et al. [10]. They evaluated student impressions of learning anatomy with MR and compared long-term information retention of female breast anatomy between students who learned with a mixed-reality supplement and their classmates who dissected cadavers. They used the HoloAnatomy [42] application developed for HoloLens in their study. They did not find a significant difference in score on the final exam, but a significant difference in long time memory when conducting a delayed post-quiz eight months later. Students using the MR system to supplement their initial learning had better long-term memory of knowledge. The results also suggested that MR facilitates teamwork more readily than a cadaver dissection. This supports the argument that technology can enhance and strengthen the advantages of CL.

The impression after going through some literature on CL and CSCL [43–45], is that CL has proven to be an effective pedagogical strategy for better learning. With the development and utilisation of digital technologies, the tools for interaction have vastly enhanced. Interactive AR technologies are one of these tools that are likely to be implemented in a wide range of topics on all levels, from primary school to universities.

2.4.1 Effective communication

> "Effective communication is the process of exchanging ideas, thoughts, opinions, knowledge, and data so that the message is received and understood with clarity and purpose. When communicating effectively, both the sender and receiver feel satisfied." [46]

Effective communication requires both the sender and receiver to have a shared understanding. The definition of communication is not an easy task, as mentioned by Betts [47], that Dance and Larson identified 126 definitions for communication back in 1976. Mc Quail and Windahl have studied communication for decades and published a book in 2015 [48] about communication models. Their general communication model implies a sender, a channel, a message, a receiver, a relationship between sender and receiver, an effect, and a context. This points to two processes, encoding and decoding. Analogue to cryptography where the sender and receiver must share a common encryption key to understand each other.

Betts [47] presents the Tubbs communication model. This model defines the types of messaging:

- **Verbal** - any spoken communication that uses one or more words.
- **Intentional verbal** - conscious attempts to communicate with others through speech.
- **Unintentional verbal** - the things said without meaning to.
- **Nonverbal** - all the messages transmitted without words or over and above the words used.
- **Intentional nonverbal messages** - the nonverbal messages wanted to transmit.
- **Unintentional nonverbal messages** - all those nonverbal aspects of human behaviour transmitted without their Control.

To obtain effective communication, it will be necessary to be aware of all types of messaging, primarily nonverbal. According to Dr Albert Mehrabian [49], the three elements of face-to-face communication are nonverbal (55%), tone (38%), and words (7%), where the percentage is the rated effect of the element in a communication setting. It might be more evident if thinking about inconsistency in our communication. Mehrabian points out in his book that inconsistency appears when expressing something verbally while our facial expressions, posture, tone of voice, or gesture say the opposite.

In other channels than face-to-face, people lack more and more nonverbal communication. However, Betts [47] refers to Fenman Ltd., a publisher of training resources, stating that within call centres, “tone” accounts for 86 % of the total communication, and words account for the remaining 14 %.

Even in text messages, people communicate nonverbal and with or without intention. How people use upper and lower case, bold, italic font, colours etc., will communicate something besides the words used.

There are a few things to be aware of and consider to gain effective communication. According to Krishna [50] and Team Goseeko [51], Francis J. Bergin [52] formulated the 7 c’s of effective communication. These principles apply both in verbal and written communication. The principles are:

- **Clarity** - Use clear and simple language. Clarity helps the receiver to understand the meaning.
- **Correct** - Correctness in grammar, spelling, and semantics, as well as correct words in the proper context. Likewise, facts and figures must be accurate.
- **Concise** - Brief and condensed messages with relevant information. Use as few words as possible to convey the message.
- **Concrete** - Concreteness implies being particular and clear rather than fuzzy and general. Avoid abstract statements and use concrete words to avoid misinterpretation.
- **Complete** - Completeness ensures that all necessary information the receiver needs or expects has been provided. Incomplete messages results in misunderstandings.
- **Consider** - Consider your audience, their viewpoint, knowledge, and education level.
- **Courteous** - Be open, friendly, and honest in your communication. Courtesy means sincerely respecting the receiver. Be sincerely polite, reasonable, reflective, and enthusiastic.

2.4.2 Collaborative learning in AR

Using collaboration to increase learning has showed to be efficient. It is a widely used method in education on all levels, from primary school to university.

AR technologies provide new options to enhance collaboration by visualising objects to be studied as described in 2.3.1. However, the AR environment will also give some restrains, especially in remote collaboration. To fully make use of the CL benefits, it is essential to have functionalities that mimic reality.

The key to effective collaboration is efficient communication. Being aware of how people are communicating is, therefore, essential. In remote locations, some nonverbal communication is difficult to fully implement, for instance, engagement, facial expressions, body language, eye gaze, and more.

In collocated collaborative sessions, nonverbal communication is more accessible than in remote locations. However, when the collaborators wear HMDs, some nonverbal communication is lost by restraining eye contact within the group.

Themeli and Prasolova-Førland [53] have published an article about "Inclusive Peer learning Pedagogy with Augmented Reality" (iPEAR). The article describes a pedagogical design focusing on peer learning and AR. The article is a part of the iPEAR project, where one of the aims is to develop AR tools for education. This EU-sponsored initiative emphasises the relevance of AR in CL. It confirms Bork et al. [10] prediction that AR will likely become an important supplementary element for efficient learning.

2.5 Related work

This section will present some relevant research on the needs for remote and collocated CL.

Additionally, an overview of other AR applications developed as educational tools for teaching anatomy and tools utilised for researching the impact of AR on learning will be provided. This overview aims to offer insights into the current landscape of AR applications in anatomy education and establish the context for the significance and novelty of the research conducted in this thesis.

2.5.1 Related research

Radu et al. [54] published a Survey of Needs and Features for Augmented Reality Collaborations in Collocated Spaces in 2021. This survey focused on papers related to VR, AR and MR systems where multiple users collaborate and where a minimum of one AR/VR headset were described. Thus, excluding systems developed solely for mobile or PC platforms.

They state that current literature does not systematically understand what features and needs have been considered for supporting collaboration in collocated AR experiences. Their research question was: “What needs and features should be considered for supporting collaboration in headset-based collocated AR experiences?”

Through their survey of 92 papers, they compiled a list of collaboration needs and a reference to each publication, giving examples of features that address those needs. They describe 18 needs, grouped into 7 groups. The numbers do not represent a prioritisation but are added for easier referencing to the individual categories.

Collaborators need to:

1. **Be aware of others' attention and activities** – Location, intention, emotions, synchronised tasks, show/hide layers, and access information on demand.
2. **Be aware of the past** – Remember actions and conversations.
3. **Coordinate attention** – Specify direction and objects of attention, and manipulate objects at the same time.
4. **Coordinate instructions** – Annotate objects and guide others.
5. **Privacy** – Personalised information and private space
6. **Manipulate virtual objects** – Move and modify virtual objects.
7. **Share the same environment** – Se the same virtual object and have a smooth networked experience.

Even though the survey focused on collocated collaboration, features developed for remote locations are also mentioned. Some of the needs can be challenging to address in remote locations. However, the need for optimal CL is the same.

2.5.2 Related AR Applications

In the work of Ravna, Haugum and Woldseth, presented in section 2.6, several AR applications for learning anatomy are presented. The most comprehensive list was found in Haugman and Woldseth [14].

AR applications used in education are experimental and complementary to traditional anatomy atlases. The motivation for developing these tools is to enhance the learning process. Some applications are meant for self-study and collocated collaborative work, while others are developed for remote locations as an extra option. The applications will also need to consider the education level, whether it is meant for introductory courses in first-year medical studies or higher classes where it is meant for complementary or replacement to cadaver dissection as a part of the study. The functionality and features built into the different applications are reflected by the intended use.

Three examples of AR applications for anatomical studies are presented. The applications have been used in research to investigate the effect of using them on learning outcomes. Some key functionality and features for collaboration are described.

VesARlius

The paper, "The Effectiveness of Collaborative Augmented Reality in Gross Anatomy Teaching: A Quantitative and Qualitative Pilot Study" [10], describes an AR application that allows medical students to engage in collaborative, team-based anatomy learning sessions. In the VesARlius application, the user can explore 3D models of the human body and display Computer Tomography (CT) above it, See

Figure 2.7. All the virtual organs were acquired from CT images using a combination of manual and semi-automatic segmentation. This results in a one-to-one correspondence between the CT images and the virtual 3D model. This allows the students to point at a specific point on one CT image, which will be highlighted in the corresponding virtual 3D model. VesARlius allows for the placement of individual content in a shared collaborative space, and this content is private for the student who placed it and can be altered without interfering with the other participants.

Specific features for collaboration between students in this application are:

- **Synchronised rooms** - the entire application state is synchronised in real-time.
- **Individual content placement** – individual positioning of virtual content. (it is not fixed in the room for all to see in the same place)
- **Laser pointer** –A small red circle displayed at the location where the gaze direction vector of the current active presenter intersects with a virtual object.
- **Coloured pins** –Users can place coloured pins on the 3D model and a list of all active pins, including the name of the associated anatomical structure.

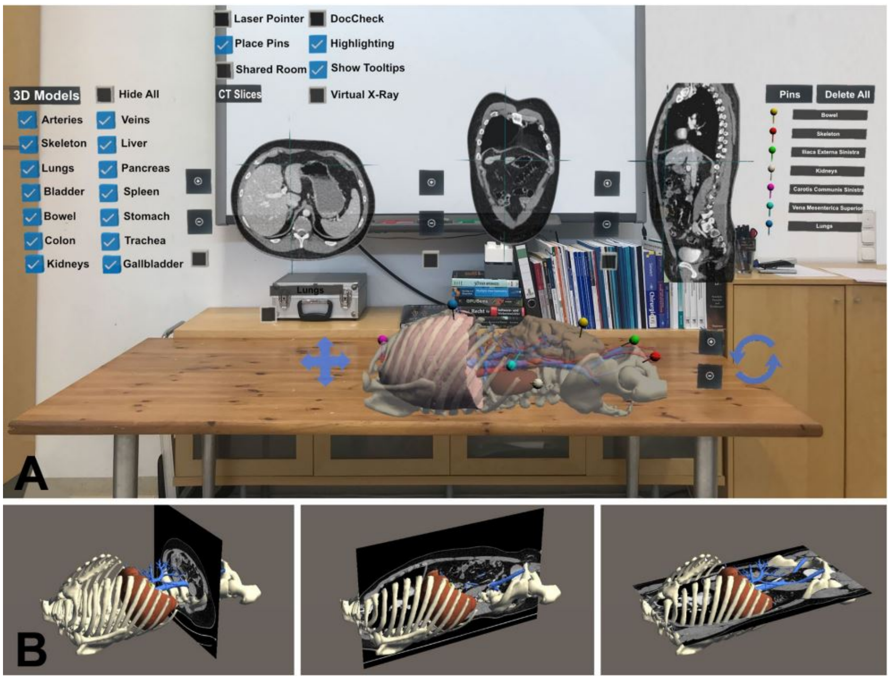


Figure 2.7: Overview of the VesARlius system. A) The different components of the VesARlius user interface; B) Computed tomography (CT) section images placed within the virtual 3D model. (From [10]

HoloBrain

HoloBrain is an AR teaching tool developed by The University of British Colombia. It is developed for the HoloLens device in collaboration with the Microsoft Garage Internship program. The HoloBrain uses 3D volumetric reconstructions from a Magnetic Resonance Imaging (MRI) scan. These scanned structures can be manipulated in the working space to fit the user's needs. Figure 2.8 shows that the HoloBrain application can visually compare 3D reconstructions and 2D MRI scans. [55] The collaboration is collocated, and all students wear HoloLens.

The HoloBrain project added functionality during the COVID-19 pandemic to record a lecture with HoloLens and broadcast them to students.

The project is ongoing (2023) and will be updated to HoloLens 2 and hence experience new ways to touch, grab and isolate brain structure. [55]

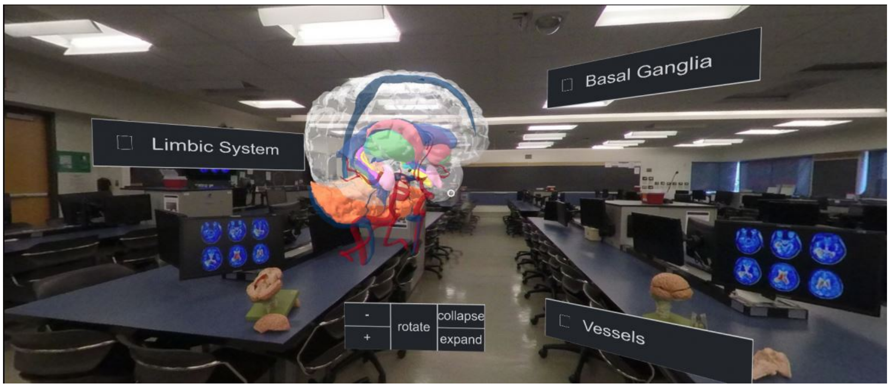


Figure 2.8: Picture from "inside" HoloBrain at a lab at the University of British Colombia. (From [55])

HoloAnatomy

Application developed for the education of human anatomy. It is both a teaching and collaborative tool. In addition to 3D representation of anatomy, the app offers some animation of organs (for example, beating heart, brain activity). The application also has a designer tool that allows the teacher to make slide shows for students to follow through their HoloLens headset. Haugman and Woldseth report that interactivity seems limited to changing between different views of the human body [14, 42]. The application can share a standard model for the teacher to use during a lecture or for the students to explore in their collaborative work, collocated and remotely.

Using traditional classroom Wi-Fi, the networking framework enables collaboration in classroom interactions for large and small groups.

Figure 2.9: Picture from “inside” HoloAnatomy. (From [42])

2.6 Previous work on the Nevrolens Application

The Nevrolens application has been developed by the Innovative Immersive Technologies for Learning laboratory (IMTEL) [56] and the Kavli Institute at the Norwegian University of Science and Technology (NTNU) in collaboration with the iPEAR project [53].

Ole V. Ravna conducts the first work [13] in his master’s thesis, "Towards Teaching Neuroanatomy in Collaborative Augmented Reality", and further developed by Haugum and Woldseth [14] in their master’s thesis, "Facilitating Different Approaches to Learning Anatomy in an Augmented Reality Environment".

The motivation for Ole V. Ravna presented in his thesis was to understand better how AR can support the teaching of neuroanatomy and dissection for medical students. He looked at how interaction should be implemented in AR to accommodate medical students and educators and how a collaborative experience shared between an HMD and a smartphone will accommodate medical users. The result was a new computer-based software application using AR with support for HoloLens 2 and Android devices. Ole V. Ravna developed the application’s core features, including the rat brain model and its interactive features, as well as setting up a lobby system allowing multiple parties to host collaborative sessions.

As previously argued in section 2.1 Augmented Reality, summarised by Ravna in his thesis, AR has shown great promise in communicating complex three-dimensional data and being a tool for CL in education.

For using the full potential of CL, the application should be suitable for both col-located and remote-located students and educators. Ravna addressed these three functional requirements:

1. Implement a brain dissection tool in AR.
2. The application must run in HoloLens 2 and at least on one mobile platform.
3. Implement cross-platform collaboration over the network.

Haugum and Woldseth conducted a research project building on the work of Ole V. Ravna and continuing the development of the Nevrolens application. Their research aimed to identify features facilitating different approaches to learning anatomy in an AR environment. Their work included implementing new features and updating the application's UI design. Their work also included implementing a voice chat in collaborative mode, following Ravna's recommendation about using Photon Voice for PUN2.

During the development work and later during the improvement work, both Ravna and Haugum and Woldseth used the research method, Design and Creation. The method uses interviews and demonstrations for data gathering and analysis to identify recommended features to improve, develop, and implement.

Recommendations from Ravna were to: (1) implement the ability to drop in a new model to avoid rebuilding and deploying the application for each model change, (2) Improve networking as the current version has some bugs and unexpected behaviour, (3) Voice chat will be needed for remote-location collaboration.

Haugum and Woldseth recognised a long list of functional requirements and prioritised them in four levels according to MoSCoW prioritising; (1) Must have, (2) Should have, (3) Could have, and (4) Won't have this time. They further implemented and improved on features they identified in their specialisation project and during the master project. Many were already implemented, and some were tested but needed improvements. They were left with four recommendations for further work; (1) Written chat, (2) Lessons with audio narration, (3) Fun Facts, and (4) Rules of thumb, where the last two can help memorise names and functionalities.

The following section will present an overview and describe Nevrolens' design and functionality at the start of this project. All figures in this section are from Haugum and Woldseth's thesis [14] and are placed at the end of the section.

2.6.1 Nevrolens version 2022

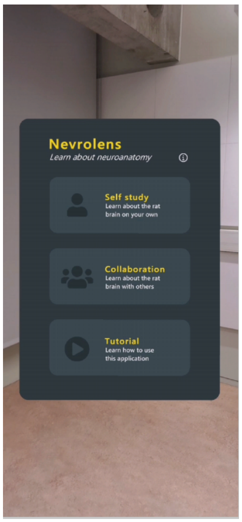
The 2022 version of Nevrolens is thoroughly presented by Haugum and Woldseth in their master's thesis [14] and in a tutorial video posted on YouTube [57]. They present that the application can run on HoloLens 2 and Android devices.

Abbas Jafari added iOS support during the fall of 2022 at IMTEL, NTNU. The Android and iOS application is practically the same.

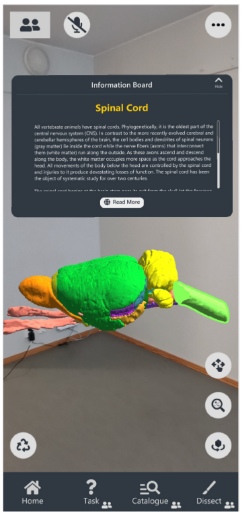
Here, key functionality and features are presented in short, illustrated with pictures from Haugum and Woldseth's thesis. Key functionality:

- **3D View of an anatomical model of a rat brain** – The key function of Nevrolens
- **Model adjustment -** Move, Scale, and Rotate
- **Model Interaction -** Selection of brain parts
- **Cross-platform functionality -** Collaboration between Hololens, Android and iOS devices
- **Presentation of textural Descriptions -** Information boards for selected parts
- **Setup of self-study and collaborative sessions -** User option when starting the application
- **User Guidelines -** Instructional hints of how features can be utilized
- **Catalogue -** Highlights brain pars from selections in a catalogue
- **Flashcard -** Take an image of the field of view and add notes to the image.
- **Save and load progress -** Save current work and load work from the previous session
- **Custom or fixed brain dissection -** Choose the Horizontal. Coronal or Sagittal layers, or custom by users' preferred angle and location.
- **Quiz -** A collection of 40 questions can be chosen randomly, and the user can answer by selecting a brain part
- **Inquiry-based problem solving -** Work and explore together to answer a prepared question
- **Challenge each other -** Multiple users can challenge others by raising a question that a random participant needs to answer. Feature for CL.
- **Voice chat -** *Voice chat is implemented, but an alternative might be needed.*
- **Synchronised collaborative features -** Features activated by a participant in a collaborative session will also be activated for other users.
- **Admin features -** The starter of a session becomes the administrator and can control some of the features for other users, including excluding persons.

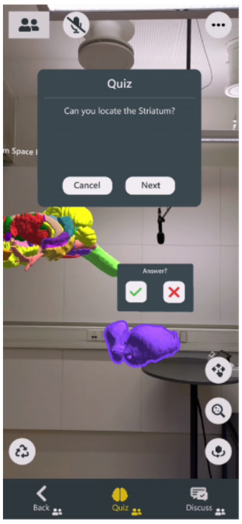
Some of the functionalities are shown in figure 2.10. Figure 2.10a shows the different options; self-study and Collaborative session. In collaborative mode, the user can join an existing session or create a new one. Figure 2.10b-2.10f shows the digital model in Nevrolens. This model can be manipulated to fit user needs. Some of these options are scaling, moving, rotation and dissection. The different anatomic parts can be moved separately to be studied more closely. There is no difference in functionality between the mobile and HoloLens applications, and all devices can collaborate online with each other (Cross-platform).



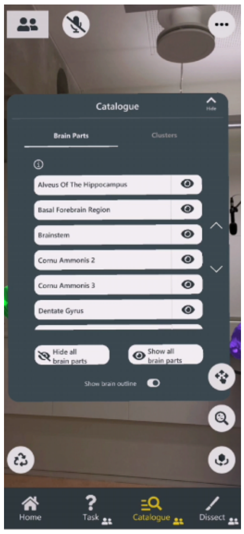
(a) The home screen



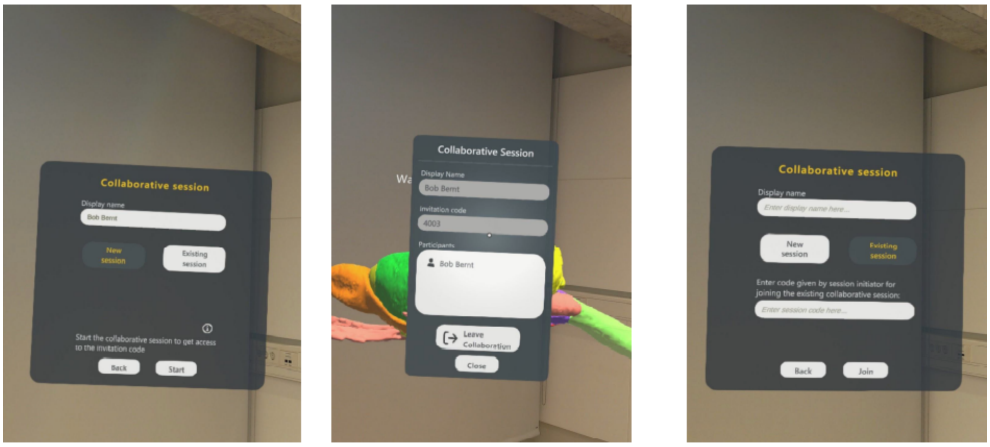
(b) The main view, using a phone



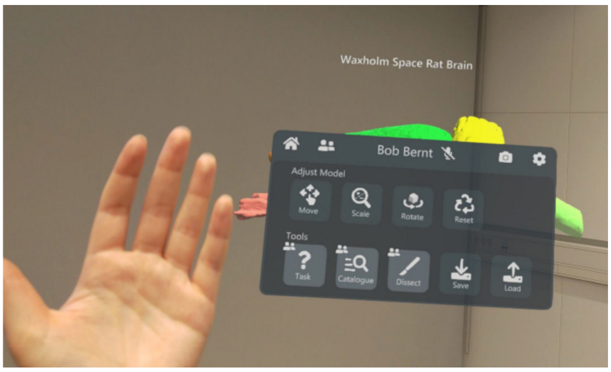
(c) The quiz functionality



(d) The catalogue functionality



(e) The collaborative session option



(f) The main view and options using Hololens 2

Figure 2.10: The current Nevrolens application

2.7 Specialisation project

The current authors conducted a pre-study called the Specialisation project in the fall of 2022. Most of the motivation for this project was already founded during this pre-study. This work is unpublished, and relevant results are presented here. The purpose of the specialisation project was to get insight into CL in AR and understand the current state of the Nevrolens application and previous studies related to Nevrolens.

The specialisation project was used to gain insight into what features should be further implemented and evaluated in a collaborative AR application for both col-located and remote-located anatomy learning.

The researchers developed research questions based on their experience and motivation and a literature review. The chosen research strategy was design and creation, as described by Oates [58]. To become familiar with data collection, a workshop was conducted where data was gathered through interviews, observations, and questionnaires.

A summary of the results obtained in the specialisation project is presented in this section, as the report is not available to the public, and its results are relevant to this project. Relevant literature is presented in the background section.

The workshop included a user test. Such a test was necessary for obtaining valuable data from after-interviews, questionnaires, and observations. The workshop's goal was to verify the results from previous work, evaluate the current state of the application with a focus on collaboration and communication, and acquire insight into the user experience. The workshop was conducted over three sessions with a total of 9 participants. The participants were students taking the NTNU course ”NEVR2030” an introduction to neuroscience.

Based on the results from the workshop, the Nevrolens application's usability, engagement, and ability to facilitate effective communication for the users were evaluated. The workshop, how it was conducted and how the format could be improved for future user tests were also evaluated.

2.7.1 Evaluation of the Workshop and its Outcome

After the workshop was conducted, it was done a brief evaluation of the workshop through a discussion among the researchers based on the observation notes, interviews, questionnaires, and the general experience of both researchers. The key takeaways from this discussion were:

- The set time of one hour for each session was too short.
- The sessions lacked structure and a clear timed schedule.
- A tutorial on the HoloLens device should be conducted to give the users familiarity with the device itself and the basic functionality of HoloLens before

testing the Nevrolens application. HoloLens is a new user interface for most people, meaning most people will not find the basic functionality intuitive.
- Downtime between sessions is necessary. This affected the ability to document observations.
- To ensure the participant gets a realistic experience of the application, the prepared task for them to solve needs to be clarified.
- Multiple supervisors observing the participants while they tested the application could de-sensitise initiative and participation.

The interview had a semi-open format with an outline of pre-made questions. The conducted interview encouraged an open discussion between the interviewer and the participants. Because of time constraints, the interview was conducted with all participants from the given session present.

The questionnaires consisted of 10 SUS statements for both mobile and HoloLens, 5 questions for mobile, 3 questions for HoloLens and 2 questions for overall experience. The questionnaires are presented in appendix A Nettskjema.

The results from the SUS test are interpreted according to Jeff Sauros' [59] adjective scale (presented in section 3.2.7). The average SUS score for mobile applications was 67.5 and 51.4 for the HoloLens application. According to Sauro, the global average SUS score is 68. The SUS score for mobile devices is average and rated OK, while the SUS score for HoloLens is on the border between Poor and OK.

How the participants rated the usability might have been influenced by several factors, for example, time to prepare, users' experience or lack of experience with similar systems, our presentation and conduction of the demonstration.

Table 2.1 presents the other statements and their mean response value. The response was rated on a scale from 1-5, where 1 was strongly disagree and 5 was strongly agree.

Table 2.1: Results of response to statements in user test

Statement	Average response
Experience with mobile application	(N=9)
I think I would use the mobile application frequently for self-study	4,33
I think I would use the mobile application frequently for collaborative study	3,00
It is easy to locate the information I want	3,89
It is easy to see what brain part my co-student (s) is looking at	2,44
I was always aware of my co-student(s) location within the application.	2,44
Experience with HoloLens application	(N=9)
It is easy to locate the information I want	3,11
It is easy to see what brain part my co-student (s) is looking at	2,67
I was always aware of my co-student(s) location within the application.	2,44
Overall experience	(N=9)
The app has been helpful to my understanding of neuroanatomy	4,22
I felt nauseous after using the application	1,67

Observations were primarily done by one of the researchers. This involved observing the participants through all stages of the test. It was taken Observation notes for each participant and more general for the participation group. These results were later compared to the responses given by the participants to better evaluate the application.

Based on findings and evaluation, it's suggested initially five features that could improve the communication aspect and two features that could increase the general functionality of the Nevrolens application.

Five features to improve communication:

- **Synchronising placement of virtual content -** Collocated users will need to see the object in the same place. Otherwise, they will be confused about what others are looking at.
- **Virtual pointers -** It will allow users to guide each other's attention towards the object of interest.
- **Make user avatars more prominent -** It will be easier to understand where other users are and in which direction they are looking in remote sessions.
- **Virtual hand emotes -** This will make it possible to give feedback from users without speaking out or writing in chat.
- **Visualise eye gaze -** It will make what other users look at clear and precise.

Two features to increase the general functionality:

- **A private virtual copy of the model -** Users can explore their copy in a shared session without interfering with the shared model.
- **Undo/redo functionality -** This will increase usability and reduce stress when doing something unintended.

2.7.2 Additional factors to consider in the main project

Voice chat is a key functionality in collaborative AR applications. The Nevrolens 2022 version implemented voice communication using the Photon engine. This option might be too expensive to be sustainable for the application. Alternative options were therefore discussed as part of the specialisation project. It was agreed on three main requirements that need to be fulfilled; (1) Supported on the HoloLens 2, (2) Cost efficiency, and (3) Good sound quality.

An alternative that was found to consider is Mirror Networking. Mirror is a high-level networking library for Unity. Mirror networking provides a back-end for multiplayer games; it is free to use and is compatible with Dissonance voice chat. In contrast to Photon, Mirror does not offer servers to host the application.

Considering the time restriction placed on this project, it was essential to find a way to prioritise what features to implement and test. The requirement of implementing an alternative voice communication method would also have to be considered.

Chapter 3

Methods

3.1 Research method

The research method is derived from Oates [58] in his book, “Researching Information Systems and Computing”. Oates presents several possible strategies and data generation methods.

The chosen research strategy in this project is design and creation, and data generation methods are, Interviews, observations, and questionnaires. The design and creation strategy focuses on producing an Information Technology (IT) artefact where this artefact itself will be the main contribution to knowledge. The IT artefact in this research project will be the software functionality implemented in the Nevrolens application. That will be referred to as features. The research method is illustrated in Figure 3.1.

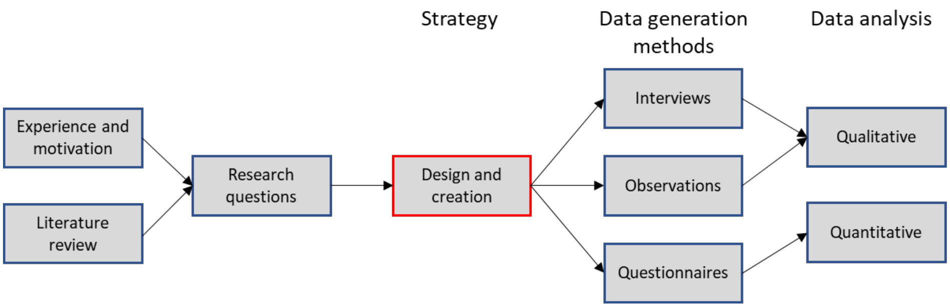


Figure 3.1: The research method used in this project. (Adopted from Oates [58])

A design and creation strategy uses an iterative process and gives the researchers new insight and theories through implementing and evaluating the features. The iterative process will consist of five steps described by Vaishnavi & Kuechler [60] and referred to in Oates’s book [58]. The five steps are awareness, Suggestion, Development, Evaluation, and Conclusion. The iterative process will be executed fluidly, meaning the steps do not need to be executed in the order they are presented. This is because helpful knowledge and experience can be gained from each step that could be beneficial at multiple stages. This is illustrated in Figure 3.2.

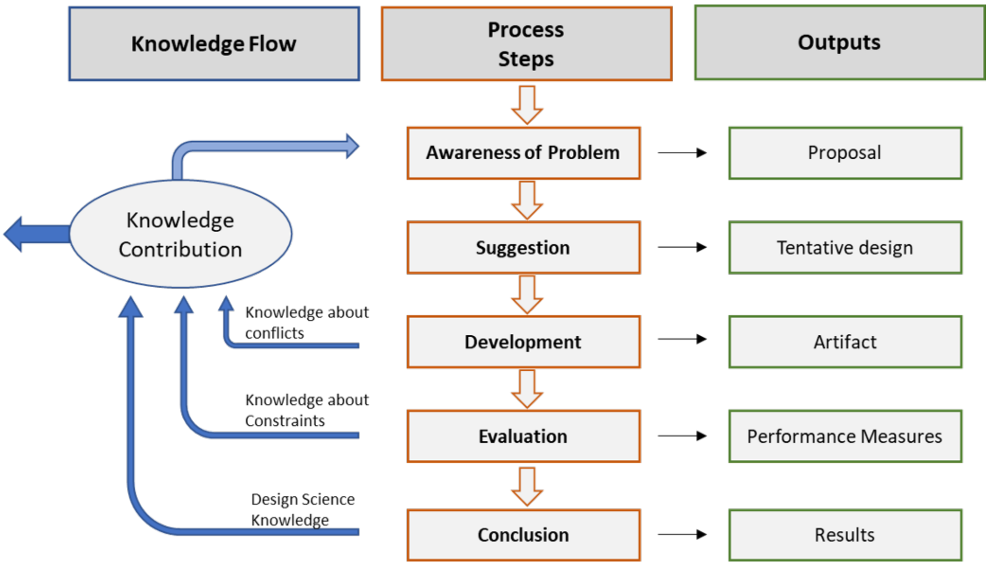


Figure 3.2: Illustration of the iterative method used in design and creation, where each step can contribute to knowledge that either can be used to increase awareness or be output to new knowledge and results. (Adopted from Vaishnavi & Kuechler [60, 61]

In the following sections, each step will be described in more detail.

The first step of the process will include acquiring knowledge and insight about CL in AR and specifically for learning anatomy. This will primarily be achieved through literature research and interviews with the end user. This will give insight into the end user's needs related to learning anatomy. The knowledge and understanding acquired in the awareness step will suggest potential features to solve the identified problems. The development step involves implementing the suggested features for the HoloLens application and mobile devices. Evaluation of the implemented features will build the foundation of the findings and what insight and knowledge are acquired. To evaluate user tests with observation, questionnaires and interviews will be conducted as methods for gathering data.

- Usability
- To what degree it increases engagement
- To what degree it provides clear and efficient communication

These aspects will be evaluated for both collocated and remote settings. This is to identify potential differences when features are assessed in each setting and on each platform. Finally, the conclusion step will take the results from the design process and identify the knowledge that has been gained, as well as unexpected results and results of learning anatomy for further research.

3.2 User tests

3.2.1 Participants

Both experts and students have been participating as users. To distinguish the anonymous System Usability Scale (SUS) questionnaire answers from experts and students, the student numbers started from one and up, and the experts started from 100.

Expert Participants

The expert participants are users that already know a lot of brain anatomy. They consist of doctors from St. Olavs Hospital and a Medisin professor from the University of Bergen. Three experts in total tested the application. One tested both in the first and last Iteration of the User tests.

Student Participants

The Students are all studying at NTNU. They have no to limited pre-knowledge of anatomy. The nine testers from the specialisation project could not continue participating in this project; therefore, four new participants were used. These four tested the application through all three iterations.

3.2.2 Workshop

There is no defined method to measure collaboration. Therefore, it was essential to conduct quality workshops to understand the user needs and map steps to improve cooperation. There are many measurements to evaluate good collaboration. A workshop in this project is defined as any interaction with users and experts where data have been collected.

The methods used to generate data to evaluate the implemented features are based on interviews, observations, and questionnaires. This was done to be able to get a complete view of needs and to be able to cross-reference statements for verification. Each participant was assigned a unique number to be identifiable without collecting personal data.

The user tests were conducted at different times throughout the project as part of the workshops. The first user test was arranged during the specialisation project and gained insight into the initial awareness of the problem. It also gave useful experiences on how to conduct a good workshop. This is presented in section 2.7.1

Some users were invited back after some development work on the application as part of the iterative design and creative strategy method. Follow-up workshops during the project were conducted to get feedback on possible improvements and usability of implemented new features. Users were either invited to the HoloLens lab, where they were introduced to the Nevrolens application or remotely joined a shared demonstration and test.

The users were interviewed immediately after the test and guided to Nettskjema (web questionnaire, see section 3.2.6) to answer the SUS test and follow-up questions.

3.2.3 Observations

Researchers observed the participant's emotions and body language while using the application during the workshops. Key aspects to keep are signs of engagement, how they interact with the User Interface (UI), how they interact with each other, overall body language, and what they say during the test.

Observation is a method of gathering data about the participant's experience from an external point of view. Afterwards, data will be compared to the results from the questionnaire and interview to evaluate whether the two viewpoints (the observer's view and the participant's view) match. Each participant was given a participation number to match the questionnaires/interviews to the observation, ensuring anonymity in reported results.

3.2.4 Interviews

Participants in the same workshop were interviewed as a group. It used open questions and kept open where the conversation led.

The predefined questions were:

1. Which functionality did you enjoy the most?
2. Which functionality do you think can be improved?
3. Did you experience any difficulty orienting the brain or the brain parts? Why/why not?
4. Was it difficult to interact and communicate with the other students? Why/why not? HoloLens vs mobile?
5. How was the collaborative experience overall? Any challenges?
6. Was the collaborative experience enjoyable (fun, engaging)? Why/why not?
7. Were there any differences between using the application in the same room vs remote in different rooms? If so, what? And why do you think so?
8. Any other feedback you would like to share? Any functionality you missed?

Interview answers were qualitatively assessed by the researchers and implemented as new knowledge for discussion and awareness in the iterative procedure.

3.2.5 Questionnaires

The participants were asked to answer five questions individually in Nettskjema (section 3.2.6).

The predefined questions were:

Experience with HoloLens application

1. It is easy to locate the information I want
2. It is easy to see what brain part my co-student (s) is looking at
3. I was always aware of my co-student(s) location within the application.

Overall experience

1. The app has been helpful to my understanding of neuroanatomy.
2. I felt nauseous after using the application.

Answers from the questionnaire were quantitatively assessed and implemented as new knowledge for discussion and awareness as part of the iterative procedure.

3.2.6 Nettskjema

Nettskjema is a web-based research tool developed by the University of Oslo. The platform provides the functionality of creating, storing, and administrating questionnaires. Nettskjema also provides the functionality of representing the data gathered in different manners, like graphs and percentages.

A choice to use Nettskjema was made to preserve the data security and integrity of the participants. Compared to other popular platforms like "Google Forms" Nettskjema is stored and managed only on Norwegian servers. This protects the data from being collected by a third party. Nettskjema is presented in appendix A.

3.2.7 System Usability Scale

The System Usability Scale (SUS) will be used to evaluate usability. SUS was developed by John Brook in 1986 and has later been accepted as an “industry standard” for assessing usability [62]. SUS evaluates various products and services, including hardware, software, mobile devices, websites, and applications [63].

The system consists of 10 statements, and the participants will be given five response options. Each option represents a value on a scale of 1-5, from ”Strongly Disagree” is 1 and where ”Strongly Agree” is 5. Five statements are positive (1,3,5,7,9), and five are negative (2,4,6,8,10).

The standard ten SUS statements are:

1. I think that I would like to use this system frequently.
2. I found the system unnecessarily complex.
3. I thought the system was easy to use.
4. I think that I would need the support of a technical person to be able to use this system.
5. I found the various functions in this system were well integrated.
6. I thought there was too much inconsistency in this system.
7. I would imagine that most people would learn to use this system very quickly.
8. I found the system very cumbersome to use.
9. I felt very confident using the system.
10. I needed to learn a lot of things before I could get going with this system.

To calculate the SUS score, assign the score value to each statement and follow the steps below [64].

- For odd items: subtract one from the user response.
- For even-numbered items: subtract the user responses from 5
- This scales all values from 0 to 4 (with four being the most positive response).
- Add up the converted responses for each user and multiply that total by 2.5. This converts the range of possible values from 0 to 100 instead of 0 to 40.

Jeff Sauro has worked with SUS for over 30 years and collected data from over 10,000 responses and hundreds of products. He has found that SUS scores can be interpreted in at least five ways, as seen in Figure 3.3 [59]. The average global SUS score evaluated this way is 68.

In this project, the adjective scale is used to interpret the results.

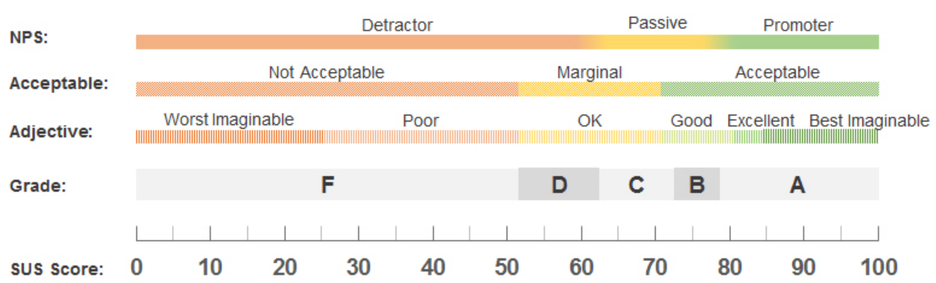


Figure 3.3: Categories associated with raw SUS scores; grades, adjectives, acceptability, and NPS. (From Jeff Sauro [59])

SUS scores were quantitatively assessed and implemented as new knowledge for awareness as part of the iterative procedure.

3.2.8 MoSCoW

MoSCoW is a tool for prioritising product requirements in a project. MoSCoW is an acronym defining four prioritisation categories: Must-have, Should-have, Could-have, and Won't-have. The system was developed by Dai Clegg in 1994. [3] The analysis consists of four steps.

1. Lay out the product requirements.

The product requirements need to be identified. This is done together with all stakeholders and the product team. When the requirements are identified, it is time to prioritise them.

2. Define the prioritisation levels.

MoSCoW has four levels of prioritising. Defining each priority agreed upon among the stakeholders and the team is essential. A general description is presented below.

- **Must-have -** These are the minimum requirements for the project. Without them, there will not be a product. Ask yourself if the project will fail without them; if yes, it is a must-have component.
- **Should-have -** These are not essential but will add substantial value. This category's features focus on fulfilling wishes and expectations rather than basic needs.
- **Could-have -** These features are interesting or fun but do not necessarily serve any greater purpose. Considerations for shifting between could-have and should-have can be based on how it will impact the product's user value.
- **Won't-have -** Features you have considered and would like to include but, for some reason, cannot.

3. Organise the requirements into priority levels.

With clearly defined requirements and priority levels, it is time to organise. Must-have is often obvious, but among the other levels, the following factors should be considered: Time constraints, Team skill set, Budgetary constraints, Team workload, and Cross-team collaboration.

4. Refine and optimise.

After the initial phase of categorising into priority levels, the list might change during the project. New ideas pop up, or unforeseen constraints appear. Development work is somehow flexible, and a sweet spot should be found between iterative assessment and a structured way of working [3].

3.3 Development of features

The development methodology employed in this project is Agile Development, which prioritises flexible and user-centred development over rigid planning. Agile development involves an iterative process of continuously developing and refining features to ensure that the end product aligns with the users' needs and preferences. [65]

This project consists of four iterations, with Iteration 0 conducted during the specialisation project and providing the foundation for formulating collaborative-enhancing features in this project and the literature search. The subsequent three iterations are undertaken in the scope of this project.

Each iteration follows a three-phase approach: Ideate, Prototype, and Test. In the Ideate phase, input from previous user tests and developer observations is discussed to identify features to be prototyped and tested. The Prototype phase involves the development of ideas and concepts. Finally, in the Test phase, the current prototype is evaluated by users, and their feedback is considered and noted for the next iteration.

This iterative approach ensures that the development process remains responsive to user feedback and enables the continuous improvement and refinement of features based on user input.

3.4 Technologies

This section describes the Technologies in this project.

3.4.1 Unity

Unity is a cross-platform game IDE engine and editor for game development. The software provides support for both 3D and 2D graphics. Scripts on this platform are written in C#. The Nevrolens application is run on a free development plan for users with a revenue of less than 1 million NOK. The unity version used in this project is 2019.4.25.

3.4.2 Visual studio

Visual Studio is a code editor from Microsoft. It is used in this project to write C# code and to deploy updated versions of the Nevrolens application to the HoloLens.

3.4.3 Photon Engine

Photon Engine is an API that provides multiplayer functionality to game development. Photon engine is compatible with Unity and works as a plugin. The Nevrolens application currently uses the free plan for up to 20 CCUs.

3.4.4 Mixed Reality Toolkit 2

Mixed Reality Toolkit 2 (MRTK 2) is an open-source plug-in to Unity that makes it easier to develop cross-platform and build mixed reality applications. The standardised component MRTK 2 provides helps accelerate MR development. Nevrolens uses MRTK 2 components to facilitate a coherent anatomy learning platform, that is, as intuitive to use as possible.

3.4.5 Hololens 2

HoloLens 2 is an MR and AR headset developed by Microsoft. It is a HMD with see-through glass, allowing the wearer to experience 3D-holo-graphic images in conjunction with the real-world environment. The headset has sensors which can detect the user's hand gestures. Hand gestures are used to navigate the Hololens 2.

3.4.6 Blender

Blender is software that offers tools to create digital objects. These objects can be exported and used in Unity.

3.4.7 Machine Learning

This subsection describes the different machine learning-specific technologies and tools used in this project.

Tensorflow
TensorFlow is an end-to-end open-source platform for machine learning.

Google colab
Google Colab is a cloud platform that provides a Python notebook with access to servers with GPU and CPU. In this project, it has been used as a tool to train machine learning models.

Baracuda
Barracuda is a lightweight cross-platform API for Neural Network inference. Barracuda is a library extension in Unity.

Open neural network exchange (ONNX)
ONNX is an open-source format for representing deep learning models. It provides a standardised way to represent deep learning methods between different frameworks; it acts as an intermediate between machine learning frameworks like TensorFlow and PyTourch Keras. This allows deep-learning models to be easily deployed across other devices. To use the trained neural network in the Unity game engine, it is recommended to use the ONNX format with the Barracuda plugin.

ImageNet

ImageNet is a pre-trained dataset, often used as a backbone when training machine learning models.

3.4.8 Microsoft Azure

Microsoft Azure is a cloud service offering a range of development services. Azure Spatial Anchor is a tool that allows the user to place digital elements in the same physical location. These anchors are saved on an Azure server. [66]

Mirror Networking
Mirror Networking is a free, open-source high-level Networking library for Unity. [67].

Dissonance Voice Chat
Dissonance Voice Chat is a real-time Voice over Internet Protocol (VoIP) system designed to be built directly into Unity games [68]. Dissonance voice chat is not supported for Unity 2019.

3.4.9 Anaconda

Anaconda is a Python packaging software that simplifies the management of Python environments. Users can create isolated environments with specific Python versions and package dependencies. With Anaconda, users can install, upgrade, and remove packages from their environments, they may also switch between them. This tool is useful when working with ML where different approaches often require different versions that are not compatible with each other.

3.4.10 GitLab

GitLab is an integral component of collaborative development in the Nevrolens project facilitated by IMTEL at NTNU. With three iterations of developers involved, GitLab serves as a vital tool for storing and organising the project's codebase. As an open-source code repository, GitLab provides a centralised platform for developers to collaborate, share, and track project codebase changes. It offers features like version control, issue tracking, and documentation, enabling efficient collaboration and seamless project management.

Chapter 4

Implementation

This chapter explains the process that was carried out to design and implement the different functionalities to enhance CL.

Through literature review, studying previous work for Nevrolens and conducting the specialisation project, awareness and knowledge of functional and non-functional requirements have been established. As a result of the development of Nevrolens by Ravna [13] and Haugum and Woldseth [14], many requirements have been suggested, evaluated, demonstrated as a proof of concept, and implemented.

This project has focused on Functional requirements (FR) with Non-Functional Requirements (NFR) in mind. The process of implementing the functionalities is presented in the following iterative steps. The functionalities were prototyped and tested in small-scale tests to verify more minor changes and input on development direction and in larger-scale workshops for more comprehensive research. This was done in all three iterations.

4.1 Requirements

4.1.1 Functional Requirements

The FR define a desired end functionality for what a system should provide the user. The requirements should be clear, concise and non-ambiguous. The functionalities in this project were defined based on the research conducted in the specialisation project and the research conducted during this project. The FR are listed and prioritised according to MoSCoW in the order of must, should, and could have and presented in Table 6.1. *(Text in italic outline the features formulated in the specialisation project and used to reformulate more general FR.)*

Table 4.1: Identified FR with priority.

ID	Description	Priority
FR 1	All shared objects in a collocated session must be located at the same physical location for all participants. - *Synchronising placement of virtual content*	Must have
FR 2	The system clearly visualise what the users in a collaborative session are working on/discussing. - *Virtual pointers, Visualise eye gaze, More prominent Avatars*	Must have
FR 3	The system allows users to express emotion in a remote collaborative setting. - *Visualise hand emotes*	Should have
FR 4	The user can work on a personal object in a shared session. - *Private copy of the model*	Should have
FR 5	The user can communicate with each other in the system using voice chat.	Should have
FR 6	The system has a chat option allowing the users to send and receive text messages.	Could have
FR 7	The user can write notes in the system.	Could have
FR 8	The user can undo and redo commands and actions. - *Undo/redo functionality*	Could have

4.1.2 Nonfunctional requirements

Non-Functional Requirements (NFR) are system qualities that guide the design of the solution. Unlike functional requirements, which specify how a system responds to specific inputs, nonfunctional requirements specify various system qualities and attributes [69].

NFR are also named quality requirements, and they are grouped and defined in the standard, ISO/IEC 25010:2011 [70, 71]. The standard list of NFR is Functional suitability, Usability, Maintainability, Performance Efficiency, Portability, Compatibility, Security and Reliability.

Nonfunctional requirements which are considered relevant for the developments carried out in this project are listed in Table 4.2.

Table 4.2: Identified non-functionality requirements

ID	Topic	Description
NFR 1	Usability	The system must be easy to use and understand. Nevrolens is intended to be used for an educational purpose, and it is important that the technical overhead is as minimal as possible to facilitate good learning.
NFR 2	Performance	While implementing new functionality, maintaining good performance was important to uphold, where HoloLens has limited computational power.
NFR 3	Maintenance	Nevrolens is an application that is developed over time by different developers that have no communication with each other. It was important to write understandable code and document changes well during development, to make the application acceptable for the next developers.
NFR 4	Portability	The features implemented should be easy to convert to HoloLens, Android and iOS applications

4.2 Iteration 1

4.2.1 Ideate

Synchronise brain

In the first iteration, research was conducted to explore ideas on synchronising the Nevrolens brain in a collocated environment. In the current application version, users were required to look at different parts of the room to collaborate on the brain. The brain would spawn at arbitrary locations in the physical environment. Following the latest workshop conducted in the specialisation project, most users expressed the need for this functionality in the system. These statements were supported by the observations made by the researchers, who also noted that most participants appeared confused by this lack of synchronisation. According to the researchers, the lack of synchronisation visibly affected the participants' communication ability. They had to raise their voices, constantly turn their heads, and couldn't point in the room to indicate points of interest. As a result, confusion arose among participants regarding whether the brain was actually in a multiplayer state where everyone could make edits. Based on this research, implementing this functionality was considered a prioritised task.

Expressing a point of interest

Another idea brainstormed during this iteration was allowing the users to express the area they specifically want to show their fellow users. Two functionalities were drafted. One where the user's hands were rendered and shared live with each participant in the session. The other was to allow the users to create a shared arrow that could be placed in the environment.

Voice Chat

The tests conducted with separate voice chat from the specialisation project was limiting. Therefore alternatives were researched. An option found was dissonance voice hosted by Mirror networking. Mirror allows the users to set up and host their own servers for voice communication.

4.2.2 Prototype

Synchronise brain

In the pursuit of synchronising the player object, the most promising option identified was utilising a function known as "Azure spatial anchor."; However, attempting to implement this function within the Nevrolens application proved unfeasible. After extensive testing with various installation approaches, it was determined that Azure spatial anchor is no longer supported in Unity 2019 and requires a newer version, specifically Unity 2020 or later. Moreover, the successful use of "Azure spatial anchor" relies on the MRTK 2 tool called OpenXR, which is incompatible with Unity 2019. Efforts were made to upgrade the project to Unity 2020. Still, despite multiple attempts, it became evident that recreating the project from scratch was the only viable solution, where scripts need to be rewritten to support OpenXR instead of the legacy tools from Unity 2019. Regrettably, this undertaking could not be accomplished within the project's timeframe due to time constraints.

Due to the acknowledged importance of this functionality, "Azure spatial anchor" was implemented in a separate application as a proof of concept. To implement the Anchor, a server was set up in Azure. The detailed steps for this setup can be found in the documentation provided in [66]. The user can create an anchor within any location in the physical room. Subsequently, they can upload the anchor to the cloud, which other users can fetch. Consequently, the anchor will be positioned at the exact same spot within the room for all participants, ensuring synchronisation.

If this feature is integrated into the application in the future, users should be provided with a brain synchronisation option before creating a multiplayer room. If the user selects this option, a step-by-step tutorial should be initiated, guiding them on the correct session setup for a spatial anchor.

Figure 4.1 illustrates the suggested design, where users are presented with textual instructions outlining the steps to create and locate a spatial anchor. Additionally, it explains the process for deleting the anchor once the session concludes.

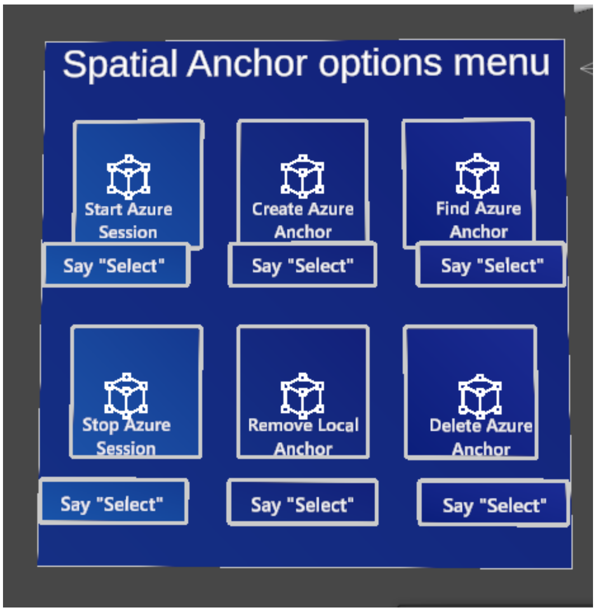


Figure 4.1: Suggested design created using MRTK for Azure Spatial Anchorin an application.

Voice chat

Voice chat faced similar challenges as the Spatial Achor feature, where the Dissonance was discontinued in Unity 2019 and earlier versions. A mock application was created and tested successfully as proof of concept. But further development on this feature was discontinued in this project due to its incapability with the unity version Nevrolens uses. Further remote tests of Nevrolens used a third-party voice communication on a separate device.

Hand mesh and hand joint

In MRTK 2, an option can be used to display rendered hand meshes and joints in the HoloLens application. This mesh does not have the functionality to be shared over the system network. This option served as a prototype for a user test.

Arrow pointer

A simple arrow that could be placed, directed and orientated in the application was developed in the application by using Unity Game Objects.

4.2.3 Test

This test focused on the prototypes developed during Iteration 1, as minimal direct changes were made to the Nevrolens application. The test involved four students and was designed to be less extensive than a complete workshop.

The test structure involved allowing the users to interact with the application and try the implemented changes. First, they tested the hand mesh and arrow pointer prototype within the Nevrolens application. Subsequently, they explored the prototype application designed to demonstrate object synchronisation. Following the showcase of these prototypes, a discussion took place to gather feedback and determine the future direction of the development process.

4.2.4 Expert interview

Two experts tested the current version of Nevrolens at a workshop organised at St. Olavs Hospital. Here they tested the application and provided valuable feedback.

Synchronise brain

From this test, the users verified the functionality "Azure spatial anchor" as the functionality they would like in Nevrolens to improve collocated collaboration, where it was convenient that all users could gather around one spot and work together in the same proximity. It was also observed that the users felt more engaged when collaborating at the same spot and seeing each other's faces.

Arrow Pointer and Hand rendering

During the test, the users provided feedback regarding the experience of placing and directing an arrow in the Nevrolens application. They found this particular feature to be imprecise and cumbersome, making it challenging to navigate accurately. In contrast, the hand rendering feature was deemed more manageable and precise by the testers. Based on this feedback and evaluation, the decision was made not to continue the development of arrow pointers. Instead, the focus shifted towards enhancing the hand rendering functionality, which was better received and offered a more satisfactory user experience.

4.3 Iteration 2

4.3.1 Ideate

Hand rendering

Based on the positive feedback received in the previous iteration, the decision was made to continue developing and improving the hand-rendering feature in the subsequent iteration. The initial focus of the discussion revolved around implementing digital hands that could be transmitted over the photon network. It was recognised that rendering entire hand meshes on the HoloLens could strain its performance. As a result, an alternative approach was considered, wherein hand joints could be represented as spheres instead of using complete hand meshes.

This approach was deemed a potential solution that would balance the need for hand representation with the performance limitations of the HoloLens device.

Local environment

A suggested feature was to allow users to create a local replica of the Nevrolens brain within the shared session. This approach would allow users to manipulate their individualised version of the brain while preserving the integrity of the shared brain. Consequently, users could freely scramble and rearrange the brain without interfering with the collective experience. Furthermore, this functionality would facilitate the opportunity to conduct brain dissections and compare the perspectives of both the 2D and 3D representations.

4.3.2 Prototype

Hand joints

In the Unity environment, the hand joints were visually represented as spheres. To enable this representation, a tracker script was developed to continuously track the endpoints of the user's right hand within the field of view of the HoloLens camera. The position of these endpoints served as the basis for transforming the position of the sphere objects associated with each hand joint.

This implementation allowed for the real-time visualisation of hand joints as spheres for both the local user and other users within the collaborative session. By transmitting the hand joint data over the photon network, all participants in a shared session could perceive and interact with the hand joints of other users. This ensured a synchronised and consistent representation of hand movements and joint positions among all participants in the collaborative environment.

Local brain

To prototype the functionality of creating a local brain copy for users to work in a shared space, a button was designed and integrated into the Nevrolens hand menu. This copy button enables users to duplicate a local rat brain within the shared environment.

The duplicated brain is visually distinguishable from the collaborative brain by its absence of colour, as all components of the duplicated brain are rendered in grey. This visual distinction helps users differentiate between the local copy they are working on and the shared collaborative brain.

4.3.3 Test

During the testing phase, the testers engaged with the Hand joints feature and explored the functionality offered by the Local brain environment. Subsequently, a post-test discussion was conducted to gather valuable feedback that could improve the next iteration of the application.

The testers responded positively to the implementation of hand joints, highlighting that it improved their ability to observe and comprehend the actions and modifications made by other users. The enhanced visibility provided a clearer understanding of the collaborative efforts, fostering heightened participant awareness.

Hand joint

During the post-test discussion, the testers desired improved accuracy when pointing to specific points of interest. They highlighted the importance of effective communication, especially when collaborating with users remotely. While the existing sphere-based representation of hand joints was appreciated, the testers needed a more precise pointing mechanism.

Local brain

The feedback regarding implementing the duplicate brain functionality was positive, with testers appreciating the freedom it provided to work in a local private environment. The ability to make changes without being constrained by the considerations of other users was seen as a valuable addition.

Testers expressed that this newfound freedom allowed them to make more experimental and crude changes without constantly considering the preferences or expectations of other users. This aspect of the application was perceived as empowering and enabled users to explore more freely.

4.4 Iteration 3

4.4.1 Ideate

Hand gesture

Taking the feedback from the testers into consideration, it was determined that the functionality of visualising hand emotes (FR 3) would be a valuable addition to enhance the precision of pointing within the application. In addition to improved pointing, users should be able to express satisfaction or dissatisfaction through hand gestures. The suggestion of using thumb-up or thumb-down gestures to symbolise satisfaction or dissatisfaction was proposed.

Two different approaches for implementing gesture recognition within the system were drafted. One approach uses algorithms to recognise and interpret hand gestures, while the other uses machine learning. These approaches were explored and evaluated to determine the most effective and accurate method for gesture recognition in Nevrolens.

Avatar

Another proposed feature is to update the User Avatar to have a more human-like appearance and improve its precision in tracking the user's gaze. This update intends to enhance the sense of connection among participants in the session. By representing the users with avatars that closely mimic their head movements and indicate their gaze direction, it aims to create a more immersive and engaging collaborative experience.

The updated User Avatar would aim to accurately reflect the user's head movements within the plane, ensuring that the avatar's orientation aligns with the user's actual head position. Furthermore, the Avatar would prominently display the direction of the user's gaze, allowing others to understand quickly where they are looking during the session. This enhancement fosters better visual communication and facilitates a more profound sense of presence and engagement among participants.

4.4.2 Prototype

Machine learning approach to hand gesture

To train the ML model, a dataset of 100 images was collected for each gesture, capturing the likely context in which these gestures would be used within the application. The dataset consisted of three gestures: thumb-up, thumb-down, and fist. To ensure a robust model, 80 images were used for training, while the remaining 20 images were reserved for validation, following an 80:20 split.

The training process utilised an ImageNet baseline model implemented with TensorFlow. The training was performed on the Google Colab platform, and the resulting model was converted from a Saved-model format to an ONNX format. To ensure the model's accuracy and performance, it underwent verification testing locally before being uploaded to the Nevrolens application.

To integrate the machine learning model into the HoloLens device, a script was adapted to facilitate running machine learning models on the HoloLens platform. This adaptation allowed for the seamless execution of the trained model within the Nevrolens application, enabling real-time gesture recognition and response [72].

During the debugging process, it was discovered that although the machine learning model was successfully loaded onto the HoloLens device, no digital elements were displayed within the Nevrolens application. To identify the cause of the issue, a mock Nevrolens project was created and stripped down to its essential components. This simplified setup confirmed that the machine learning model ran accurately and made correct predictions.

Based on these tests and observations, it was concluded that while the HoloLens is capable of running machine learning models and performing predictions, the hardware limitations of the device restrict its ability to handle resource-intensive processes. The complete Nevrolens application, being more demanding regarding computational requirements, could not be effectively run in parallel with the machine learning feature. Consequently, further development on this specific feature was discontinued.

Algorithmic approach to hand gesture

The algorithmic approach to gesture recognition was implemented through a C# script. This method utilises the joint positions of the user's right hand, obtained from the hand joint feature, to determine whether a gesture is being performed in the HoloLens camera field of view. When a gesture one of the gestures: Thumb-up, Thumb-down, waving or pointing, is detected, a corresponding mesh is rendered within the application. The mesh, designed using Blender, is displayed for the user performing the gesture and all other users in the shared session.

Two joint positions determine the orientation of the gesture mesh. This means that if the user's hand moves in a particular direction while maintaining the gesture, the gesture mesh will align and adjust accordingly to the user's movement, ensuring accurate representation within the application.

4.4.3 Workshop

The final iteration of the project was reviewed in a workshop where experts and students tested Nevrolens. The workshop comprised two parts: the first involved a co-located expert, while the second involved a remote expert. A separate test was conducted with four students who tested Nevrolens in co-located and remote settings.

4.4.4 Expert interview

Co-located

As only one of the two experts from St. Olavs could attend, one of the researchers stepped in as the collaborator in the user test.

Remote

To evaluate the updated version of the Nevrolens application in a cross-city remote use case, a Professor from the medical studies in Bergen, who had previously tested the application at the IMTEL lab conference at Dragvol, was coordinated to participate in the remote testing session. Given their expertise and prior experience with the application, their feedback and insights were precious.

To facilitate the testing process, the researchers prepared a guide that outlined the steps for downloading the current version of the Nevrolens application. This guide is attached in Appendix: B, aimed to assist users without a technical background in accessing and installing the application on their HoloLens devices. However, recognising that exporting a HoloLens application can be challenging for non-technical users, an alternative approach was adopted for the remote testing session.

In this case, the application was live-streamed to the professor. This allowed the professor to view and evaluate the updated version of Nevrolens remotely.

Chapter 5

Results

5.1 Implemented functionality

This section presents the features developed in this project. The new and implemented functionalities to Nevrolens are listed in Table 5.1, and features tested as proof of concept are presented in section 5.2. Note that two solutions were explored to estimate the user's hand gestures: one algorithmic and one using Machine learning (ML). The algorithmic is presented here, and the ML option is presented as proof of concept in subsection 5.2.

See the video from 1.1 for an overview of the implemented features.

Table 5.1: Implemented Functionality in Final design of Nevrolens

Implemented Functionality
Hand tracking
Gesture recognition using algorithm
User Avatar
Local brain copy
Written chat

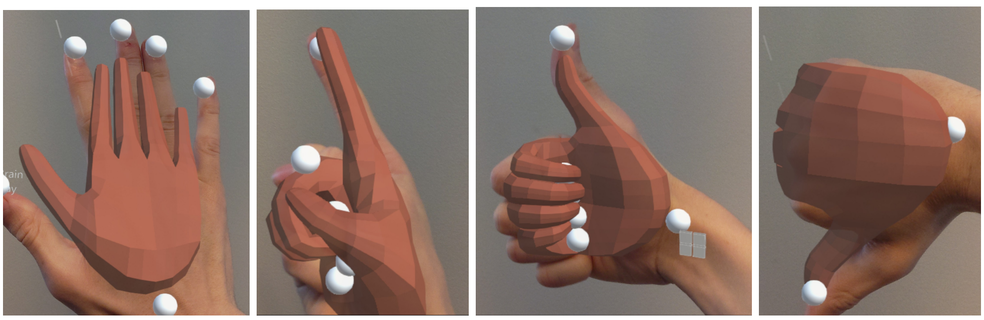
5.1.1 Hand tracking

The Nevrolens application allows users to see every user's "hand joints" tracked and rendered as spheres. When the user's hand enters the field of view of the HoloLens, the user's joints are shown and continuously sent through the Photon network, where all other devices fetch the data of the joint position. The user can also see other users' joints. These spheres' location is updated in real-time.

Figure 5.1: The tracked finger positions, with no gesture detected

5.1.2 Gesture recognition with algorithms

A hand mesh with a predefined stance appears whenever the user performs the following gestures: waving, pointing, thumb-up, and thumb-down, as shown in Figure 5.2. This stance is live updated and transmitted to all participants of the Nevrolens collaborative session. The stance is determined by measuring the position of each finger's endpoint joint to the wrist position of the hand within a threshold. Hand mesh gesture will follow the user as the gesture is detected. For example, if a user keeps a pointing pose but moves their hand, the hand mesh will follow their hand until the gesture is not detected. Figure 5.3 presents how this looks, where the avatar uses gestures. Figure 5.4 shows how the pointing feature can be used to identify specific parts of interest in the shared model.



(a) Flat hand waiving **(b)** Pointing **(c)** Thumb-up **(d)** Thumb-down

Figure 5.2: The basic hand gestures

(a) Pointing at it self

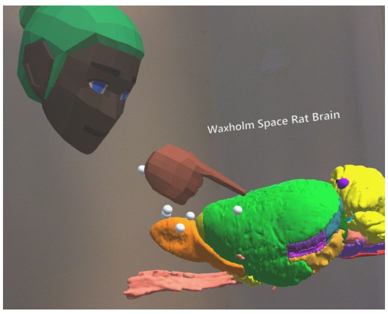
(b) Pointing at you

(c) Gives you Thumbs up

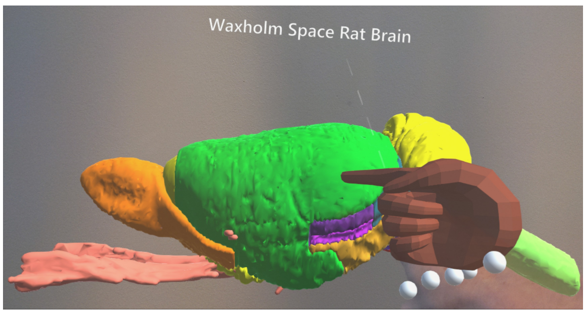
(d) Gives you Thumbs down

(e) Waving to you

Figure 5.3: Collaborators represented with an Avatar and its hand gestures



(a) A collaborator is pointing

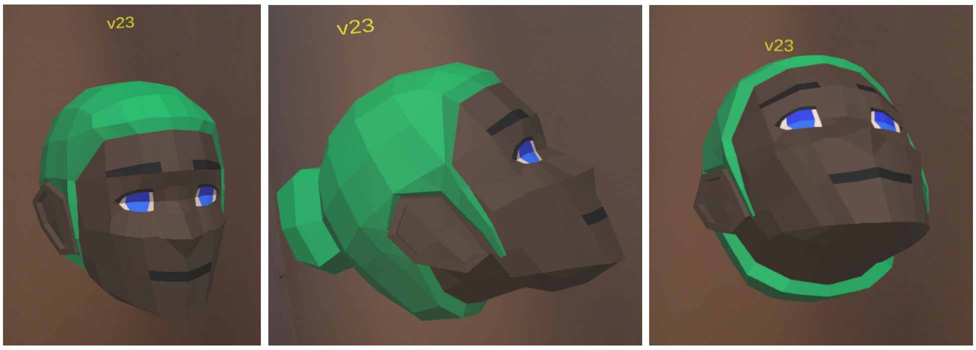


(b) A collaborator is pointing.

Figure 5.4: Pointing in shared rat brain model

5.1.3 User Avatar

In the Nevrolens collaborative session, each user's head position is transmitted to other users as an avatar. The avatar's gaze position and movements correlate with the user's gaze and head movements in real-time. This is accomplished by tracking the user HoloLens' positions and rotation in correlation to the rat brain in Nevrolens and matching it with the humanoid Avatar.

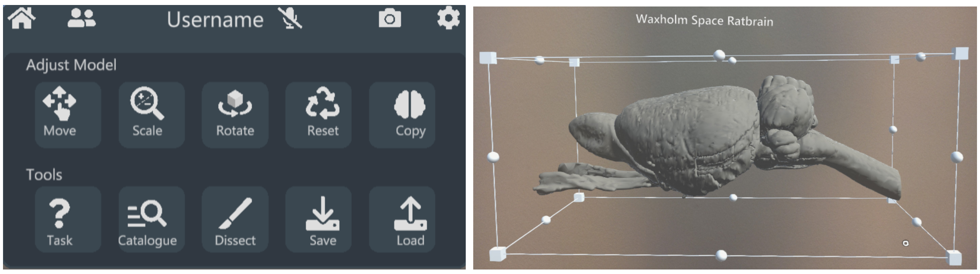


(a) Idle position **(b)** Side position **(c)** Up position

Figure 5.5: Different angles of the user avatar.

5.1.4 Local brain copy

The Nevrolens application allows the user to make a local copy of the brain in collaborative and self-study mode. To copy the brain. On HoloLens, the user needs to raise their hand and click the copy button option, and in the Android application, the user clicks the menu button instead. The brain copy is not coloured to distinguish it from the original brain. The brain copy is only seen and accessible to the user that created it.

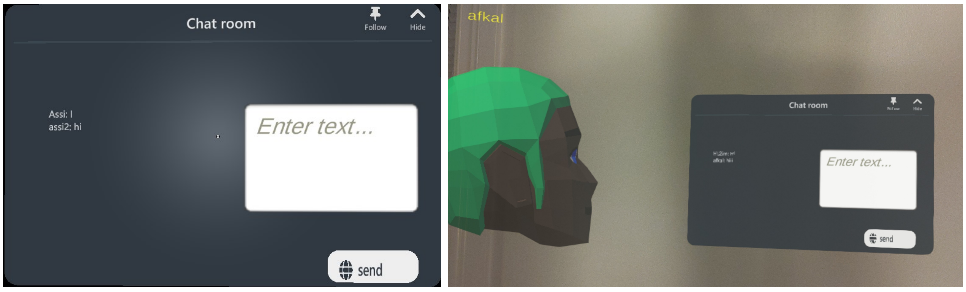


(a) The "copy" button with a brain logo **(b)** Example of a copy of a brain

Figure 5.6: Brain Copy, a) The menu including the button for making a Copy, b) How the brain copy looks

5.1.5 Written Chat

The Nevrolens application has a written chat that the users can use to communicate. When joining an online session, the user is presented with the option to connect to a chat room. When the user is connected to a chat room, they can send public messages to every other user in the same session with connections to the chat. Users' messages are distinguished by their username when connecting to the collaborative session or the one randomly assigned to them if they did not input a username in the current session. The user can minimise the chat window and expand it during the session. The user can also pin the chat stationary in the room or have it follow their field of view.



(a) Chat board close **(b)** Chat board from a distance.

Figure 5.7: Chat board with text from two users. Note that the text differs from the two pictures due to being captured at different instances.

5.2 Proof of concept functionality

Two functionalities have been explored and tested as proof of concept as presented in Table 5.2.

Table 5.2: Features tested as proof of concept

Proof of concept functionality
Azure Spatial Anchor
Gesture recognition using ML

5.2.1 Azure spatial anchor

The following is the implemented mock application with Azure spatial anchor. The user can place, find and delete a spacial Anchor. This example uses the Azure API from [73] [74], and is hosted by a private Azure server where the Anchor metadata is saved.

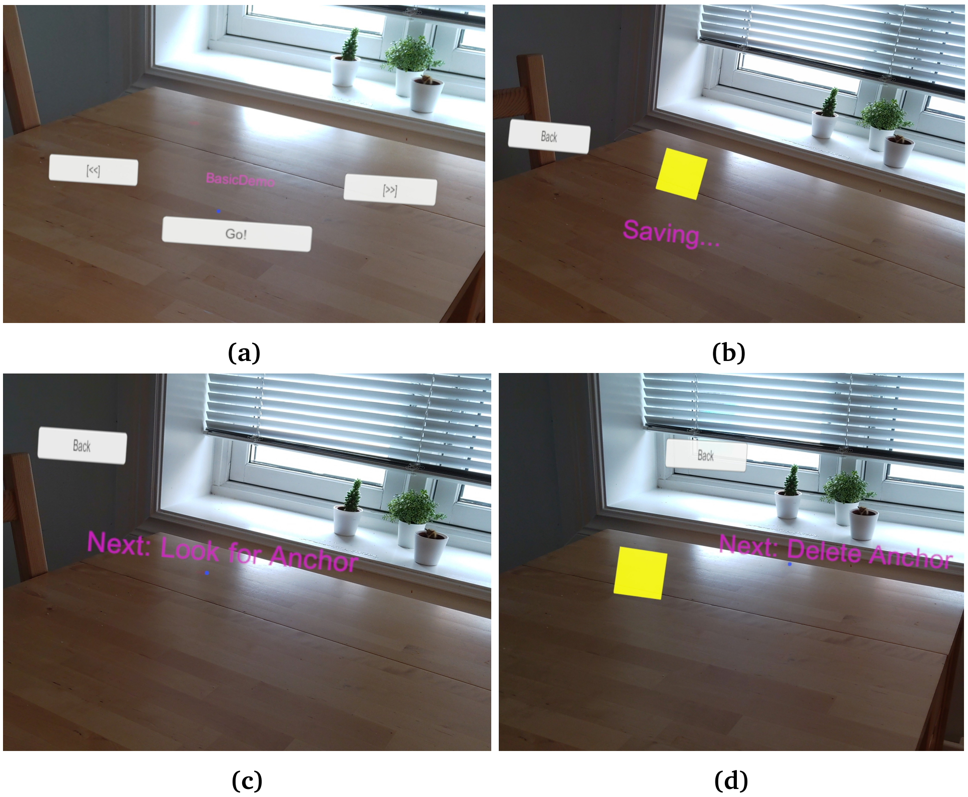


Figure 5.8: Azure demo: (a) Start page Azure demo. (b) Save an Anchor in the environment on the Azure server. (c) The system is trying to find a saved Azure anchor from the server. (d) The anchor is found and shown in the same spot in the environment as it was placed. The user next has the option to delete it from the Azure servers.

5.2.2 Gesture recognition using ML

Examples of the dataset used to train and evaluate the ML model are presented in Figure 5.9.

Results on inference time on computer is presented in 5.10 and the inference time and prediction on HoloLens is presented in 5.11.

The inference time on the prediction varied between 100 ms to 400 ms and had 90 % to 100 % confidence level on its predictions. Note the model is trained and tested on one of the researcher's hands. The implementation is built upon the framework presented in this GitHub: [72].

(a) First example of Thumb-up

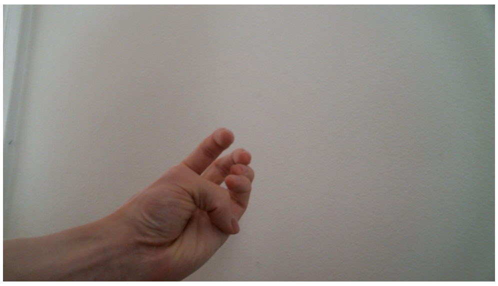
(b) Second example of Thumb-up

(c) First example of thumb-down

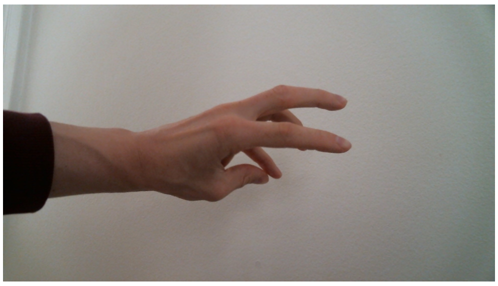
(d) Second example of thumb-down

(e) First example of fist

(f) Second example of fist

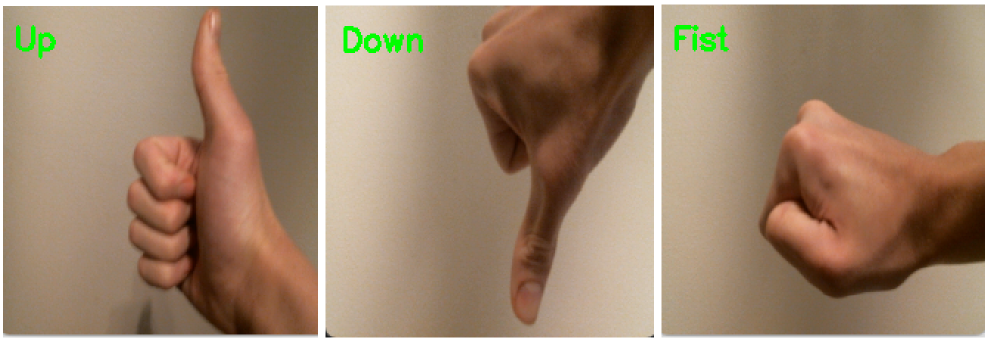


(g) First example of none



(h) Second example of none

Figure 5.9: Examples of Machine learning images used in the dataset.

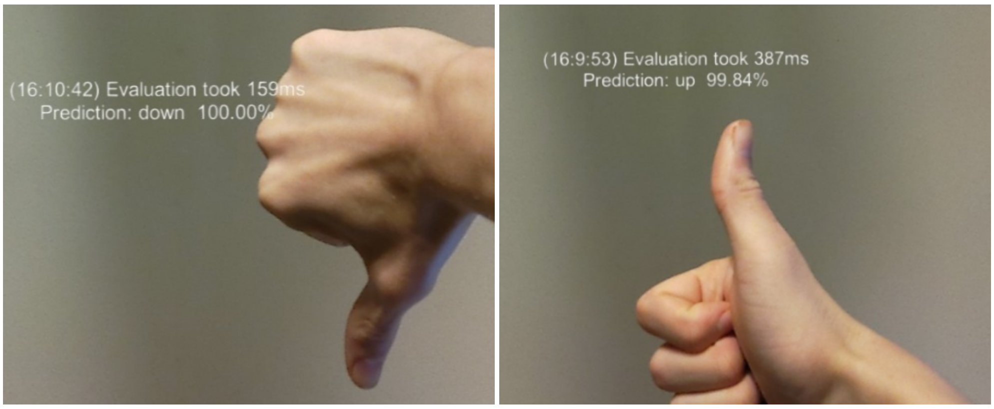


(a) Thumb up
Inference time 10 ms

(b) Thumb down
Inference time 11 ms

(c) Fist
Inference time 9 ms

Figure 5.10: Machine learning inference time on computer



(a) Thumb down on HoloLens
Inference time 159 ms
Prediction down 100,0 %

(b) Thumb up on HoloLens
Inference time 387 ms
Prediction up 99,8 %

Figure 5.11: Machine learning inference time and prediction on HoloLens

5.3 User tests

5.3.1 Interviews and observations

Interviews and observations conducted in workshops gave the researchers qualitative information. This information has been used during the development of features. Some of this is already mentioned in the implementation chapter 5.1.

Here is the researcher's interpretation of the obtained information structured and presented as results.

General feedback on the Nevrolens application

Students emphasised that the application was fine, fun, engaging and easy to communicate. They preferred voice-over text chat when challenged about voice and text options. Some mentioned that it would be good if it were visualised who was talking in the collaborative session.

The experts responded equally with positive statements like fun, playful and interesting concepts. They thought it was fun to collaborate with AR and thought it would lead to better learning than self-study if this technology were fully adopted. They appreciated the functionality, both remote and collocated. However, helpful guidance/supervision was necessary for this positive experience.

The experts also expressed that the application was still exploitative and unsuitable for advanced anatomy learning. One expert said that a human brain model would be more useful than a rat brain and that more detailed information about the brain parts could give even more learning. Experts were also concerned about the cost of HoloLens glasses and found that restrictive for full implementation as a learning application.

Other feedback was the importance of voice chat and a suggestion to implement voice commands. It was also mentioned that a more intuitive UI could reduce the time for learning the application.

User Avatar

Both students and experts appreciated this feature. They found the Avatar easy to understand, and the communication was better with these new Avatars present. The Avatar enhanced the feeling of true collaboration. One user specifically expressed that seeing an Avatar with eyes was good.

Brain Copy

Only the students gave specific feedback on the brain copy. They expressed that they understood the usefulness of the concept. It was easy to move but difficult to edit. It was OK that it was always visible and possible to adjust. However, some found it challenging to find it in the menu. Some mentioned it was unnecessary when a few peers were in the session, but it would be necessary with many participants. A suggestion was to make it possible to share a private copy. Some disliked the grey/white colour and mentioned that the framing would make it unique and distinct from the shared brain object.

Brain manipulation

Students pointed out that the snap in place of brain parts was not sensitive enough. They also found the standard pointer challenging to use. One of the experts agreed with the students that placing parts back was difficult, and he also mentioned that undo/redo could have been better. Another expert said he needed training and would appreciate a tutorial/user manual. One of the experts did not have any difficulties but noted that the calibration of fingers could be a little bit more precise.

Written chat

The students expressed that this feature was difficult to use. It was too much to click, and pinch was not always registered. It was also challenging to know what was clicked, and one user observed that the chat only sent single letters. It was commented that it was necessary to make it easier to click on the chat board and that this function was probably more relevant for mobile devices than for HoloLens.

Hand gestures

Both students and experts were positive about hand gesture functionality. Several expressed that it helped in communication. A suggestion was to make the thumb up/down prefabricated and rotatable. One expert found it easy to point accurately in the brain, collocated and remotely. Some even expressed that it was incredible that the hands could be sent live.

Object location

The lack of a synchronised object in collocated sessions was the most frustrating experience. The lack of a local anchor made it difficult in collocated sessions but was no issue in remote sessions. This feedback was unanimous.

Observations by researchers during user tests

It was observed that the users had difficulties clicking the input fields and buttons in the HoloLens application. Also, the HoloLens keyboard was observed to generate frustration. After some time, the clicking was observed to be easier for the users. A user with some experience with HoloLens before this session managed the clicking well and was observed to move around easily. Users that had no previous experience needed more guidance and struggled the most. However, some learned quickly and became comfortable during the test session.

5.3.2 SUS score and response to queries

The individual SUS scores are presented in Table 5.3 and the average SUS scores in Table 5.4.

The individual responses from the questionnaires are presented in Table 5.5, and the average response for each individual question is presented in Table 5.6.

Expert user 102 participated twice, and hence answers from the second response are not used to calculate average values either for SUS scores or for question response.

Table 5.3: Individual SUS score for all participants

User ID	100	102	103	10	11	12	13	*102**
Score / Quest.**	**75**	**67.5**	**67.5**	**45**	**37.5**	**55**	**62.5**	***72.5***
1	4	4	2	2	2	3	3	*4*
2	2	2	2	2	4	2	2	*2*
3	5	4	4	3	2	3	4	*4*
4	3	4	1	4	4	4	1	*3*
5	4	4	5	3	2	3	3	*4*
6	2	2	2	4	2	3	1	*2*
7	4	3	4	4	3	4	2	*4*
8	2	2	2	3	4	3	3	*2*
9	4	4	3	2	3	4	4	*4*
10	2	2	4	3	3	3	4	*2*

** Second score for participant 102*
*** SUS questions are presented in section 3.2.7*

Table 5.4: Average SUS score for all participants, experts and students

Subgroups	**n***	**Average**	**SD**
Experts	n=3	70	± 4.3
Students	n=4	50	± 11.0
All users	n=7	58.6	± 13.5

** n = Number of included users*

Table 5.5: Individual results from questionnaires

User ID / Quest.**	100	102	103	10	11	12	13	*102**
HoloLens								
1	4	4	2	4	2	3	3	*4*
2	2	4	4	5	2	4	4	*5*
3	4	4	2	3	2	3	2	*4*
Overall								
1	4	4	2	4	2	4	3	*4*
2	2	1	1	1	1	2	1	*2*

** Second score for participant 102*
*** The numbered questions are presented in Table 5.6*

Table 5.6: Average score on the individual questions

No	Questions	Average
	Experience with HoloLens application	n=7
1	It is easy to locate the information I want	3.14
2	It is easy to see what brain part my co-student (s) is looking at	3.57
3	I was always aware of my co-student(s) location within the application	2.86
	Overall experience	
1	The app has been helpful to my understanding of neuroanatomy	3.29
2	I felt nauseous after using the application	1.29

Chapter 6

Discussion

6.1 Implemented functionalities

A list of implemented features, potential improvements and their related research question are presented in Table 6.1

The implemented functionalities have been carefully considered to meet the general needs of the collaborators, as postulated by Radu et al. [54]. Their study categorised these needs into seven main groups, as described in subsection 2.5.1. Furthermore, they presented more specific needs within each category.

Table 6.1: The identified and implemented functionality requirements and their relation to RQ

Functionality	Description	Suggested improvement	RQ
Hand tracking	The fingertips of the user's right hand are traced in the 'field of view' of the HoloLens. Virtual spheres then follow these positions.	Implement the option for tracking the left hand and the ability to turn the functionality on and off	RQ3
Gesture recognition by using algorithms	Recognises and creates a corresponding mesh of the gesture. Thumb-up, Thumb-down, pointing and waving.	Implement the ability to turn the function on and off.	RQ2, RQ3
User Avatar	An Avatar model follows the user's head movement and position when wearing an HMD.	Make the Avatar customisable so that each user can express and differentiate themselves with a unique Avatar	RQ2
Local brain copy	The user can create a local and personal duplicate of the brain in the shared environment. This brain can be moved, scaled and edited.	Make it possible to remove the local brain. Make it possible to share it. Differentiate it from the shared brain with different colours instead of all grey	RQ1
Written chat	A user can send and receive messages. It can function as a note-taking tool	The keyboard on the HoloLens is unreliable. This can make typing difficult. An alternative is to implement voice commands and 'speech to text'.	RQ3

6.1.1 Hand tracking

The general feedback regarding the hand tracking visualised with finger endpoint joint spheres was positive, indicating that it enhanced the visibility of users' actions. Participants found observing and understanding what others were working on more accessible, even without specific gestures. Hand tracking contributed to a stronger sense of collaboration and connection between users, aligning to promote a more immersive and engaging collaborative experience. These findings suggest that hand tracking in collaborative AR applications can improve coordination and communication within the learning environment. Further research with a larger user group is recommended to validate these results.

This follows the findings of Radu et al. [54] that collaborators need to be aware of others' attention and activities. Hand tracking will contribute to knowing the activity of the others within the session.

6.1.2 Gestures and User Avatar

Including gestures such as thumbs-up and a humanoid avatar enhanced user expression and fostered a sense of connection in collaborative sessions. The goal was to create an application that closely resembles real-life interactions when used remotely. The human-like avatar design received positive feedback from both users and experts. Participants reported a stronger sense of working together than being separate entities. This contributed to a more immersive and engaging collaborative experience. The answers confirm the importance and impact of non-verbal communication, as described in section 2.4.1. Even though an Avatar cannot fully replace a person, the results suggest that it can improve communication.

Avatars and hand gestures will meet the first need on Radu et al.'s list of needs, being aware of others' attention. It will also contribute to non-verbal communication and some possibility of giving immediate feedback to others.

In Figure 5.4, the avatar is shown using the new pointing gesture to point at a specific area of the rat brain. The implemented pointing gesture in the collaborative AR application proved to be an effective tool for remote collaboration and communication. During the workshop, participants could accurately point at specific areas of the rat brain using the pointing gesture, and the observers could identify the targeted areas correctly. This suggests that the 'pointing gesture' feature accurately indicates and highlights specific anatomical structures or regions of interest.

The feedback on hand gestures also confirms the role of non-verbal communication. Especially the pointing feature was said to be precise and suitable for communication. Clarity is one of the things that help in effective communication, as described in section 2.4.1. Precise pointing is clear and consistent and will reduce the level of confusion and use of words. It meets the need for collaborators to coordinate both attention and instruction, which is need number three and four according to Radu et al.s list [54] (Section 2.5.1).

6.1.3 Brain Copy

The ability to copy the brain to a shared session was well-received by users in both remote and collocated sessions. It provided a valuable feature for CL and interaction.

Regarding the colour representation of the brain model, opinions were divided among users. Some users appreciated the greyscale colouring, providing a consistent and neutral representation. However, others found distinguishing different brain parts challenging without colour differentiation. It may be beneficial to explore alternative colour schemes or visual cues that maintain clarity while aiding in identifying other brain regions.

However, there was divided feedback regarding constantly showcasing the resize functionality. Some users found it beneficial, allowing for easy resizing and precise manipulation of specific components. They appreciated the convenience of having this functionality readily available on the main model.

While other users expressed concerns about its potential for distraction and confusion. They found that the continuous display of the resize option made it easy to accidentally resize instead of performing other actions, such as moving specific brain components.

Some even missed the option to share their copy with the group. The full potential of adding private content and how this will add to better learning has not been studied in this project. However, according to Radu et al. [54], collaborators need privacy, as presented in section 2.5.1. Each collaborator might want to explore things alone because they will not bother the rest of the group or might not want to reveal what they are uncertain about.

This feedback sheds light on the importance of carefully designing and presenting interaction options within the application. Balancing the accessibility of features with the potential for unintentional actions is crucial to provide a seamless and intuitive user experience. Users have different wishes, backgrounds and knowledge, so further testing on a more extensive test group within the target group of this application is necessary to assess the best direction for most users.

6.1.4 Written chat

The written chat functionality in the Nevrolens application was found to have limited use on the HoloLens device due to the limitations of the HoloLens keyboard. Users experienced varying degrees of difficulty with the keyboard, with some encountering frequent bugs and issues. This inconsistency in user experience highlights the challenge of text input on the HoloLens and suggests that there may be better mediums for text-based communication.

During the testing phase, it became evident that voice communication was the preferred method among users. Voice communication provides a more natural and efficient interaction, especially in CL scenarios. However, it is essential to consider alternative communication options, such as a mobile application, where voice communication may not always be feasible or preferred (e.g., in noisy environments or when users cannot speak).

The chat display also could serve as a note-taking feature during Nevrolens sessions. While the usefulness of this functionality could not be thoroughly evaluated within the limited scope of this project, it holds the potential for enhancing CL experiences. Note-taking facilitates information retention and serves as a valuable user reference during and after the session.

This will be in accordance with need number two on Radu et al. list [54], to be aware of the past by helping remember actions and conversations.

6.2 Proof of concept functionality

Table 6.2: Identified and tested as proof of concept functionality requirements and their relation to RQ

Functionality	Description	Suggested improvement	RQ
Azure spatial anchor	The user can choose to synchronise a digital object at the same physical location	Recommend upgrading Nevrolens to Unity 2020+ with OpenXR to implement this feature.	RQ2
Gesture Recognition with ML	Recognise a gesture shown in the field of view of the HoloLens	Not viable in Nevrolens to hardware limitations.	RQ2, RQ3

6.2.1 Azure spatial anchor

The feedback from users regarding the Azure spatial anchor mock application indicated that its implementation is essential for co-located collaborative anatomy learning. This feature allows users to synchronise digital objects in the exact physical location, facilitating a shared understanding of anatomical structures during collaborative sessions.

By leveraging the Azure spatial anchor functionality, users can anchor and align digital objects, enhancing coordination and communication among collaborators. This feature creates a more immersive and interactive learning experience resembling real-life interactions.

This has also been recognised as a need for collaborators by Radu et al. [54]. On their list, this is need number seven, to share the same environment, including the same virtual object.

6.2.2 Gesture recognition with Machine Learning

The integration of ML capabilities within the HoloLens device showed promising results while evaluating the Nevrolens application. Specifically, displaying evaluation time, prediction, and confidence numbers as text proved effective and provided valuable information to users. This successful implementation demonstrates the potential for ML on the HoloLens, especially in future iterations with improved hardware capabilities.

The accuracy of the predictions achieved an impressive average of 99%, indicating the reliability and effectiveness of the ML model used.

However, it is essential to note that the inference time on the HoloLens is significantly slower than running the same model on a computer. The average inference time of 200 ms on the HoloLens is approximately 20 times slower than 10 ms on a computer. This discrepancy highlights the HoloLens device's hardware limitations when executing computationally intensive tasks such as ML.

Although the slower inference time may be a limitation in the current state of the HoloLens, it also highlights the potential for improvement. As hardware advancements continue to enhance the processing capabilities of the next generation of HoloLens or similar hardware, ML could be used on the device simultaneously as a more computationally demanding application like Nevrolens is.

The ML model employed in this project utilises an ImageNet backbone that was trained using TensorFlow and converted to the ONNX format for execution on the HoloLens. As part of future research, there is potential to optimise this model further to enhance its effectiveness, which could have significant implications for ML on the HoloLens platform.

Possible ways to improve the ML model could be performing hyperparameter optimisation, which involves fine-tuning the various model parameters and training configurations to achieve better performance. This process can help identify optimal hyperparameter settings, such as learning rate and batch size.

Additionally, considering a more lightweight backbone architecture like EfficientNet could help with the performance of running the model on HoloLens. EfficientNet is designed as a more lightweight mode, making it suited for hardware-constrained technologies like the HoloLens.

6.3 User tests

The user tests consist of both qualitative and quantitative data. By interviewing the users, they can elaborate on their thoughts about the tested application. When developing an application, the developers might miss vital information like user skills, previous experiences, expectations of performance, usefulness of the application and more.

There was a limited number of users in this project. However, having experts and student representatives ensured that both groups' opinions were heard.

When conducting the specialisation project (section 2.7), nine students were testing Nevrolens, interviewed and gave answers to the SUS test. Having the same group testing and providing feedback on the newly developed features would have been beneficial. A new semester made these students unavailable, so new users were selected.

The usefulness of the answers and feedback from the test group must be evaluated upon their background and previous experience. As observed with the student group, 3 of 4 students had their first time trying HoloLens. Some training and skills are mandatory to understand this new environment and to control the commands. The researchers noted this in their specialisation project (as described in section 2.7.1). Reducing the number of users in the same test session in this project made it possible to give better instructions and some help to overcome unnecessary frustration.

In the workshops, there was a focus on getting feedback on the new features of the Nevrolens application. Hence, the usefulness and potential for learning were not asked for specifically. Some general feedback on the Nevrolens application was still recorded and appreciated.

6.3.1 Interviews and Observations

Most of the interview feedback is used in the discussion of implemented features. Here are general observations and feedback discussed.

Both students and experts agreed that Nevrolens was fun and playful and, to some extent, enhanced the engagement. These are all factors that can increase motivation and hence be a factor for better learning, as reported by Chang et al. in their meta-analysis of (quasi-) experimental studies to investigate the impact of AR in education [32].

An expert also mentioned that collaboration with AR could lead to better learning than self-study. This is following other researchers' findings. Laal and Laal specifically say that they had found that CL generally improves classroom results and is especially helpful in motivation [39]. Other researchers like Bork et al. [10] investigated the use of AR in education and reported positive findings for AR in anatomy learning as presented in section 2.4.

For the main object, the rat brain, the users would like it to be easier to snap in place brain parts and have a redo/undo functionality. This will reduce stress and time to move on and increase learning.

6.3.2 SUS score and response to queries

SUS score

The SUS is used throughout the industry to evaluate various products and services within computer systems. The SUS score measures the users' subjective opinion regarding the system's usability they have been asked to assess. Many of these SUS tests are used to improve already implemented systems that most users have experience with, for example, a website's functionality or mobile applications. In these cases, the users have experience with similar systems, and the results then measure whether this system is better or worse than what they expect.

When using SUS to evaluate Nevrolens usability, there must be considered that ARon HoloLens is quite different from more mature technologies. Several users tried AR in HoloLens for the first time.

There was a clear difference between the experts, who scored an average of 70.0, and the students, who scored 50.0. To put this on a global adjective scale, it means the expert rated the usability as OK to Good, while the students rated it as poor. The experts had some previous knowledge about the system and might also see the potential of the application more clearly than the students and, therefore, more willing to give it a good score.

As part of the specialisation project, the researchers tested nine students. The average SUS for the mobile application was 67.5 but only 51.4 for HoloLens. This indicates that testing on a familiar device like a mobile phone might give a better score. The change in score for the student groups was minor, but when including experts with previous knowledge, the average score increased from 51.4 to 58,6. From this limited number of test persons and the different variations in the groups, it can't be concluded that the change is significant.

An interesting observation is that expert no 102 tested the application before and after implementing the new features. The score went up from 67.5 to 72.5. This might be because he had fewer difficulties due to some experience and found new functionality to increase usability.

Hagum and Woldseth [14] found an average SUS score of 73. They had the score made several times through 4 iterations and tested the application's learning outcome. Then it is expected that the users gain valuable experience with the system and find it beneficial for their learning. In a development situation, the SUS can give valuable information to the developer. Still, it is clear that the context and type of users are essential to know and that the SUS score must be interpreted accordingly.

Response to queries

More specific statements were asked about the users' experience with the HoloLens application, as seen in Table 5.6. The same questions were asked to the students participating in the specialisation project, as seen in Table 2.1. Here there are some interesting changes in the answers.

Especially the question, "It is easy to see what brain part my co-student (s) is looking at". The score was 2.67 before and 3.57 after implementing the new functionality. This was the highest score of all statements and is taken as a confirmation that the users appreciated the pointing feature.

Another statement that scored higher the second time was “I was always aware of my co-student (s) location within the application”. This changed from 2.44 to 2.86. Not all the users in this project had the opportunity to explore the Avatars, and a limited number of users were participating simultaneously. This statement would have been more appropriate if many participants were active in the same collaborative session. In these sessions, a clear representative of the other peers will be more helpful and help in communication.

A statement with a lower score in this project was “The app has been helpful to my understanding of neuroanatomy”. The student group participating in the specialisation project scored 4.22, and the group in this project scored 3.29. The first student group was taking an introduction course to Neuroscience; hence, they had some knowledge about neuroanatomy and found the application useful for their understanding. The group in this project consisted of both experts in the field of anatomy and students that did not have the same specific interest in learning anatomy. Then it is natural that this score becomes lower.

6.4 Research Questions

The research questions posed in this study aimed to investigate various aspects of CL, engagement, interaction and communication in designing and developing an educational AR application on a Head Mounted Display (HMD). The following section will discuss how these research questions have been addressed and how they have been answered in this project.

RQ: How can the design of an educational AR application on a Head Mounted Display (HMD) be optimised to enhance remote and collocated CL experiences in the field of anatomy?

The following sub-questions aim to answer this central question.

RQ1: What collaborative features should be implemented to enhance the learning of anatomy?

This project did not test the learning potential of collaborative features. However, a need for private content was identified in addition to the features already implemented in Nevrolens for CL. Radu et al. [54] found several studies claiming collaborators need personalised information. They found that it is helpful for students to investigate their private representation of the shared content. The VesARlius application has features for private content as described by Bork et al. [10].

The implemented function, local brain copy, represents such a feature. This feature allows the individual student to independently investigate a copy of the brain even though they are in a shared session. Having this option might enhance the effectiveness of learning. This might be a more needed and effective learning tool when the application is used to give a shared lecture than when the application is used in Peer learning. When a teacher lectures on the shared object, the students can have their own copy to explore themselves, as they will not interfere with the shared lesson and gain personalised learning.

RQ2: What interaction and communication features should be incorporated to increase engagement in the educational AR application?

The project incorporated additional interaction and communication features such as waving, thumbs-up, and thumbs-down gestures to Nevrolens in addressing this question. These features aimed to enhance user expressiveness and foster a more engaging collaborative experience. Feedback from users and experts indicated that these features indeed increased engagement and created a sense of working together rather than as separate entities.

To answer this question, the project implemented a user avatar feature. The feedback from users indicated that this feature enhanced collaboration by allowing users to interact and communicate effectively in remote and collocated sessions. The user avatar, in particular, provided a sense of presence and made users feel more connected, simulating a real-life collaborative environment. The users communicated that the application felt more engaging with this feature.

RQ3 What interaction and communication features should be integrated to facilitate effective user communication in the educational AR application?

The project explored various interaction and communication features to facilitate effective communication. For instance, the finger tracker feature and pointing gesture allowed users to easily see what others were working on, even without explicitly expressing a specific gesture.

The Azure spatial anchor allows users to interact with a digital object at the exact location. This feature will enable participants to effectively point with the "real hand" talk and look at the other participants.

6.5 Limitations

6.5.1 Limited Unity version

During the development of the Nevrolens application, it became evident that the original version of Unity used (Unity 2019) lacked support for several new features necessary for the desired functionality, including spatial tracking and dissonance voice chat. An upgrade to Unity 2020 or a newer version was considered to address this limitation. However, it was realised that upgrading the project to a newer version would be time-consuming and may not directly address the research questions. As a result, it was decided to work around the limitations by treating unsupported features as proof of concepts and focusing on developing features that were supported by the current version of Unity. This approach allowed for the project's advancement while acknowledging and managing the limitations imposed by the software version.

6.5.2 Limited experience

The developers of this project initially lacked prior experience in MRTK, AR, and Unity development. As a result, a learning curve was involved in understanding and utilising these technologies to implement the desired features. This learning process introduced additional overhead in the development phase, as the developers had to invest time in acquiring the necessary knowledge and skills.

The development of the Nevrolens application builds upon the foundation laid by two previous research projects. Because of this inheritance, the current researchers required some time to familiarise themselves with the project structure, the various coding techniques employed by the late developers, and the different hierarchical components within Unity. Understanding the existing codebase and its organisation was crucial to develop new features for the application effectively. This process involved studying the previous iterations, analysing the code, and gaining a comprehensive understanding of the underlying architecture of Nevrolens.

6.5.3 Limited resources

Hardware Limitations

The research primarily utilised the HoloLens as the AR device for the application. However, the HoloLens has certain limitations regarding processing power, display resolution, and battery life. These limitations have limited the implemented feature on the application.

Developing and testing on the HoloLens has time constraints. To test a new functionality or bug test a developed feature, each run must be exported to the HoloLens, where the Unity editor does not give a proper representation of features in most cases. These deployments are time-consuming, where each compilation time takes around 20 min.

User Sample Size

The user studies conducted as part of this research involved a limited number of participants. While efforts were made to ensure diverse representation, the findings may not be fully generalised to a larger population. Increasing the sample size and diversifying the user group in future studies would provide a more comprehensive understanding of the application's effectiveness.

Time Constraints

This project was conducted within a specific time frame of one semester, which imposed constraints on the extent of development and evaluation. Some features or optimisations that could have been explored were not fully implemented due to time limitations. Future research can delve deeper into these aspects to enhance the application further.

Technical Challenges

Developing an AR application involves addressing technical challenges related to tracking accuracy, gesture recognition, and network connectivity. While efforts were made to overcome these challenges, certain limitations persisted. Addressing these technical limitations through advanced algorithms, hardware improvements, and network optimisations would contribute to the refinement of the application.

External Factors

External factors, such as the learning environment, user familiarity with AR technology, and individual preferences, may influence the usability and effectiveness of the AR application. These external factors could introduce variability in the results and user experiences. Future research can explore the impact of these external factors in more detail to enhance the application's adaptability and effectiveness.

Cost Factor

HoloLens 2 costs 52,669.00 NOK for each device. The current price point is a limiting factor for the accessibility of HoloLens in the broader market, as one of the experts from this project stated that the cost limited the current relevance, where the university did not have the funds to cover this cost. However, it is fair to assume the price will drop drastically with future product iterations and more competitors entering the market. A new AR glass option was just announced by Apple, potentially bringing new opportunities to the field of AR [75].

Chapter 7

Conclusion

This project aimed to design and develop features for Nevrolens, an educational Augmented Reality (AR) application on a Head Mounted Display (HMD) for remote and collocated collaborative anatomy learning. Through extensive research, testing, and evaluation of various features, valuable insights were gained regarding the effectiveness of collaborative, interaction and communication features and their impact on engagement and communication in the learning process.

Implementing features such as finger tracking, gestures, and avatar representation enhanced collaborative anatomy learning experiences. The ability to point at specific parts of the brain using finger tracking facilitated remote collaboration and improved visualisation. Additional gestures allowed users to express themselves and foster a sense of connection during collaborative sessions. The feedback from users and experts highlighted the positive impact of these features on teamwork and engagement.

The chat functionality, although limited by the HoloLens keyboard, could be helpful on Android and iOS applications or serve as a tool for note-taking during sessions. However, it was recommended to explore text communication as an alternative for effective and efficient communication, particularly in noisy environments.

The Azure spatial anchor and remote rendering functionalities showcased their potential in overcoming hardware limitations and enabling detailed models to be rendered on the cloud and transmitted to the HoloLens.

Machine learning on the HoloLens demonstrated high prediction accuracy but with relatively slower inference times compared to traditional computer setups. Future research should focus on optimising the machine learning models by exploring alternative backbone architectures and hyperparameter optimisation techniques to improve performance on the HoloLens.

In conclusion, the project's findings indicate that integrating collaborative features, interaction techniques, and communication functionalities has positively impacted engagement and communication in the educational AR application on the HMD and hence, enhancing learning. The insights from addressing the research questions contribute to a deeper understanding of designing and developing compelling CL experiences using AR technology.

The implementations from this project can hopefully guide the development of future AR applications aimed at improving CL experiences in anatomy education and other domains.

7.1 Future Work

One important suggestion for future work in developing the Nevrolens application is to upgrade the Unity version from 2019 to a newer version with OpenXR support. This upgrade holds the potential to unlock significant opportunities for implementing crucial functionalities in the application as covered in this project, Azure spatial tracking, Azure rendering capabilities and Dissonance voice. Additionally, upgrading to a newer Unity version with OpenXR support ensures future compatibility with upcoming hardware advancements and emerging technologies in the AR and VR landscape, keeping the application relevant and effective in anatomy education.

Another suggestion is to make the gesture and avatar functionality customisable. Currently, the Nevrolens application only detects gestures on the right hand. The user should be able to select which hand the gestures appear (right, left or both hands). The user should also be able to turn off both their own hand gestures and the other users' hand gestures in a collaborative session. The user should also be able to customise their own avatar to distinguish themselves in a session and to express more of their own personality. The avatar should also be able to enable/disable if wished so by the user.

Azure remote rendering is another service offered by Azure. This functionality has not been tested in this project, but the utilisation of Azure for remote rendering presents a promising solution to overcome the limitations of HoloLens hardware capacity in displaying detailed models. By offloading the rendering process to the Azure cloud, more intricate anatomy models, human avatars, hand gestures and the rat brain in Nevrolens, can be rendered and transmitted to the HoloLens device.

Considering the limitations of the HoloLens keyboard and the preference for voice communication, future versions of the Nevrolens application could explore voice command integration as an alternative text input method to improve the chat functionality. Then they could share messages by simply dictating messages. Finding effective ways to facilitate communication and note-taking within the Nevrolens application will provide a more seamless and productive CL experience.

The Machine Learning models used in this study demonstrated high prediction accuracy but suffered from longer inference times on the HoloLens. Future research could focus on optimising these models, exploring lightweight backbone architectures, and leveraging hardware acceleration to improve inference speed and overall performance.

Conducting more extensive user studies and evaluations with a larger and more diverse participant pool would provide a deeper understanding of the application's effectiveness and usability. This could involve collecting quantitative data on learning outcomes, user satisfaction, collaboration effectiveness, and qualitative feedback through interviews and observations.

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Appendix A

Nettskjema

Vis | Bygg skjema | Kodebok | Innstillinger | Innhent svar | Se resultater

PC | Mobil | Last ned som PDF | Sjekk universell utforming i skjemaet

Nevrolens usertest

What is your participant number?

Please answer the following statements about usability when using the MOBILE application

These statements are about your experience using the application on the phone. Choose the option that best matches your experience on a scale from Strongly Agree to Strongly Disagree.

	Strongly disagree	Disagree	Neither agree or disagree	Agree	Strongly agree
I think that I would like to use this system frequently.	○	○	○	○	○
I found the system unnecessarily complex.	○	○	○	○	○
I thought the system was easy to use.	○	○	○	○	○
I think that I would need the support of a technical person to be able to use this system.	○	○	○	○	○
I found the various functions in this system were well integrated.	○	○	○	○	○
I thought there was too much inconsistency in this system.	○	○	○	○	○
I would imagine that most people would learn to use this system very quickly.	○	○	○	○	○
I found the system very cumbersome to use.	○	○	○	○	○
I felt very confident using the system.	○	○	○	○	○
I needed to learn a lot of things before I could get going with this system.	○	○	○	○	○

Please answer the following statements about usability when using the HOLOLENS application

These statements are about your experience using the application on the hololens. Choose the option that best matches your experience on a scale from Strongly Agree to Strongly Disagree.

	Strongly disagree	Disagree	Neither agree or disagree	Agree	Strongly agree
I think that I would like to use this system frequently.	○	○	○	○	○
I found the system unnecessarily complex.	○	○	○	○	○
I thought the system was easy to use.	○	○	○	○	○
I think that I would need the support of a technical person to be able to use this system.	○	○	○	○	○
I found the various functions in this system were well integrated.	○	○	○	○	○
I thought there was too much inconsistency in this system.	○	○	○	○	○
I would imagine that most people would learn to use this system very quickly.	○	○	○	○	○
I found the system very cumbersome to use.	○	○	○	○	○
I felt very confident using the system.	○	○	○	○	○
I needed to learn a lot of things before I could get going with this system.	○	○	○	○	○

Please answer the following statements about your experience with the mobile application.

Choose the option that best matches your experience on a scale from Strongly Agree to Strongly Disagree.

	Strongly disagree	Disagree	Neither agree or disagree	Agree	Strongly agree
I think I would use the mobile application frequently for self-study	○	○	○	○	○
I think I would use the mobile application frequently for collaborative study	○	○	○	○	○
It is easy to locate the information I want	○	○	○	○	○
It is easy to see what brain part my co student(s) is looking at	○	○	○	○	○
I was always aware of my co-student(s) location within the application.	○	○	○	○	○

Please answer the following statements about your experience with the holo-lense application.

Choose the option that best matches your experience on a scale from Strongly Agree to Strongly Disagree.

	Strongly disagree	Disagree	Neither agree or disagree	Agree	Strongly agree
It is easy to locate the information I want	○	○	○	○	○
It is easy to see what brain part my co student(s) is looking at	○	○	○	○	○
I was always aware of my co-student(s) location within the application.	○	○	○	○	○

Please answer the following statements about your overall experience

Choose the option that best matches your experience on a scale from Strongly Agree to Strongly Disagree.

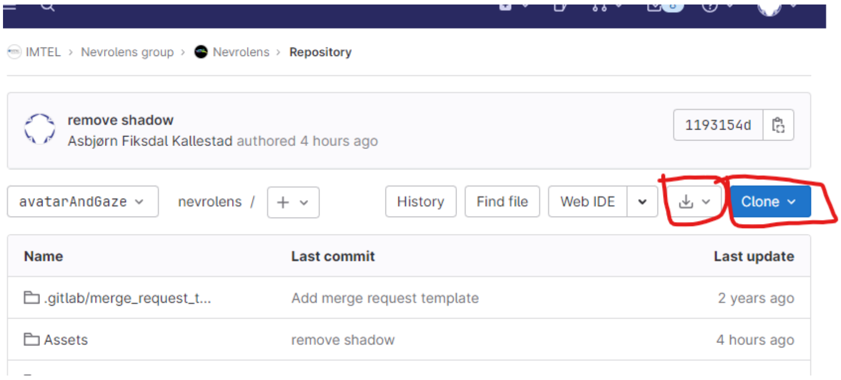
	Strongly disagree	Disagree	Neither agree or disagree	Agree	Strongly agree
The app has been helpful to my understanding of neuroanatomy	○	○	○	○	○
I felt nauseous after using the application	○	○	○	○	○

Appendix B

How to deploy Nevrolens to HoloLens

Step 1: clone or downlod(if download downliad the avatarAndGaze branch) the project from

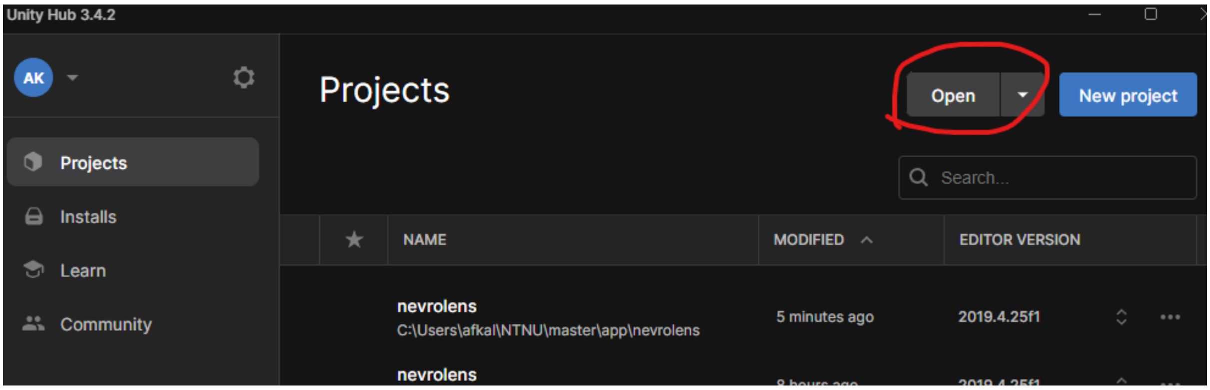
https://gitlab.stud.idi.ntnu.no/imtel/nevrolens-group/nevrolens/-/tree/avatarAndGaze?ref_type=heads



In a git terminal if the project was cloned write “git switch avatarAndGaze”

Step :

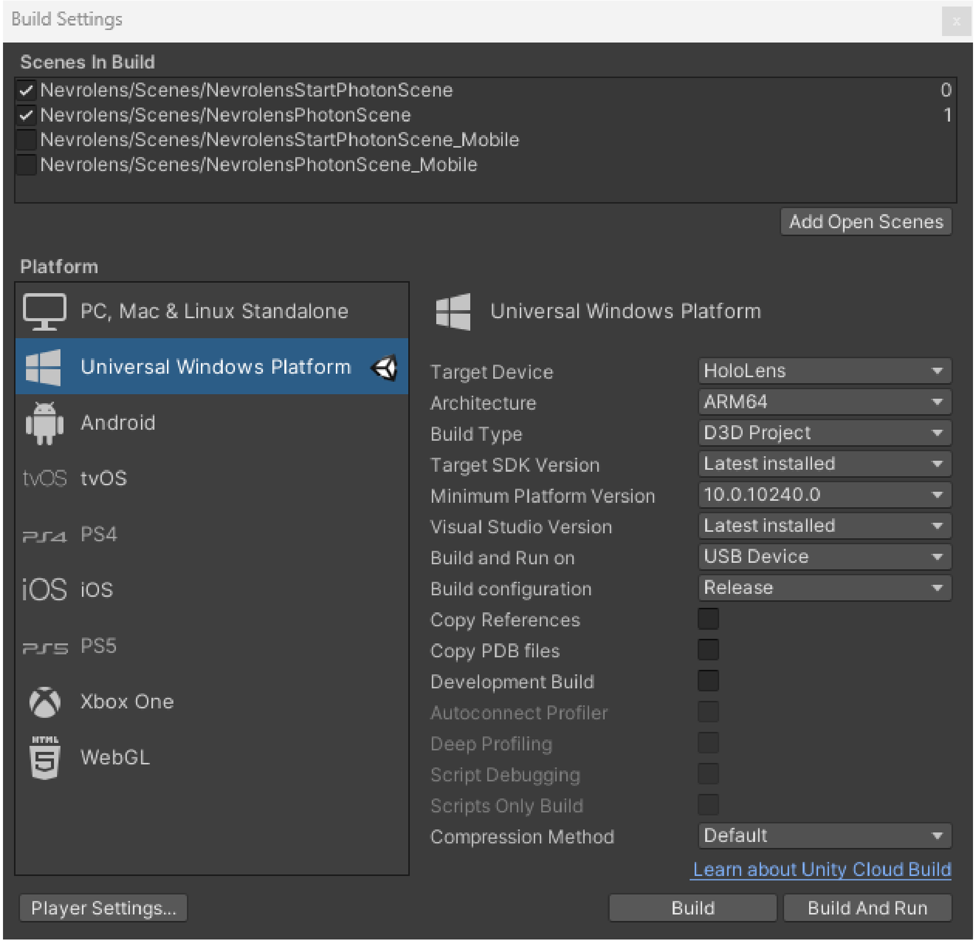
Open the Nevrolens folder with unity hub:



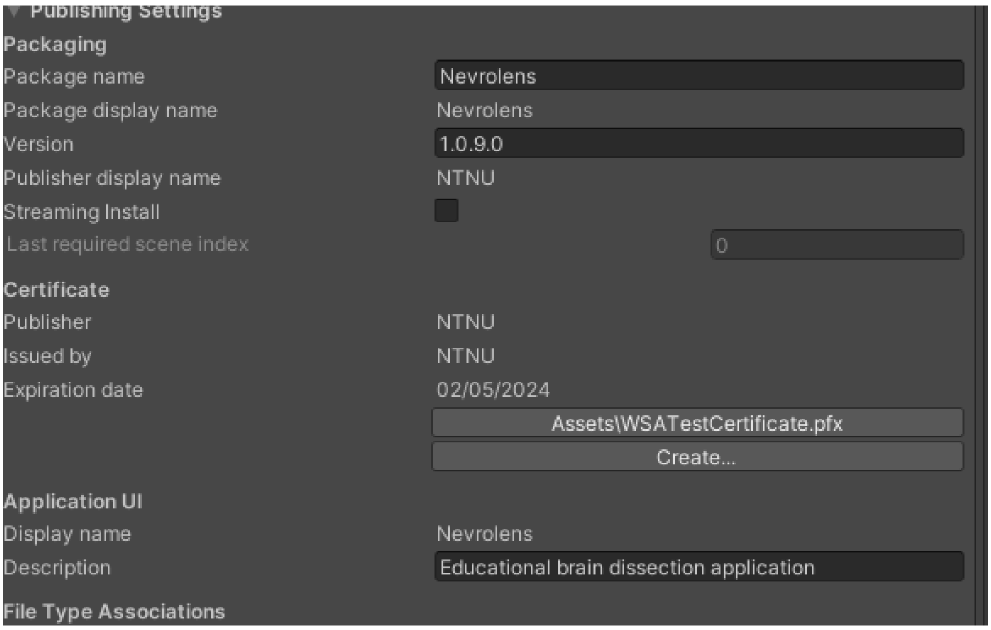
Then enter the folder called nevrolens downloaded earlier and hit the open option down right in the file explorer prompt. The Click download on all the suggested prompts.

Step :

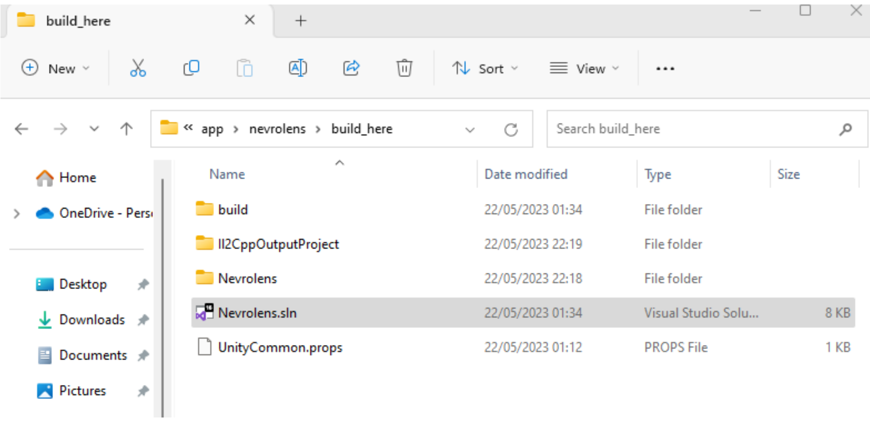
In unity top right corner hit File< Build settings. Click on the option called windows universal platform and switch to this. Then change the settings to the same as the one on the piceture below.



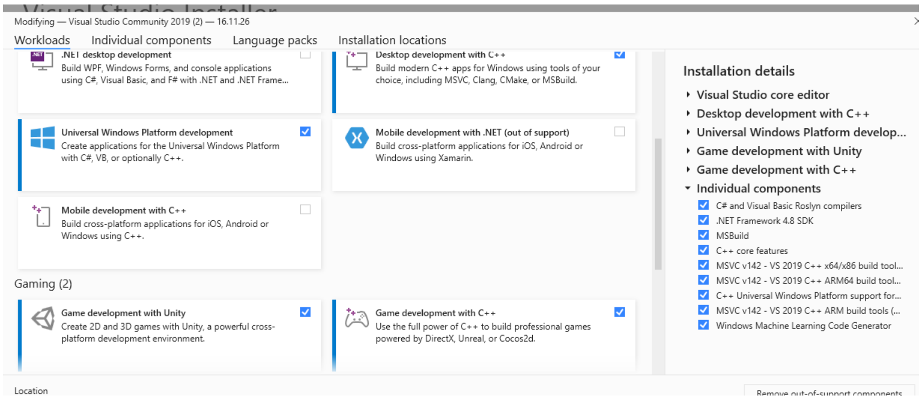
Click the player setting option at the bottom left of the above image. Check under publishing settings that the certificate is valid. If it is not valid click the certificate placed above create and just delete it from the file explorer. Close this window.



Back in the build settings hit build enter the “build_here” folder and hit open. After building is a folder will appear. here open the Nevrolens.sln file.



Then visual studio will open. Make sure these packages are downloaded in visual studio installer:



On your hololens make sure “developer settings” are turned on. This is done by going to Settings<Update and select “for developers menu item. Also turn on “Device discovery”. There is a pair option here, save this code for when it is prompted.

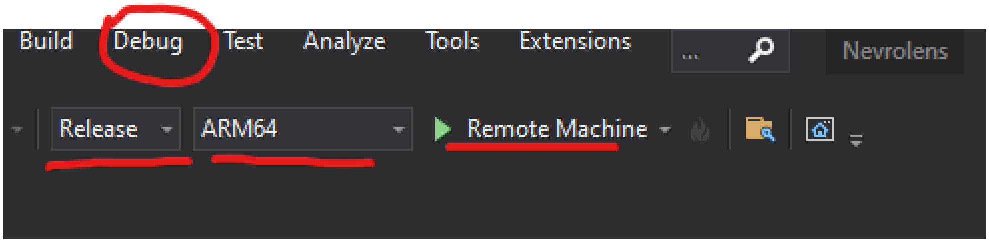
Same for your computer:

1. Go to **Settings**.
2. Select **Update and Security**.
3. Select **For developers**.
4. Enable **Developer Mode**, read the disclaimer for the setting you chose, and then select **Yes** to accept the change.

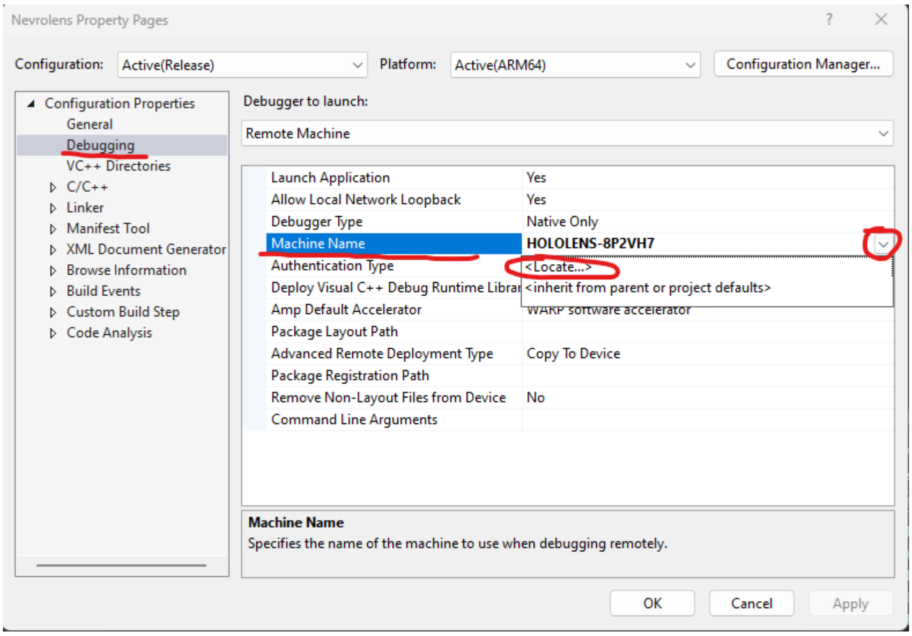
The two devices should also be on the same network.

Back to the visual studio opened earlier select the Release ARM64 and Remote Machine option in the top bar.

After that select the Debug item list and select the bottom option "Debug properties"



In the properties menue click Debuging then the empty down arrow on the white field on the right side of the "Machine name" row. Click locate here.



Hololens should appear as an option. Click it, click select, then click apply and close this window. Now press **F5** and the download to hololens should start. Remember to keep hololens charged during this.

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