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Mixed reality for surgeons training in neurosurgical procedures

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Abstract

Neurosurgery demands high precision and advanced training techniques to ensure optimal patient outcomes. This thesis presents NeuroMix, an innovative mixed reality platform designed to enhance neurosurgical training through immersive, risk-free simulations. NeuroMix leverages the Meta Quest 3 headset to provide a highly interactive training environment, which combines realistic 3D anatomical modeling with tools for accurate spatial measurement and transparency adjustments. The platform specifically addresses the need for improved training in intraventricular catheter placement, a procedure critical for managing elevated intracranial pressure, where inaccuracies can lead to severe complications. This pilot study explores the current landscape of MR technologies in surgical training.

Through assessments conducted with neurosurgery residents, NeuroMix has shown high usability and acceptance, as evaluated using standardized metrics like the System Usability Scale, NASA Task Load Index, and the Technology Acceptance Model. Results indicate that NeuroMix not only enhances skill acquisition but also reduces reliance on traditional cadaver-based training, promoting more accessible surgical education. The thesis concludes by proposing future enhancements to NeuroMix, including automated 3D alignment and haptic feedback capabilities, underscoring its potential to set new standards in neurosurgical training and to foster the development of highly skilled surgeons.

Sommario

La neurochirurgia richiede alta precisione e tecniche di formazione avanzate per garantire risultati ottimali ai pazienti. Questa tesi presenta NeuroMix, un'innovativa piattaforma di realtà mista progettata per migliorare la formazione neurochirurgica attraverso simulazioni immersive e prive di rischi. NeuroMix sfrutta le cuffie Meta Quest 3 per fornire un ambiente di formazione altamente interattivo, che combina una modellazione anatomica 3D realistica con strumenti per la misurazione spaziale accurata e la regolazione della trasparenza. La piattaforma risponde in modo specifico all'esigenza di migliorare l'addestramento nel posizionamento dei cateteri intraventricolari, una procedura fondamentale per la gestione dell'elevata pressione intracranica, dove le imprecisioni possono portare a gravi complicazioni. Questo studio pilota esplora l'attuale panorama delle tecnologie di risonanza magnetica nella formazione chirurgica.

Attraverso le valutazioni condotte con gli specializzandi in neurochirurgia, NeuroMix ha dimostrato un'elevata usabilità e accettazione, valutata utilizzando parametri standardizzati come la System Usability Scale, il NASA Task Load Index e il Technology Acceptance Model. I risultati indicano che NeuroMix non solo migliora l'acquisizione delle competenze, ma riduce anche la dipendenza dalla formazione tradizionale basata sui cadaveri, promuovendo una formazione chirurgica più accessibile. La tesi si conclude proponendo futuri miglioramenti a NeuroMix, tra cui l'allineamento 3D automatizzato e le funzionalità di feedback aptico, sottolineando il suo potenziale nel definire nuovi standard nella formazione neurochirurgica e nel promuovere lo sviluppo di chirurghi altamente qualificati.

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List of Acronyms

Below are the acronyms used in this document:

VR Virtual Reality

MR Mixed Reality

AR Augmented Reality

XR Extended Reality

EVD Extra Ventricular Drainage

CSF Cerebrospinal Fluid

SUS System Usability Scale

NASA-TLX NASA Task Load Index

TAM Technology Acceptance Model

TAM-PU Perceived Usefulness (from Technology Acceptance Model)

TAM-PE Perceived Ease of Use (from Technology Acceptance Model)

HMD Head-Mounted Display

CTH Catheter Tract Hemorrhage

FOV Field of View

SDK Software Development Kit

Introduction

Intraventricular catheter placement is a **vital**, life-saving procedure used to address elevated intracranial pressure. It is a common neurosurgical intervention performed both in emergency situations such as external ventricular drainage (EVD) and in elective surgeries like ventriculo-peritoneal or ventriculo-atrial shunts. The procedure involves inserting a catheter into the brain's ventricles to drain cerebrospinal fluid (CSF), thereby alleviating pressure on the brain. Despite its *relative technical simplicity*, improper placement of the ventricular catheter can lead to **severe consequences** for patients.

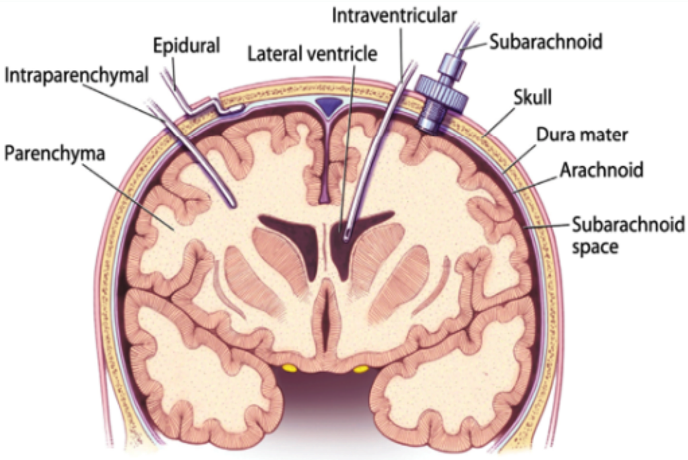


Figure 1: EVD procedure image.

Complications arising from misplacement of intraventricular catheters are a significant concern in neurosurgery. Improper catheter placement can result in inadequate CSF drainage, leading to persistent intracranial hypertension. Additionally, incorrect positioning may damage critical brain structures, resulting in neurological deficits. Hemorrhagic complications, such as intraventricular hemorrhage or intracerebral hematoma, are also associated with misplacement and multiple insertion attempts. These complications not only pose immediate risks to patient health but also increase the length of hospital stay and overall healthcare costs.

While technical skill and proper surgical training are crucial to minimize perioperative complications and ensure accurate anatomical placement, the *standard freehand EVD technique* results in catheter misplacement in up to 60.1% of procedures (ranging from 12% to 60%). Additionally, about 20% of cases require multiple attempts to achieve correct catheter positioning. Misplacement is often compounded by hemorrhage and catheter obstruction, which are major reasons for additional surgeries aimed at replacing the ventricular catheter.

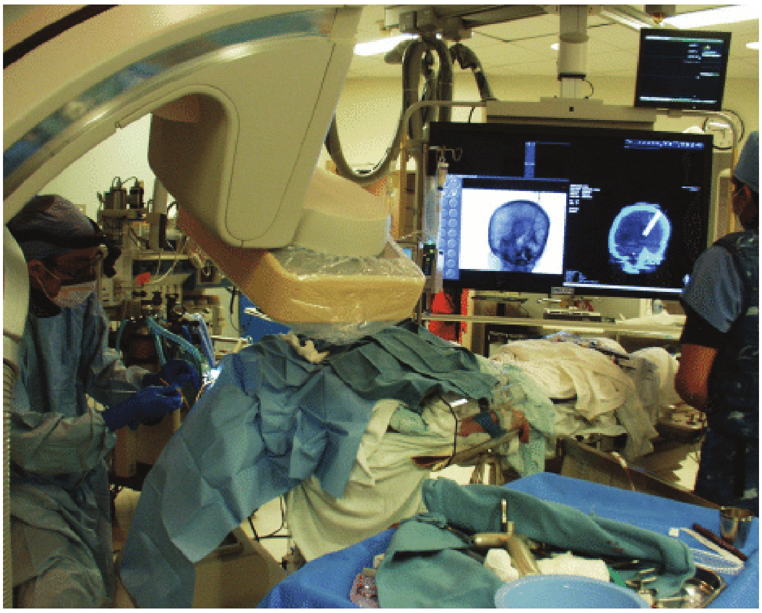


Figure 2: A neurosurgeon inserting an intraventricular catheter during a procedure.

Patients who undergo catheter replacement experience a 29% rate of ventriculostomy-related infections, compared to a 6% rate in those who do not require replacement. The estimated cost for diagnostics, procedures, and materials for EVD replacement ranges from approximately $1,300 to $3,200 per replacement. Pericatheter hemorrhage or catheter tract hemorrhage (CTH) has been reported in 14% to 21% of patients. **Improving catheter placement accuracy in the operating room** can reduce the risk of CTH and malfunction.

The neuronavigator is a device that assists neurosurgeons in reconstructing the exact location of intracranial pathologies requiring surgery, based on pre-operative neuroimaging such as CT scans, MRI, fMRI, and tractography. It also maps adjacent critical brain areas, providing guidance in planning and executing the surgical procedure. However, this technology has limitations, including *high costs*, the time needed for planning, and its *unavailability in all operating rooms*.

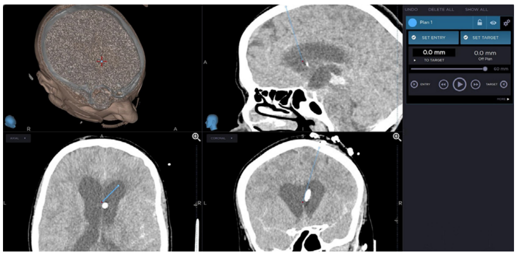


Figure 3: A neuronavigation system used in neurosurgical procedures Stuart et al. (2021).

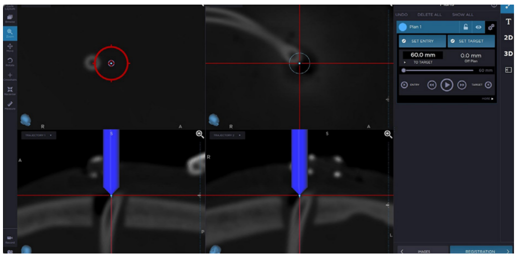


Figure 4: Intraventricular catheter viewed trough a neuronavigation Stuart et al. (2021).

Additionally, neuronavigation systems require meticulous preoperative planning and registration processes to align the patient's anatomy with the imaging data. Any patient movement can lead to registration errors, decreasing the accuracy of the navigation. Intraoperative changes such as brain shift, caused by factors like CSF leakage or tissue resection, can further reduce the reliability of neuronavigation. These limitations can compromise the precision of catheter placement, potentially leading to suboptimal patient outcomes.

Extended Reality (XR), encompassing Virtual Reality (VR), Augmented Reality (AR), and Mixed Reality (MR), has gained significant attention in the medical field. XR technologies offer immersive and interactive experiences, allowing for enhanced visualization and simulation in medical training, surgical planning, and intraoperative navigation.

The use of XR in medicine provides several advantages:

- **Enhanced Visualization**: XR can overlay digital information onto the physical world, providing surgeons with real-time guidance and improving spatial awareness during procedures.
- **Improved Training and Education**: Medical professionals can use XR simulations to practice complex procedures in a risk-free environment, enhancing their skills and reducing the likelihood of errors.
- **Cost-Effectiveness**: XR technologies can reduce the need for expensive physical models or cadavers, making training more accessible.
- **Remote Collaboration**: XR enables remote assistance and collaboration

among medical teams, which is particularly valuable in situations where specialist expertise is required.

By integrating XR technologies into neurosurgical procedures, there is potential to overcome the limitations of traditional methods and neuronavigation systems. XR can provide more intuitive and accessible guidance for catheter placement, potentially improving patient outcomes and reducing complications.

for the CLEAR investigators et al. (2018), Saladino, White, Wijdicks, and Lanzino (2009), Stuart et al. (2021)

Neurosurgery is a field that continuously pushes the boundaries of medical technology and precision. This thesis aims to address the pressing need for enhanced and more accessible neurosurgical training methods by developing and evaluating an immersive mixed reality platform known as **NeuroMix**. The primary objective of this thesis is to make neurosurgical training more accessible and easier for residents, particularly by reducing the reliance on expensive and complex resources such as cadaver dissections and neuronavigators. By providing an alternative training platform, **NeuroMix** aims to offer an effective and affordable solution that can be widely adopted in both clinical and educational contexts.

The key contributions of **NeuroMix** are as follows:

- **Development of a Standalone Mixed Reality Training System**:
  By leveraging the capabilities of the **Meta Quest 3** headset and the **Unity** game engine, **NeuroMix** offers a portable and user-friendly platform that does not require additional hardware or external computing power. This standalone nature enhances the flexibility and accessibility of neurosurgical training, allowing users to practice in various settings without complex setups.

- **Realistic Simulation of Intracranial Procedures**:
  The system provides an interactive simulation of cannula insertion, enabling users to understand the spatial and dimensional aspects of the procedure in a virtual environment. This hands-on experience closely mirrors real-life surgery, offering a valuable alternative to traditional training methods that rely on physical cadavers or costly neuronavigation systems.

- **Facilitating Accessible Training for Neurosurgical Residents**:
  One of the primary objectives of **NeuroMix** is to make neurosurgical training more accessible and easier for residents. By providing a cost-effective alternative to expensive tools like cadaver dissections and neuronavigators, the system allows residents to gain practical experience without the financial

and logistical barriers associated with traditional methods.

- **Advanced Visualization Features**:
  NeuroMix incorporates innovative features such as mesh-based distance measurement, transparency and opacity controls, and 1:1 mapping between 2D DICOM images and the 3D skull model. These features enhance the user's spatial awareness and understanding of complex anatomical structures, which is critical for accurate surgical planning and execution.

- **Interactive DICOM Annotation**:
  The system allows users to directly annotate DICOM images via the headset, integrating these annotations with the 3D model. This interactive capability fosters a deeper engagement with the medical data and facilitates better comprehension of anatomical relationships.

- **Enhancement Over Traditional Neuronavigation Systems**:
  By providing a mixed reality environment that integrates both volumetric DICOM data and 3D anatomical models, **NeuroMix** offers an improved alternative to traditional neuronavigation systems that primarily display 2D images. This advancement enhances decision-making processes and spatial awareness during surgical procedures.

- **Cost-Effectiveness and Accessibility**:
  The use of affordable and widely available hardware like the **Meta Quest 3** makes the system more accessible to a broader audience, promoting wider adoption in clinical and educational contexts. This aligns with recent trends in adopting XR technologies for surgical training due to their ease of use and ability to offer immersive, real-time guidance Zhang, Lu, and Khanduja (2023).

The thesis begins with the **Introduction to XR technologiess** chapter provides an overview of immersive technologies and their applications in surgical training. VR, AR, MR, and XR have shown significant promise in medical training, allowing for enhanced spatial awareness and interaction with digital models in a simulated environment. Each of these technologies is explored in the context of how they can support and revolutionize surgical training. This section establishes a technological foundation that supports the subsequent introduction of the NeuroMix system as a pioneering tool in neurosurgery education Li et al. (2017); Rauschnabel et al. (2022).

In the **Neurosurgery Through Mixed Reality - The NeuroMix System** chapter, the design, features, and capabilities of the NeuroMix platform are presented in detail. Utilizing the Meta Quest 3 headset, NeuroMix provides medical professionals and students with a hands-on experience in a controlled, virtual environment. With advanced functionalities such as 1:1 DICOM-to-3D model mapping, mesh-based distance measurements, and adjustable transparency settings, NeuroMix offers an immersive way to understand and interact with complex anatomical structures. This chapter emphasizes the potential of NeuroMix as a robust training tool that combines medical imaging with interactive learning Izard et al. (2018).

The **Tests on Neurosurgery Residents** chapter details the assessment and evaluation of NeuroMix in a real-world setting. Through usability tests conducted with neurosurgery residents, this section highlights the platform's effectiveness and acceptance as a training tool. Using standardized evaluation metrics like the System Usability Scale (SUS), NASA Task Load Index (NASA-TLX), and the Technology Acceptance Model (TAM), the results show that NeuroMix could not only improves training outcomes but also could reduces the need for physical practice on cadavers, thereby facilitating more accessible surgical training Benmahdjoub et al. (2023).

The thesis concludes with a **Discussion and Future Work** chapter, where the potential advancements for the NeuroMix system are explored. This chapter discusses possible improvements, such as extending testing to a more diverse audience, incorporating automated tracking for precise 3D model alignment, and adding haptic feedback for a more tactile experience. These developments aim to ensure that NeuroMix remains at the forefront of neurosurgical training, capable of supporting a new generation of highly skilled surgeons. The anticipated advancements highlight how NeuroMix could continue to evolve as a comprehensive, versatile, and realistic training tool for surgical education Khor et al. (2016).

This structured approach not only addresses a critical gap in neurosurgical training but also explores the broader implications of immersive technologies in medical education and patient care. The subsequent chapters will build on this introduction by delving into each topic in detail, showcasing how NeuroMix could play a pivotal role in the future of neurosurgical training and practice.

Chapter 1

XR applications in medicine

1.1 Introduction to XR technologies

In the world of immersive technologies, understanding the distinctions between VR, AR, MR, and XR is crucial. **VR** creates a completely digital environment, immersing users in a fully computer-generated world, often via a headset, isolating them from the physical surroundings. **AR**, on the other hand, overlays digital elements, such as images or data, onto the real-world environment, enhancing reality rather than replacing it. **MR** goes a step further by blending the physical and digital worlds, allowing interaction between virtual objects and the real environment in real-time. Finally, **XR** serves as an umbrella term that encompasses all these immersive technologies, including VR, AR, and MR, highlighting the continuum between real and virtual experiences.
To be able to live these experiences one needs an **Head-Mounted Displays** (HMD).

1.1.1 What is an HMD?

Until recent years, interaction with virtual environments was limited to traditional displays such as TV monitors and computer screens. While this medium remains reliable and relatively inexpensive, it presents limitations due to its mostly static nature, making it less practical for tasks that could be performed more efficiently with greater immersion, such as surgical simulations or pilot training.

To overcome these challenges, **HMDs** were developed. An HMD is a display device worn on the head or integrated into a helmet, featuring a small display optic positioned in front of one eye (monocular HMD) or both eyes (binocular

HMD). These devices offer enhanced immersion and have numerous applications in fields such as gaming, aviation, engineering, and medicine.

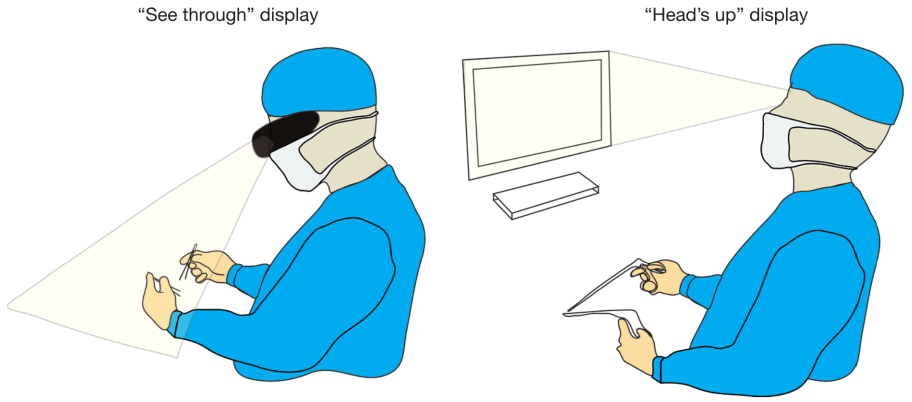


Figure 1.1: HMD vs display Li et al. (2017).

1.1.2 Differences between the types of HMDs

HMDs can come in many shapes and sizes depending on their specific purpose. For our case, they will be divided into four classifications, each of which has its own specifications.

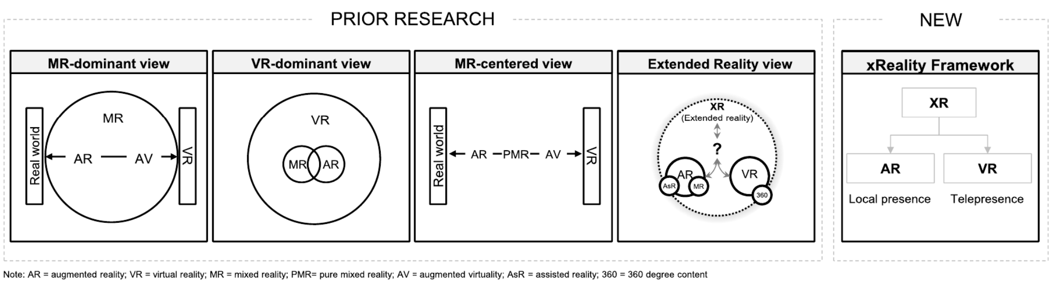


Figure 1.2: Schematic representation of prior "views" on new reality formats Rauschnabel et al. (2022).

VR HMD

A **VR** HMD is a device designed to provide **immersive experiences** in virtual environments.
Users can **interact** with and experience these **computer-generated environments** that **simulate** real-world experiences or entirely imaginary worlds. These devices **do not** allow interaction with the outside world, isolating the user to provide an experience as immersive as possible. They can be tethered to a

computer or console, or they can also be independent stand alone systems. While also touting positional tracking, the system does not usually have the tracking directly implemented within the headset, instead relying on external devices to track it. This limits its use to areas with these supplemental devices already pre-deployed (**Outside-in tracking** Figure 1.3).

MR HMD

An **MR** HMD is a device primarily used for **blending virtual content with the real world**.
Mixed Reality experiences, where digital content is seamlessly integrated into the user's physical environment, allowing for **interactions with both virtual and real-world** elements simultaneously.
This type of devices is very similar to a VR HMD, as they also can be tethered to a computer, console or be independent stand alone systems, with the main difference between these two types of headsets being that a modern MR HMD has an **embedded tracking system** equipped for both the surroundings and users actions (**Inside-Out tracking** Figure 1.3). They are also usually equipped with several high definition color cameras attached to the front and sides of the HMD to ensure good tracking, view, and interaction with the outside world.

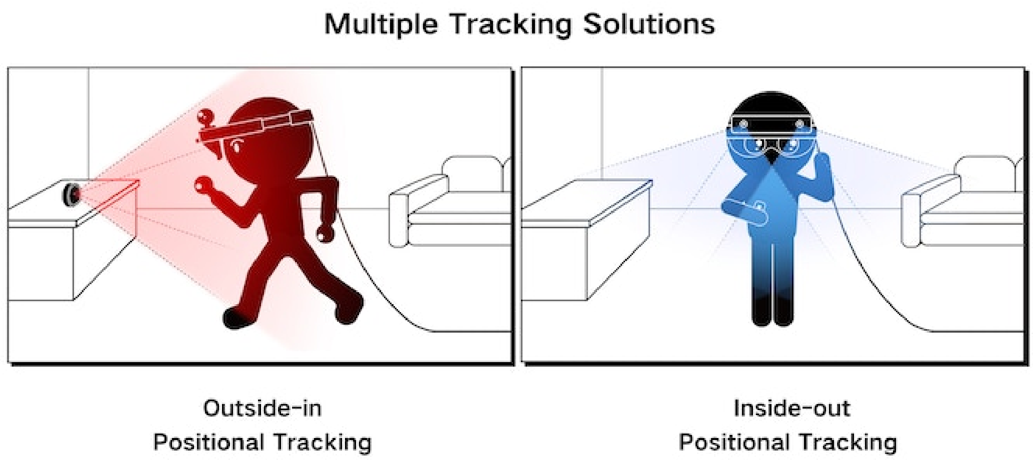


Figure 1.3: Inside-out vs Outside-in tracking *Source*.

AR HMD

An (**AR** HMD, is a device designed to overlay digital content onto the user's real-world environment.
Augmented Reality, is where virtual objects or information are **superimposed** onto the user's view of the physical world, enhancing their perception and interaction with their surroundings.
These devices are **much lighter** than MR or VR HMDs and require a much **lower computational capacity** to function at their best as they do not have to track the user's surroundings and movements, allowing them to be much **more energy efficient** as well.
Furthermore, they **do not** actively block the user's **field of view** (FOV) but add overlay information to the device's lenses, which are transparent.
The experience of **Augmented Reality is not limited only to the use of HMDs**, as it can be also experienced through smartphones, tablets or any other devices with a camera and a screen.

XR HMD

An **XR** HMD, is a device that facilitates immersive experiences encompassing VR, AR, and MR. "XR" devices have the its capability to support a **spectrum of reality-altering technologies**, allowing users to engage with virtual environments, overlay digital content onto the real world, and seamlessly blend virtual and physical elements together for enhanced interactive experiences.
This type of devices can be described as a mix of all the prior mentioned types of HMDs by inheriting all their particular capabilities.

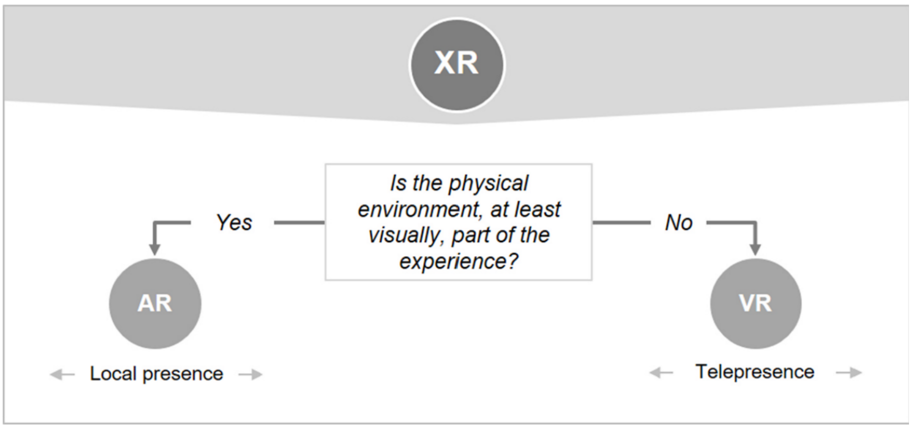


Figure 1.4: XR as an umbrella term for AR and VR Rauschnabel et al. (2022).

1.1.3 Popular HMDs

The most popular HMDs currently on the market cover a wide range of XR technologies (VR, AR, and MR), each with specific features that define their use in various fields. Below are some of the most widely used devices.

Meta Quest 3

The *Meta Quest 3* is one of the most popular mixed reality headsets for both consumer and professional use. It is a standalone device, meaning it does not require an external PC to function, making it highly portable. Equipped with high resolution and color passthrough capabilities for mixed reality, the Quest 3 is perfect for both VR and MR applications. Thanks to its ability to provide high-quality immersive experiences without additional equipment.

Figure 1.5: Meta Quest 3.

Microsoft HoloLens 2

The *Microsoft HoloLens 2* is a mixed reality device particularly used for visualizing and interacting with 3D models overlaid onto the physical environment. With its advanced tracking and improved ergonomics, it is ideal for long periods of use without causing discomfort to the user.

Figure 1.6: Microsoft HoloLens 2.

Google Glass Enterprise Edition 2

The *Google Glass Enterprise Edition 2* is an AR headset designed for enterprise applications. It allows users to view real-time information without obstructing the view of the real world. With its lightweight and discreet design, it offers an AR experience without blocking the user's view, making it ideal for hands-free tasks.

Figure 1.7: Google Glass Enterprise Edition 2.

Varjo XR-3

The *Varjo XR-3* is a high-end mixed reality headset with extremely high resolution and eye-tracking capabilities. Its ability to blend the real and digital worlds offers users detailed and interactive visualization experiences.

Figure 1.8: Varjo XR-3.

HTC Vive Pro 2

The *HTC Vive Pro 2* is one of the most highly regarded virtual reality headsets due to its 5K resolution and precise tracking. Its controllers allow for high precision in virtual interactions, making it suitable for applications requiring complex movements.

Figure 1.9: HTC Vive Pro 2.

Sony PlayStation VR2

Although primarily aimed at gaming, the *Sony PlayStation VR2* offers advanced features such as precise tracking and high visual quality, providing highly engaging immersive experiences.

Figure 1.10: Sony PlayStation VR2.

1.2 Evaluation of XR Tools

The evaluation of XR tools typically employs various standardized methods to assess usability, user experience, and workload. Three widely adopted methods in the field are the **NASA-TLX**, the **TAM**, and the **SUS)**. These evaluation techniques are crucial for determining the effectiveness and user satisfaction with immersive technologies across different applications, from education to healthcare.

1.2.1 NASA-TLX

The *NASA-TLX* is a widely used tool to measure perceived workload in performing tasks, particularly in demanding environments such as those involving XR technologies. It assesses six dimensions of workload: mental demand, physical demand, temporal demand, performance, effort, and frustration. Each dimension is rated by users, and the resulting scores provide insight into how taxing an XR system is on cognitive and physical levels. The NASA-TLX has been frequently used to evaluate the cognitive load imposed by VR, AR, and MR systems, making it a standard tool in the assessment of these technologies.

1.2.2 TAM

The *TAM* evaluates how users accept and use new technology by focusing on two main factors: perceived usefulness and perceived ease of use. In the context of XR, TAM helps understand how likely users are to adopt a new XR system based on how beneficial and user-friendly they find the technology. TAM is particularly relevant in assessing XR tools, as it gauges not only the effectiveness of the technology but also how willing users are to integrate it into their daily practices. This model has proven effective in providing insight into user behavior and acceptance in various immersive technology applications.

1.2.3 SUS

The *SUS* is a simple, yet effective tool for measuring the usability of a system. It consists of a 10-item questionnaire that provides a score from 0 to 100, where higher scores indicate better usability. SUS has been extensively used in the evaluation of XR systems, providing a quick and reliable way to assess how intuitive and user-friendly the interface of an XR tool is. The SUS is particularly beneficial in comparing different systems or versions of the same technology in terms of their usability.

1.2.4 Application of Evaluation Methods in XR

These methods have been widely adopted in the evaluation of XR technologies due to their ability to provide comprehensive insights into different aspects of user experience and system performance. In the study by Benmahdjoub et al. (2023), the authors employed NASA-TLX, TAM, and SUS to evaluate XR tools, highlighting the importance of using multiple assessment methods to capture a broad picture of both the cognitive workload and the overall usability of XR systems. This combination of methods allows researchers and developers to refine XR tools, making them more efficient and user-friendly.

In general, combining these evaluation tools provides a robust framework for assessing the effectiveness, acceptance, and usability of XR technologies. By applying such methods, designers and engineers can better understand how users interact with XR tools and how these tools can be improved to meet their needs.

1.3 Medical Applications of XR tools

As illustrated in *subsection 1.1.2*, virtual reality can take different forms depending on the use case. As far as the medical field is concerned, there are two areas where these technologies are having a huge impact: **Surgical Education** and **Surgical Aid** Zhang et al. (2023). In this chapter will be explored these two important fields of the healthcare system, showing the currently feasible applications and possible evolutions of this technology.

1.3.1 Surgical Education

Surgical Simulators

With realistic environments that allow surgeons to hone their abilities without endangering patients, VR simulators have emerged as indispensable instruments for **surgical education**. The effectiveness of these simulators depends on the creation of **automatic feedback systems**, the design of **evaluation metrics**, and the processes for **obtaining data**. The following text will examine the structure used to develop and assess virtual reality surgical simulators in a simplified way. It highlights the importance of haptic devices, the collaboration between engineers and medical professionals, and the use of machine learning algorithms to improve performance evaluation. We will also explore the innovative strategies driving advancements in surgical education and training, looking at the entire process from data collection to automated feedback systems.

- **Data Acquisition**

  VR/MR **surgical simulators** are based on efficient data acquisition, which is mainly dependent on **haptic device feedback**. These systems convert **physical movements** into **matching actions** within the virtual environment, providing vital information about positional data. The position and orientation of the **haptic device** helps engineers figure out the right **force feedback**, **cutting angles**, and **tissue interactions**. Developers must appropriately analyze the raw data pertaining to the haptic device handler's position in order to extract useful metric values.

- **Evaluation Metric Design**

  Engineers and doctors must work together to create efficient evaluation **metrics** for VR/MR surgical simulators. The ability of surgeons to apply their knowledge and practical insights is essential for **converting surgical information into useful evaluation criteria**. It is also necessary for developers to become acquainted with the particular surgical techniques that the simulator aims to replicate. **Effective performance measurement** can be accomplished through a variety of strategies, including talking to medical professionals, reading literature, or creating new measurements. These measurements, which include things like **force application**, **cutting angles**, **tissue damage**, and **procedural efficiency**, are genrally grouped according to the surgical tasks that are being assessed.

- **Evaluation Metric Generation**

  The two main categories of evaluation metrics are **qualitative** and **quantitative** metrics, each of which has a specific function in evaluating the performance of the simulator. Qualitative metrics analyze visual and **tactile fidelity**, **stability**, **real-time performance**, and **user-friendliness**. These measurements are often collected through user feedback **questionnaires**. Conversely, quantitative metrics provide quantifiable information based on

pre- and post-test results or direct simulation outcomes, such as operating time, procedural errors, and tissue damage. Quantitative evaluation requires the identification of **critical parameters** and the quantification of metrics for these parameters. Furthermore, performance comparisons with commercially available simulators offer insightful information about a simulator's capabilities.

- **Surgery simulators examples**
  - **Laparoscopic**

    The development of skills required for **laparoscopic surgery** might be difficult because there are not many opportunities for trainees to practice in the operating room safely. Surgical simulators have become essential to laparoscopic training facilities in order to address this. Common simulators include LapSim, Lap Mentor, MIST-VR, and Simendo Li et al. (2017). **These simulators offer trainees the opportunity to practice basic and procedural skills in a controlled environment**, reducing the risks associated with patient exposure during training. While earlier systems like MIST-VR provided rudimentary training capabilities, newer iterations like LapSim and Lap Mentor offer more **comprehensive skill assessment and training features**. Despite advancements, none of these simulators have incorporated HMD technology into their design, as laparoscopic procedures primarily rely on monitor (Figure 1.1) observation for critical tasks such as camera manipulation and hand-eye coordination. Research suggests that while combining **VR simulators with HMD helmets enhances immersion**, it does **not significantly impact training outcomes**.

  - **Orthopedic**

    The research conducted in **orthopedic surgery** over the past 20 years indicates that the development and application of simulators has proceeded at a significantly slower pace than in other surgical specialties. Simulators for **arthroscopy training** stands out among the scant material currently available. Developed by Mentice AB, Sweden, the Procedicus KSA surgical simulator and Procedicus Li et al. (2017) virtual arthroscopy simulator have been used for knee arthroscopy training since the early 2000s. These simulators make **training tasks on virtual knees easier** with their haptic feedback and anatomical images. However, there isn't enough data to suggest that short-term training improves performance. With its **life-size plastic shoulder,**

pre-programmed portals, and haptic feedback, 3D Systems' Insight Arthro Shoulder Simulator in the United States allows residents to practice a variety of postures and duties specifically related to shoulder arthroscopy. For the quantitative evaluation of arthroscopy skills, Japanese researchers have created a virtual reality simulator equipped with an **electromagnetic motion monitoring** system and an artificial knee model. Virtual reality simulators have also been investigated for open **orthopedic surgery**, including total hip replacement (THA), hip trauma, and fracture fixation. Preoperative planning and navigation are key components of these simulators, such as HipNav for THA training and TraumaVision for broken femur orthopedic simulation. Moreover, systems such as the one created by Jun et al Li et al. (2017). use virtual surgical simulation and 3D knee models generated from CT scans to assist surgeons in determining custom implant components and total knee replacement (TKR). These developments in preoperative planning and training for orthopedic surgery simulation present encouraging paths forward; however, additional study and validation are necessary to maximize their efficacy.

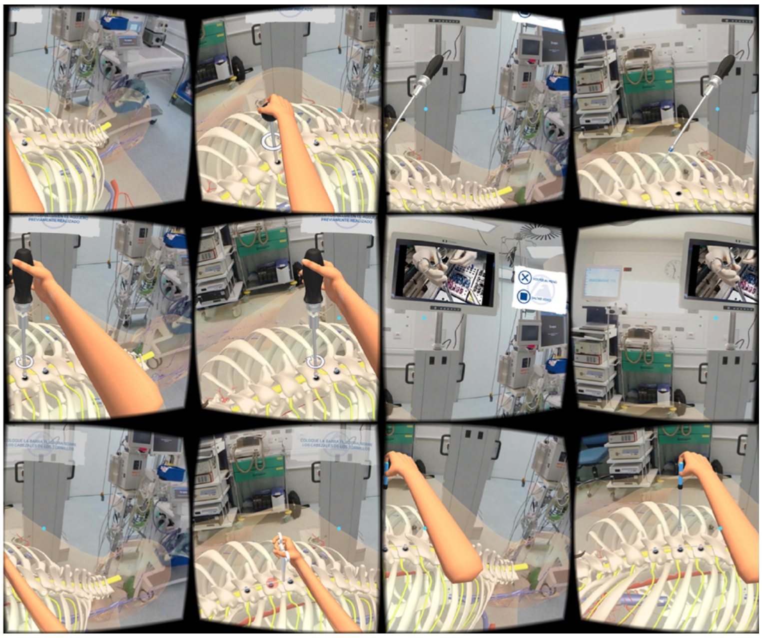


Figure 1.11: Screenshots of the steps for a surgery Izard et al. (2018).

Broadcasting and recording surgeries

The medical community has taken notice of the first live **worldwide broadcast** of the VR surgical environment, which provides viewers with a 360-degree view from the head of the operating table similar as shown in Figure 1.12. The inexpensive cost of VR, achieved by using devices such as Google Cardboard, has the potential to make surgical education a more immersive platform. Since AR makes interaction with digital and real-world elements realistic, it becomes the best option for live surgery. In Paraguay and Brazil, **live operations** utilizing augmented reality have shown that basic procedures are feasible. Long-distance guidance by other medical professionals is made possible by innovations such as **Virtual Interactive Presence and Augmented Reality (VIPAR)** Khor et al. (2016), which allow remote surgeons to project their hands onto another surgeon's monitor. With the help of platforms like Proximie, surgeons in underdeveloped nations will be able to view recorded or live procedures carried out by professionals all around the world. Furthermore, by projecting holographic models of surgical areas and facilitating contact between surgeons in disparate environments, holoportation—which makes use of Microsoft Hololens—offers greater resources in the operating room. Future educational advancements could be greatly aided by AR in conjunction with triggers such as 3D printed items that play instructive films. Nonetheless, handling such potentially sensitive material from sources with a lot of data needs careful thought. With possible applications extending to patient data incorporated into augmented reality and mobile applications, secure solutions for image and video collection, storage, and documentation are crucial. Similar to the aircraft sector, the idea of recording-enabled HMD acting as medical "*black boxes*" has substantial medico-legal ramifications for clinical practice.

Figure 1.12: Example of a 180 degree camera in an operating theatre *Source*.

1.3.2 Clinical Applications

Surgical Aid

Surgery has seen a notable transformation recently due to the utilization of cutting-edge technologies including VR, AR, and MR. These developments have radically changed **postoperative monitoring**, **intraoperative guidance**, and **surgical planning** in a wide range of surgical specialties. Enhancements in surgical safety, precision, and patient results have been demonstrated in several specialties, such as general surgery, **maxillofacial** surgery, and **neurosurgery**. VR, AR, and MR technologies have enabled more exact intraoperative execution of challenging surgical procedures and more precise diagnosis through the use of **immersive 3D visualization**, simulation, and **real-time navigation**. The following section will elaborate on these aspects by showing examples of real applications of these systems.

- **Neurosurgery**

  VR, AR, and MR technologies have revolutionized **surgical planning**,

intraoperative guiding, and **postoperative tracking** in the field of **neurosurgery**. To mimic the surgical methods utilized in several neurosurgical specializations, such as **endoscopic neurosurgery** and **cranial tumor surgery** Choudhury, Gélinas-Phaneuf, Delorme, and Del Maestro (2013), numerous interactive 3D virtual reality applications have been created. **Virtual reality simulation** has been useful for pedicle screw placement, cerebral aneurysm cutting, microvascular decompression, and bone dissection in clinical settings. Additionally, by assisting in lesion diagnosis and offering assistance during craniotomy and vascular surgeries, AR has demonstrated use in **neuro-oncological** therapies. Uses for augmented reality-based navigation systems and the implantation of external ventilators in tumor-related surgical procedures have been assessed. **AR** has also been used in craniosynostosis, meningiomas, and intracranial tumor excision surgeries. Because it allows for more precise and thorough 3D imaging, magnetic resonance imaging (MR) technology has greatly **enhanced neurosurgery procedures** by facilitating greater surgical navigation and pre-processing. The use of magnetic resonance imaging (MR) in a variety of neurosurgical procedures, such as brain tumor surgery, intracranial anatomy visualization, and therapeutic surgery viability assessment in thoracic surgery, orthopedics, and pediatric surgeries, has been shown by case studies and clinical research. The **precision** and **effectiveness** of neurosurgical procedures have significantly **improved** as a result of these developments, improving patient outcomes.

- **Maxillofacial Surgery**

  Surgery involving the mouth, neck, face, and jaws is referred to as **oral** and **maxillofacial surgery (OMS)** Zhu et al. (2017). OMS has embraced the use of surgical simulators, VR, AR, and dental MR to duplicate a range of surgical procedures, including **implantology**, **orthognathic** surgery, and **mandibular reconstruction**. This is due to the advancements in technology in **simulation-based surgery**. Studies have used VR to model drilling and cutting procedures to evaluate how well simulated surgical plans match real-world results. The promise of virtual reality in OMS has been demonstrated by the use of VR in hardware manufacture and virtual surgical planning for mandibular fractures. Augmented reality has shown promise in reducing risks associated with maxillofacial and dental implantology through **preoperative planning** and **intraoperative navigation**. With AR, patient-specific diagnostic picture data may be shown in a see-through video mode, improving surgical precision in orthognathic surgery. These days, operating rooms include MR technologies, such as Microsoft's HoloLens, to help surgeons make faster decisions. Additionally, MR has been utilized in **orthognathic surgery** for mandibular tracking, visualization, and surgical telepresence. For mandibular oncological surgery, marker-less MR implementations have been created. These programs have been extended to CT imaging in order to **enhance the planning and performance of surgeries**. These technological developments might improve patient outcomes by **raising the accuracy and effectiveness** of OMS operations.

- **General Surgery**

  AR has a variety of uses in different surgical techniques, such as open, **laparoscopic, and endoscopic surgery**, in addition to the uses covered in **neurosurgery and maxillofacial surgery**. Specifically in pancreaticoduodenectomy and pancreaticoduodenal artery dissection, AR has been used in open surgery for operations including pancreatic and hepatobiliary lesion detection, safe dissection, and navigation. Research has looked into the use of **AR in open liver surgery, open urological surgery, and hilar cholangiocarcinoma** Golse, Petit, Lewin, Vibert, and Cotin (2021). Fluorescence guiding is part of hybrid surgical guidance ideas that have been used for distal laparoscopic interlocking surgery on intramedullary nails and sentinel lymph node biopsy in penile cancer cases. Proposed are MRI ultrasonic guiding devices that provide for improved visibility and guidance during operations. HMD-based MRI devices have been reported to **visualize intricate anatomical features in open surgical procedures**, including open **hepatic surgery**. VR and AR applications have also proven beneficial for laparoscopic surgery, which includes gynecological laparoscopic surgery, distal laparoscopic pancreatectomy, and laparoscopic liver surgery. This is because laparoscopic surgery has distinct skill needs and patient safety issues. Across a broad spectrum of surgical disciplines, these technical advances in AR and MR have the **potential to improve surgical precision, safety, and patient outcomes**.

Figure 1.13: Use of Accuvein to image veins on patient Khor et al. (2016).

Figure 1.14: Use of Google Glass in theatre Khor et al. (2016).

Pain management

VR has shown **great promise in the treatment of pain** by providing innovative methods for treating both **acute and chronic pain**. VR technology was first presented by Hoffman et al. in 1998 Li et al. (2017), and since then, it has shown promise in l**owering burn-related pain and controlling pain** in a variety of settings. VR technology provides an **alternative to pharmaceutical therapies** for the management of acute pain. Research has examined the application of VR games in the treatment of burn injuries, demonstrating that **VR technology offers analgesia with little adverse effects**. Additional research has validated the efficacious reduction of acute pain when conventional analgesia is combined with virtual reality gaming. **Virtual reality hypnosis (VRH)** Li et al. (2017), which blends VR technology with hypnosis techniques to relieve pain, is another cutting-edge method. VRH has demonstrated encouraging outcomes in lowering patients' pain and anxiety levels. **Traditional pharmaceutical therapies** for pain that lasts more than three months **may not be useful** in managing chronic pain. Though there is currently a alck of research in this field, developments VR technology presents novel therapy options for chronic pain. Research has looked at the application of VR to chronic pain disorders such chronic neck pain and complex regional pain syndrome. Sophisticated VR **mirror visual feedback systems** have been created to address complicated regional pain condition, and they may improve the effectiveness of analgesics. Furthermore, **tracker-based virtual reality** systems have been studied for the treatment of persistent neck discomfort, and the findings have been encouraging in terms of increasing cervical range of motion. All things considered, virtual reality technology has great potential as a useful supplementary therapy for pain management, providing novel and perhaps successful methods for treating both acute and chronic pain disorders Mosso-Vázquez, Gao, Wiederhold, and Wiederhold (2014).

Chapter 2

Neurosurgery Through Mixed Reality: NeuroMix

NeuroMix is a system designed to provide an interactive mixed reality simulation for the insertion of a cannula into a human skull, developed using Unity and the Meta Quest 3 headset. The goal of the system is to offer an immersive and realistic training environment for medical students and professionals to practice this surgical procedure.

Thanks to **NeuroMix**, it becomes significantly easier to understand the *spatial* and *dimensional* aspects of the procedure without relying on physical cadavers or objects, which are traditionally used in medical training. The mixed reality environment allows users to visualize the intricate details of the operation in a controlled, virtual space, providing a *hands-on experience* that closely mirrors real-life surgery. This not only eliminates the ethical and logistical challenges associated with the use of cadavers but also enables a more cost-effective and accessible training method Izard et al. (2018).

XR encompassing VR, AR, and MR, has been widely studied for its potential in surgical training, pre-operative planning, and intra-operative guidance. For example, XR-assisted surgery has been shown to improve surgeons' spatial awareness and understanding of critical anatomical landmarks, leading to shorter operating times and reduced surgical errors Zhang et al. (2023). Similarly, in the case of NeuroMix, the system allows surgeons and students to familiarize themselves with complex anatomical structures and to practice the insertion of the cannula in a low-risk, high-fidelity environment, which can directly translate into improved surgical outcomes Zhang et al. (2023).

Moreover, the **Meta Quest 3** operates as a *standalone device*, requiring no additional hardware or external computing power, making it a highly portable and user-friendly tool. This feature enhances the *flexibility* of the training, as users can practice in a variety of settings without the need for complex setups or dedicated training facilities. The headset's self-contained functionality ensures that **NeuroMix** delivers a *seamless and efficient* experience, empowering users to focus solely on honing their skills in a realistic and immersive environment. This aligns with recent studies showing that XR technologies such as VR and AR are increasingly being adopted due to their ease of use and the ability to offer immersive, real-time guidance during complex surgical procedures Zhang et al. (2023).

2.1 Technological Choices and Collaborations in the Neuromix Project

The *Neuromix* project was developed through a close collaboration between the Virtual and Augmented Reality Laboratory at the University of Bologna and Bellaria Hospital, both located in Bologna. The development team is composed of Andrea Loretti and Alessio Di Pasquale as the main developers, with the supervision of Prof. Pasquale Cascarano. Prof. Gustavo Marfia, the professor responsible for the laboratory, acted as the senior supervisor. Dott. Matteo Martinoni, a renowned neurosurgeon, contributed as a specialist consultant.

2.1.1 Technology Selection

For the development of the project, the **Unity** game engine was used together with the **Meta Software Developement Kit** (SDK) version 62.0.0, intended for **Meta Quest 3** hardware.

Reasons for Choosing Unity Unity was chosen for its ease of use and the ability to migrate the project in the future with greater flexibility compared to other game engines. Its large developer community and the availability of additional resources and plugins further motivated this choice.

Reasons for Choosing Meta Quest 3 The *Meta Quest 3* was selected as it represents the most affordable and widespread mixed reality headset on the market. This choice makes the project more accessible to a wider audience and facilitates the adoption of the technology in both clinical and educational contexts.

2.2 Key Features of NeuroMix System

The **NeuroMix** system offers several cutting-edge features designed to enhance the experience and precision of medical training. Below is a list of the core functionalities:

- Intracranial Catheter Insertion Problem
- Mesh-Based Distance Measurement
- Transparency and Opacity Controls
- 1:1 Mapping between 2D DICOM and 3D Model
- Direct DICOM Annotation via Headset
- Mixed Reality Enhancement over Traditional Neuronavigation

Each of these features is explained in detail in the sections below.

2.2.1 Intracranial Catheter Insertion Problem

NeuroMix is a system designed to provide an interactive mixed reality simulation for the insertion of a cannula into a human skull, developed using Unity and the Meta Quest 3 headset. The goal of the system is to offer an immersive and realistic training environment for medical students and professionals to practice this surgical procedure.

A key advantage of **NeuroMix** is that it operates as a standalone device, unlike many other AR-based systems that require external computing power. For example, in the study by Benmahdjoub et al. Benmahdjoub et al. (2023), which evaluated AR visualizations for catheter insertion tasks, the Microsoft HoloLens 2 was used—an optical see-through (OST) AR device that relies on an external computer to process and display 3D visualizations. This adds complexity to the setup and increases costs. In contrast, **NeuroMix** runs entirely on the Meta Quest 3 headset, which is a more affordable and self-contained device, eliminating the need for additional hardware. This cost-effectiveness and portability make **NeuroMix** an attractive solution for widespread training applications.

Moreover, while the study by Benmahdjoub et al. focuses exclusively on AR approaches, which project virtual models over the real world, **NeuroMix** leverages a broader XR approach. XR encompasses not only AR but also virtual and mixed reality, providing a fully immersive environment. This allows trainees to practice the entire catheter insertion procedure in a controlled, simulated space, gaining experience in understanding the spatial and dimensional aspects of the procedure without relying on physical models or cadavers.

In terms of user experience, the **Meta Quest 3** offers a seamless, highly portable solution that is easier to set up and more user-friendly compared to AR devices like the HoloLens 2. Users can practice in various settings without requiring a complex technical infrastructure, which also reduces the logistical and financial barriers to adoption. This flexibility aligns with the growing trend of adopting XR technologies for surgical training, as shown by recent studies indicating their ability to enhance spatial awareness and provide real-time guidance during complex procedures Zhang et al. (2023).

In neurosurgical procedures such as EVD placement, where accurate catheter positioning is critical to prevent complications like hemorrhage or malposition, systems like **NeuroMix** offer a distinct advantage. In comparison to freehand techniques, which result in malposition rates of up to 45% Stuart et al. (2021), the guidance systems simulated by **NeuroMix**—similar to the orthogonal trajectory models studied by Benmahdjoub et al.—can significantly improve accuracy. However, by combining this precision with the convenience and cost-effectiveness of a standalone XR system, **NeuroMix** holds the potential to make high-quality surgical training more accessible and effective for a wider range of users.

2.2.2 Mesh-Based Distance Measurement

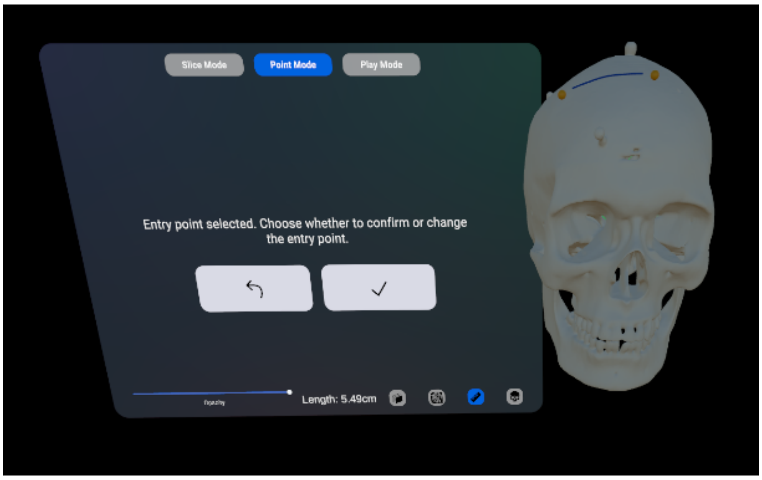


Figure 2.1: Geodesic Distance between two points.

The functionality of measuring geodesic distances on 3D models of the skull, as provided by *NeuroMix*, is a critical feature for ensuring accurate spatial localization of anatomical structures. The ability to precisely determine the distance between specific points on the skull allows users to better understand the geometry and proportions of the skull, which is essential in surgical contexts. In procedures such as EVD placement, every millimeter matters: accurate distance measurement helps establish the optimal insertion point and trajectory for the cannula, thereby minimizing the risk of errors.

This accuracy is particularly important in procedures like ventriculostomy, where small deviations in angle or distance can result in misplacement, hemorrhagic complications, or even neurological damage. According to the study by Stuart et al. (2021), orthogonal techniques significantly improve placement accuracy compared to freehand methods, reducing the risk of malposition from 38% to 20% Stuart et al. (2021). The ability to measure geodesic distances with tools like *NeuroMix* enables the implementation of such techniques with greater safety.

The importance of precise measurement is further supported by the literature, which highlights how AR and VR tools are revolutionizing the surgical field. Khor et al. (2016) emphasize the integration of AR to overlay virtual anatomical information onto real images, providing surgeons with high-precision visual data during operations Khor et al. (2016). Such technology can also be applied to preoperative planning, enhancing the understanding of distances and angles, potentially reducing errors and optimizing surgical outcomes.

2.2.3 Transparency and Opacity Controls

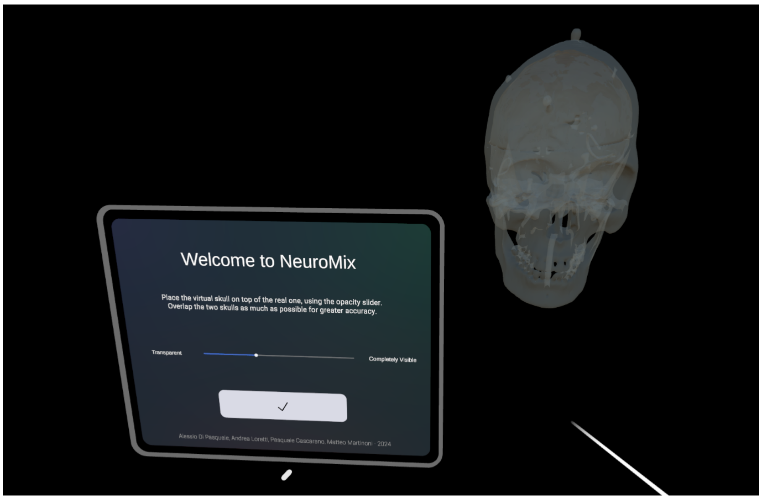


Figure 2.2: Skull transparency selection.

NeuroMix provides a significant advantage in neurosurgical training by allowing users to toggle between a transparent view, which reveals the internal structures, and an opaque view, which simulates the external anatomy of the skull more realistically. This flexibility in visualization is crucial for understanding the complex relationships between cranial structures, especially during procedures such as EVD placement or cannula insertion.

The ability to visualize internal structures in real-time, while also retaining a clear view of the external skull, is invaluable for surgical accuracy and training. During ventriculostomy, for example, accurate trajectory determination is critical to avoid complications such as malposition or damage to critical brain regions. Stuart et al. (2021) demonstrated that precise cannula placement in the ventricles is essential, and that inaccuracies in this regard can lead to high rates of malpositioning—ranging up to 38% in freehand techniques Stuart et al. (2021). The transparent view in *NeuroMix* helps users to better understand the internal anatomy, such as the lateral ventricles, aiding in reducing these risks by ensuring the correct trajectory from the skull's surface to deeper structures.

Additionally, by switching between transparent and opaque modes, the user can appreciate the relative positioning of surface landmarks (such as Kocher's point) in relation to internal structures like the ventricles. This dual-mode visualization fosters a more comprehensive understanding of the anatomy involved in procedures, which can be difficult to grasp with standard opaque models alone. In cases of brain shift or distortion due to trauma or pathology, this insight is particularly valuable, helping to adapt surgical plans dynamically.

Moreover, the use of transparent visualization complements the advancements in AR and VR technologies that are becoming increasingly integrated into the surgical field. Khor et al. (2016) highlighted the utility of AR for providing enhanced views of anatomical structures during surgery, allowing for better decision-making and surgical precision Khor et al. (2016). The capacity to visualize internal structures, as enabled by the transparent view in *NeuroMix*, parallels the benefits of AR by presenting crucial internal details in a clear and interactive format. This leads to improved understanding during training and greater success in actual procedures, where such visual information can significantly reduce error rates.

2.2.4 1:1 Mapping between 2D DICOM and 3D Model

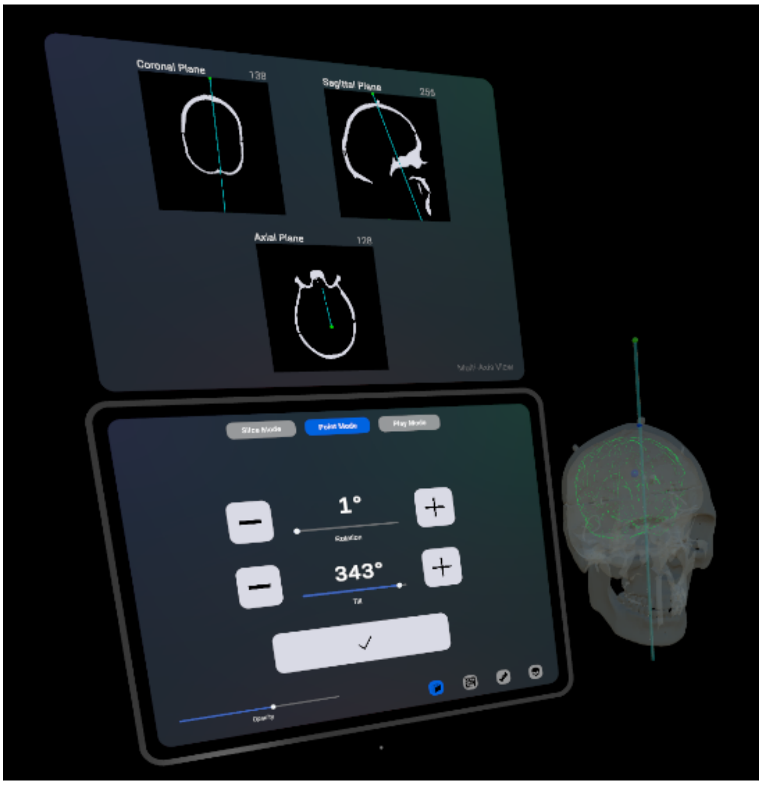


Figure 2.3: Direction selection for the cannula pre-surgery.

One of the most advanced features of *NeuroMix* is its ability to provide a true 1:1 mapping between 2D DICOM images and the 3D skull model. This feature ensures that the 3D model corresponds precisely with the patient's medical imaging data, allowing users to view the same anatomical structure in both two-dimensional and three-dimensional formats. The synchronization of these two types of data gives users a comprehensive understanding of the anatomy, enhancing the ability to correlate different representations of the same medical data.

In current literature, such seamless synchronization between 2D and 3D models is largely absent. Traditional methods in neurosurgery and medical training either rely heavily on the interpretation of 2D DICOM images or, separately, on the use of 3D models generated from medical imaging. However, these two modalities are typically not perfectly aligned. Stuart et al. (2021) noted the high rates of inaccuracies in freehand techniques for procedures like EVD insertion, largely due to the lack of advanced visualization tools that can simultaneously present accurate 2D and 3D perspectives of the patient's anatomy Stuart et al. (2021). By integrating both views with precise correlation, *NeuroMix* introduces a significant improvement in medical visualization that could potentially reduce the rates of malposition and other procedural complications.

The capability of *NeuroMix* to offer a 1:1 mapping enhances training and preoperative planning, where correlating 2D DICOM slices with a corresponding 3D skull model helps practitioners visualize the anatomy from different angles and depths. For example, the insertion trajectory for cannulas or other instruments, as discussed by Khor et al. (2016), can benefit from both the detailed internal view provided by 2D images and the external, spatial understanding offered by the 3D model Khor et al. (2016). This dual-view method provides an unprecedented advantage in ensuring that anatomical relationships are well understood, reducing reliance on purely 2D interpretation, which often lacks the spatial context required for more complex procedures.

Despite the critical importance of correlating 2D and 3D medical imaging, the current surgical literature lacks widespread examples of tools that offer this functionality. Most systems allow either 2D or 3D visualizations but do not link them dynamically to represent the same anatomical structures. The 1:1 mapping in *NeuroMix* addresses this gap by ensuring that both 2D slices from medical imaging and 3D models are spatially synchronized in real time, allowing for more accurate planning and execution of procedures. This alignment minimizes potential errors during operations, such as those caused by inaccurate trajectory estimations or a poor understanding of the relative positions of structures.

Moreover, this precise correspondence between 2D and 3D views in *NeuroMix* holds significant implications for the future of surgical training and education. As noted by Khor et al. (2016), AR and VR technologies are rapidly becoming integrated into surgical practice, offering interactive and immersive environments for training. However, these technologies often lack the precise alignment with real-world data that *NeuroMix* provides Khor et al. (2016). By bridging this gap and delivering synchronized, multi-dimensional visualization, *NeuroMix* not only enhances the accuracy of surgical planning but also serves as a powerful educational tool for trainees to better understand anatomical structures and their spatial relationships.

2.2.5 Direct DICOM Annotation via Headset

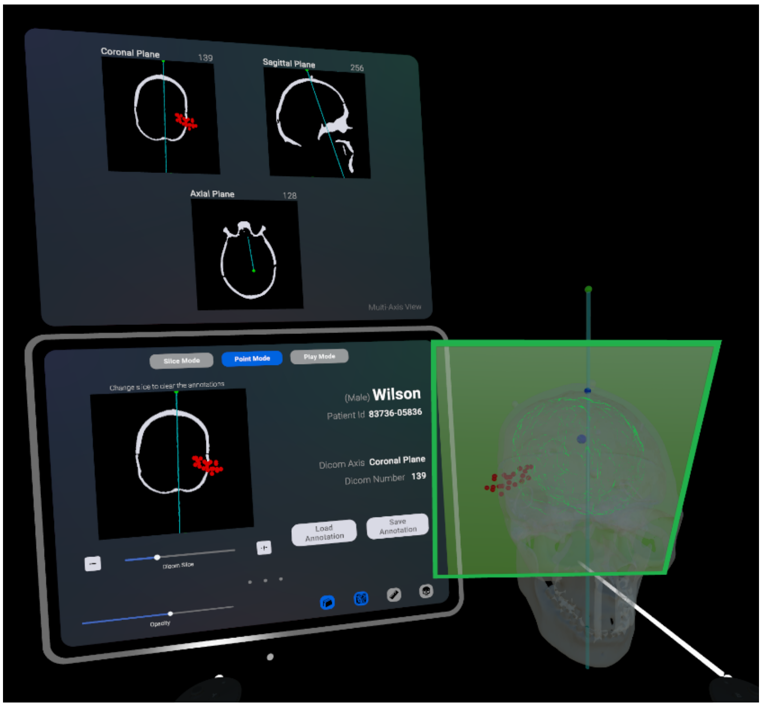


Figure 2.4: DICOM annotations example.

NeuroMix integrates an innovative feature that allows users to annotate DICOM images directly through controller-based inputs, enhancing the user's interaction with the medical data during simulations. This feature allows the annotation process to be intuitive, mimicking the natural action of marking critical areas using a brush-like tool. As the user interacts with the virtual environment, they can highlight important features of the medical scans without having to rely on traditional mouse-and-keyboard setups or touchscreens. This direct interaction not only improves the precision and efficiency of the medical simulation but also maintains the immersion within the VR environment.

In addition to this, annotations made on DICOM images in *NeuroMix* will have an immediate effect on the 3D model generated from the scan data, creating a corresponding visual representation of the drawn annotations. This allows users to observe the impact of their annotations not only on the 2D DICOM images but also directly within the 3D model, ensuring a more comprehensive understanding of the spatial relationships and critical areas within the anatomy. This real-time feedback strengthens the interactive experience, enabling more precise annotations and facilitating deeper analysis of complex anatomical structures.

Furthermore, *NeuroMix* enables users to save and load annotations made during their interaction with the DICOM images. This feature enhances the functionality by allowing users to revisit previous annotations, modify them, and integrate them into ongoing simulations or collaborative discussions with other professionals. The ability to save and load annotations supports continuity in learning and analysis, as users can track their progress and refine their understanding over multiple sessions.

The use of controller-based inputs in medical simulations, particularly in VR environments, is still an emerging field, with limited literature available that addresses this specific interaction mechanism. Golse et al. (2021) discuss the growing role of VR in medical education and training, emphasizing how VR simulations can revolutionize surgical procedures by providing an immersive environment for learning and skill development Izard et al. (2018). However, even in their detailed overview, the authors note that most existing systems rely on passive interaction, with few offering interactive tools that allow for direct manipulation of the environment, such as the annotation capabilities provided by *NeuroMix*.

Currently, the literature on VR in medicine primarily focuses on the ability of VR to simulate surgical procedures and environments, such as scoliosis surgeries or dissection rooms, as highlighted in the work of Izard et al. (2018). These simulations offer high levels of immersion, allowing medical students and professionals to engage with complex anatomical structures and observe procedures from a 360-degree perspective Izard et al. (2018). However, most systems described in the literature focus on observation and passive learning rather than direct, interactive manipulation of the medical data, such as annotating DICOM images in real-time.

While immersive VR environments are gaining traction, few platforms integrate precise tools for modifying or interacting with the data. This is where *NeuroMix* fills a critical gap. Its controller-based input system allows users to engage directly with DICOM images in the virtual environment, providing a practical and innovative tool for highlighting, marking, and focusing on critical anatomical features. Moreover, the added capability to save and load annotations further enhances its utility in training and collaborative environments. Users can revisit their annotations, collaborate with colleagues by sharing marked data, or even reanalyze previously annotated areas, thus fostering continuous learning and improvement.

The ability to annotate DICOM images using a brush-like tool in *NeuroMix* is a substantial technological advance in VR for medical training. The use of intuitive controller-based inputs offers a seamless interaction between the user and the medical data, ensuring that the annotation process does not interrupt the flow of the simulation. The inclusion of an interactive tool like the one provided by *NeuroMix* further enhances this by allowing the user to focus on specific areas of interest, facilitating more detailed and personalized training experiences.

Additionally, the feature of saving and loading annotations introduces a new layer of functionality. Users can save the annotations they create during the simulation, which can later be reloaded for further analysis or collaboration. This capability ensures that important observations and learning points are preserved across multiple sessions, supporting a continuous learning model. It also enables collaborative use cases where one practitioner can annotate specific areas of interest and share those insights with others, thus fostering collaborative medical education and diagnostics.

Another significant benefit of such an interaction system is that it allows medical professionals to repeatedly practice marking and annotating critical areas of the anatomy, thus aiding in the precision required for delicate surgeries. However, *NeuroMix* goes a step further by integrating the annotation feature, which allows users not only to practice procedures but also to mark areas of concern, save their progress, and revisit it later, creating a more comprehensive and versatile learning tool.

While the potential of MR in medical training has been well established, the literature lacks detailed discussion on systems that offer controller-based annotations, especially those that are integrated into DICOM image analysis and offer features like saving and loading annotations. Existing systems focus on either immersive environments or passive learning, without the interactivity required for tasks like marking anatomical structures in real-time. Izard et al. (2018) discuss the benefits of using VR for surgical simulations and learning environments, but they do not explore the interactive features such as those offered by *NeuroMix* Izard et al. (2018).

2.2.6 Mixed Reality Enhancement over Traditional Neuronavigation

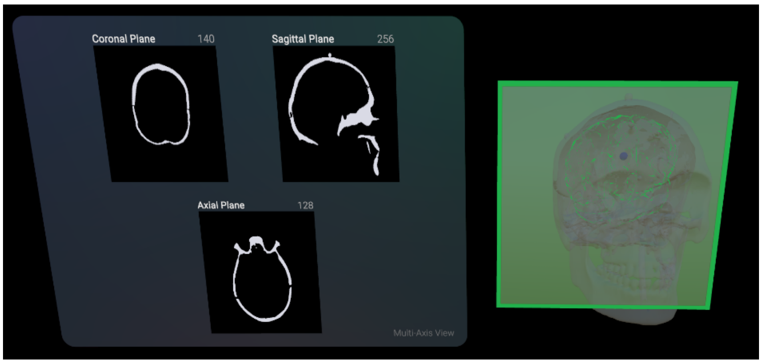


Figure 2.5: DICOM in comparison with the 3D model.

Unlike traditional neuronavigation systems, which primarily display 2D medical images, *NeuroMix* introduces a cutting-edge feature by integrating a 3D transparent model of the anatomy. This mixed reality approach enables users to visualize both the volumetric DICOM data and the 3D anatomical model simultaneously, providing a more comprehensive understanding of the spatial relationships involved in surgical procedures. This combined view significantly enhances the decision-making process and spatial awareness during surgery, making it easier for surgeons and trainees to navigate complex anatomical structures.

Traditional neuronavigation systems, while essential, typically rely on 2D representations of patient data, which limits the ability to fully understand the spatial depth and relationships between structures. These systems often involve switching between different planes of 2D images, such as axial, coronal, and sagittal views, to infer the 3D position of anatomical landmarks. Although effective, this method requires considerable mental effort to reconstruct a full understanding of the patient's anatomy in real time Golse et al. (2021).

NeuroMix, by contrast, alleviates this cognitive load by merging 2D DICOM data with a 3D transparent model, creating an immersive mixed reality environment. This not only allows for real-time 3D visualization but also maintains a continuous relationship with the original medical imaging data. The volumetric DICOM data can be superimposed onto the 3D model, offering users a dynamic, multi-layered view that aligns with the anatomical structures. As noted in the literature, having access to both 2D and 3D data simultaneously can greatly improve surgical accuracy and reduce the likelihood of errors during procedures Izard et al. (2018).

The mixed reality environment offered by *NeuroMix* enhances spatial awareness during surgery, allowing surgeons to better appreciate the complex spatial relationships between different anatomical structures. This is particularly critical in surgeries involving delicate areas, such as the brain or spine, where a small misjudgment in spatial positioning can lead to serious complications. As Golse et al. (2021) suggests, one of the main advantages of using augmented or mixed reality in surgery is the improvement of spatial orientation and the ability to make more informed, real-time decisions based on visual data.

Furthermore, this approach directly addresses a gap in the current literature. While many systems focus on either 2D or 3D visualization, very few integrate both seamlessly into a single platform. According to Izard et al. (2018), existing VR systems for medical training often limit themselves to either immersive 3D simulations or passive viewing of 2D images, without fully merging the two. By allowing users to see the 3D model of the patient's anatomy overlaid with the 2D DICOM slices, *NeuroMix* offers a holistic view that is currently unmatched in the literature.

In addition, the ability to visualize transparent 3D models allows users to see through anatomical layers, providing an internal view of the anatomy that would not be possible with traditional 2D imaging alone. This feature significantly enhances the surgeon's ability to plan and execute procedures with greater precision. For instance, in complex surgeries such as scoliosis or brain tumor removal, the surgeon can better anticipate challenges by understanding how deep structures are positioned relative to one another Golse et al. (2021). As noted by Izard et al. (2018), the ability to visualize the internal anatomy in real time and interact with it provides a valuable learning and operational advantage.

The integration of 3D transparent models with DICOM data in *NeuroMix* is a clear step towards the future of mixed reality applications in medicine. Not only does this system enhance spatial awareness and decision-making, but it also provides a platform for collaborative work. By offering the ability to save and share these complex views, *NeuroMix* enables surgeons to collaborate across different locations, sharing real-time insights and detailed anatomical views to improve patient outcomes.

Moreover, as noted by Izard et al. (2018), one of the key advantages of VR and mixed reality platforms is their ability to support repetitive learning and simulation without the need for physical cadavers or live patients. The 3D model integration allows for repeated practice and visualization, which is especially useful for surgical training and preoperative planning. Medical students and professionals can repeatedly simulate procedures, adjusting their approach based on the real-time feedback provided by the system.

Despite the growing interest in VR and mixed reality for medical training, current platforms often lack the ability to provide a seamless connection between 2D DICOM images and 3D anatomical models. The literature thus far has mainly focused on individual aspects of either 2D imaging or 3D simulations, but *NeuroMix* bridges this gap by integrating both into a cohesive tool that can be used in real-world surgical applications Golse et al. (2021).

Chapter 3

Tests on Neurosurgery Residents

This section presents the evaluation of NeuroMix in two modules, Visualization and Operation, as part of a pilot study. Neurosurgery residents assessed the modules to examine usability, task load, and technological acceptance. This pilot study utilized established metrics, including the **SUS**, **NASA-TLX**, and **TAM**, to provide preliminary insights into the system's effectiveness in supporting DICOM image manipulation and neurosurgical procedure simulations.

3.1 Actions Done for Evaluation: Visualization Task

The NeuroMix Visualization module was structured to evaluate users' experience with a specific MR application, NeuroMix, used for the visualization and manipulation of DICOM images. The objective was to analyze the ease of use, perceived workload, and technological acceptance of the application.

The user task was to identify a target point on all three axes of DICOM images.

To evaluate the usability and effectiveness of NeuroMix, four neurosurgery residents participated and performed the following steps:

1. Watched a video tutorial to understand the system;
2. Familiarized themselves with the headset and controls for approximately 5 minutes;
3. Overlapped the virtual skull with the physical one;
4. Visualized DICOM images in slice mode for each axis;

5. Manipulated the 3D model in free mode, rotating it at least 180 degrees;
6. Annotated on a DICOM page and saved the notes;
7. Measured the distance from an entry point to one of the canonical points using the ruler tool;
8. Displayed the target point on all three DICOM axes (Task).

Resident	Time (seconds)
0-1	22
0-2	26
0-3	34
0-4	29

Table 3.1: Task completion times by residents.

The times taken by the participants to complete the task were: 22 seconds, 26 seconds, 34 seconds, and 29 seconds, showing some variance in performance but overall indicating manageable task completion times.

3.1.1 SUS Results

The SUS evaluated the perceived usability of NeuroMix through ten questions. The results showed that most participants found NeuroMix easy to use, with positive responses in the following areas:

- Frequency of use (SUS1);
- Ease of learning and using the system (SUS3 and SUS7);
- Integration of system functions (SUS5);
- Confidence in using the system (SUS9).

However, some participants noted that the system could be complex and might require technical support to fully leverage its capabilities (SUS2 and SUS4). This feedback highlights potential areas for improvement in reducing perceived complexity.

Code	Question	Answer Type
SUS1	I think that I would like to use this system frequently.	5-point Likert scale
SUS2	I found the system unnecessarily complex.	5-point Likert scale
SUS3	I thought the system was easy to use.	5-point Likert scale
SUS4	I think that I would need the support of a technical person to be able to use this system.	5-point Likert scale
SUS5	I found the various functions in this system were well integrated.	5-point Likert scale
SUS6	I thought there was too much inconsistency in this system.	5-point Likert scale
SUS7	I would imagine that most people would learn to use this system very quickly.	5-point Likert scale
SUS8	I found the system very cumbersome to use.	5-point Likert scale
SUS9	I felt very confident using the system.	5-point Likert scale
SUS10	I needed to learn a lot of things before I could get going with this system.	5-point Likert scale

Table 3.2: SUS Questions: Visualization Task.

3.1.2 NASA-TLX Results

The NASA-TLX was used to assess the mental and physical load required during the use of NeuroMix. The highest scores were observed in the following areas:

- **NASA1 - Mental Demand:** Participants reported a low-to-medium level of mental effort required;
- **NASA2 - Physical Demand:** The physical load was reported to be low, consistent with expectations for a mixed reality system;
- **NASA3 - Temporal Demand:** The task's pace was generally seen as adequate.

Code	Question	Answer Type
NASA1	How mentally demanding was the task?	10-point Likert scale
NASA2	How physically demanding was the task?	10-point Likert scale
NASA3	How hurried or rushed was the pace of the task?	10-point Likert scale
NASA4	How successful were you in accomplishing what you were asked to do?	10-point Likert scale
NASA5	How hard did you have to work to accomplish your level of performance?	10-point Likert scale
NASA6	How insecure, discouraged, irritated, stressed, and annoyed were you?	10-point Likert scale

Table 3.3: NASA Task Load Index (TLX) Questions: Visualization Task.

3.1.3 TAM Results

The TAM measured technological acceptance by evaluating perceptions such as perceived usefulness and ease of use. Results indicated that participants viewed NeuroMix as an effective tool for manipulating DICOM images, with agreement on the TAM-PU (Perceived Usefulness) and TAM-PE (Perceived Ease of Use) questions:

- **TAM-PU1 and TAM-PU4:** Participants felt the application improved control and specificity for DICOM image analysis;
- **TAM-PU5 and TAM-PU6:** Participants noted slight time savings and increased efficiency, as evidenced by task completion times;
- **TAM-PU8 and TAM-PU12:** Participants achieved superior results compared to traditional methods and experienced increased productivity.

The task completion times, ranging from 22 to 34 seconds, with an average of 27.75 seconds, align with the positive feedback on efficiency and usability.

Code	Question	Answer Type
TAM-PU1	Doing the task (i.e. finding the blue target point on all three axes DICOM images) without the application would be challenging.	5-point Likert scale
TAM-PU2	Utilizing the application gives me better control over the manipulation of DICOM images.	5-point Likert scale
TAM-PU3	Using the application enhances my ability to manipulate DICOM images.	5-point Likert scale
TAM-PU4	The application addresses my specific needs for manipulating DICOM images.	5-point Likert scale
TAM-PU5	Learning with the application saves me time when mastering manipulating the DICOM images.	5-point Likert scale
TAM-PU6	The system/application allows me to manipulate DICOM images more efficiently.	5-point Likert scale
TAM-PU7	The application supports critical aspects of the DICOM images manipulation process.	5-point Likert scale
TAM-PU8	Learning from the application enables me to achieve better results than traditional methods for mastering DICOM images manipulations.	5-point Likert scale
TAM-PU9	Using the application reduces the time I spend on less effective software for DICOM manipulation images.	5-point Likert scale
TAM-PU10	Learning from the application enhances my proficiency in manipulating DICOM images.	5-point Likert scale
TAM-PU11	Using the application improves the quality of my skills in DICOM images manipulation.	5-point Likert scale
TAM-PU12	Using the application increases my overall productivity in mastering manipulation of DICOM images.	5-point Likert scale
TAM-PU13	Using the application simplifies the process of manipulating DICOM images.	5-point Likert scale
TAM-PU14	Overall, I find the system/application valuable for manipulating DICOM images.	5-point Likert scale

Table 3.4: TAM-PU Questions: Visualization Task.

Code	Question	Answer Type
TAM-PE1	I often find the interface of the application confusing when manipulating DICOM images.	5-point Likert scale
TAM-PE2	I make mistakes frequently when using the application to manipulate DICOM images.	5-point Likert scale
TAM-PE3	Interacting with the application can be frustrating during my DICOM manipulation process.	5-point Likert scale
TAM-PE4	I need to refer to the experimenters' guidance frequently when using the application to manipulate DICOM images.	5-point Likert scale
TAM-PE5	Interacting with the application demands a significant amount of mental effort during DICOM images manipulation.	5-point Likert scale
TAM-PE6	I find it easy to recover from errors encountered while using the system/application for DICOM images manipulation.	5-point Likert scale
TAM-PE7	The application's interface is rigid and inflexible when it comes to manipulating DICOM images.	5-point Likert scale
TAM-PE8	I find it easy to achieve my DICOM images manipulation goals using the application.	5-point Likert scale
TAM-PE9	The application sometimes behaves unpredictably during my DICOM images manipulation sessions.	5-point Likert scale
TAM-PE10	I consider the application user-friendly for manipulating DICOM images.	5-point Likert scale
TAM-PE11	My interaction with the application is straightforward to understand when manipulating DICOM images.	5-point Likert scale
TAM-PE12	It is easy for me to remember how to perform tasks using the application for manipulating DICOM images.	5-point Likert scale
TAM-PE13	The application provides helpful guidance while I'm manipulating DICOM images.	5-point Likert scale
TAM-PE14	Overall, I find the application easy to use for mastering manipulating DICOM images.	5-point Likert scale

Table 3.5: TAM-PE Questions: Visualization Task.

3.2 Actions Done for Evaluation: Operation Task

The NeuroMix Operation module is structured to evaluate users' experience with a specific MR application, NeuroMix, used for simulating neurosurgical procedures. The objective is to analyze the perceived ease of use, workload requirements, and technological acceptance of the application. The module is divided into five sections, each designed to collect data on different aspects of user interaction with the system.

The user task was to perform a simulation of an EVD procedure. The participants completed the following steps:

1. Set an entry point;
2. Entered slice toggle in point mode;
3. Aligned the cannula ghost with the target using DICOM images;
4. Performed the surgery simulation with a transparent 3D model (Task).

3.2.1 Resident Task Results

Four residents completed the simulation tasks, with specific data recorded on accuracy, percentage success, and time for each task. Below are the aggregated results for each resident, displaying their task performance in terms of distance error (in cm), accuracy (percentage), and time taken (in minutes).

Resident	Task	Distance Error (cm)	Accuracy (%)	Time (min)
0-1	1	6.704	32.96	2.33
	2	0.594	94.06	1.57
	3	1.423	85.77	1.05
	4	0.227	97.73	1.15
	5	0.652	93.48	0.55
0-2	1	0.453	95.47	2.14
	2	0.160	98.40	1.30
	3	0.125	98.00	1.08
	4	0.365	96.35	1.21
	5	0.191	98.09	0.59
0-3	1	0.355	96.34	2.56
	2	0.382	96.18	4.37
	3	0.072	99.28	3.59
	4	0.311	96.89	2.05
	5	0.127	98.73	3.41
0-4	1	0.238	97.61	2.51
	2	0.184	98.16	2.00
	3	0.155	98.45	2.06
	4	0.110	98.90	2.32
	5	0.195	98.05	3.22

Table 3.6: Resident Performance Metrics for NeuroMix Simulation Tasks.

The data related to the residents' performance in the NeuroMix simulation tasks show the following results:

- **Average values**:
  - Average distance error: 0.651 cm
  - Average accuracy: 93.45%
  - Average time: 2.05 minutes
- **Highest value**:
  - Maximum distance error: 6.704 cm (resident 0-1, task 1)
  - Maximum accuracy: 99.28% (resident 0-3, task 3)
  - Maximum time: 4.37 minutes (resident 0-3, task 2)
- **Lowest value**:

- Minimum distance error: 0.072 cm (resident 0-3, task 3)
- Minimum accuracy: 32.96% (resident 0-1, task 1)
- Minimum time: 0.55 minutes (resident 0-1, task 5)

- **Standard deviation**:
  - Distance error: 1.456 cm
  - Accuracy: 14.55%
  - Time: 1.03 minutes

Parameter	Average	Standard Deviation
Distance error (cm)	0.651	1.456
Accuracy (%)	93.45	14.55
Time (min)	2.05	1.03

Table 3.7: Average and standard deviation for each parameter in Operation Task.

3.2.2 SUS Results: Operation Task

The SUS assessed the usability of NeuroMix. The responses showed:

- **Frequency of use**: Participants generally found the system beneficial for frequent use, with a tendency to agree that it would be useful in recurring tasks (SUS1).
- **Ease of learning and using the system**: There was a consensus that the system was relatively easy to use, though some participants noted areas where technical assistance might improve the learning experience (SUS3 and SUS4).
- **System integration**: Responses indicated that participants viewed the system's functions as well-integrated (SUS5).
- **User confidence**: Most participants felt reasonably confident using the system, suggesting it fosters a strong sense of user control (SUS9).

Code	Question	Answer Type
SUS1	I think that I would like to use this system frequently.	5-point Likert scale
SUS2	I found the system unnecessarily complex.	5-point Likert scale
SUS3	I thought the system was easy to use.	5-point Likert scale
SUS4	I think that I would need the support of a technical person to be able to use this system.	5-point Likert scale
SUS5	I found the various functions in this system were well integrated.	5-point Likert scale
SUS6	I thought there was too much inconsistency in this system.	5-point Likert scale
SUS7	I would imagine that most people would learn to use this system very quickly.	5-point Likert scale
SUS8	I found the system very cumbersome to use.	5-point Likert scale
SUS9	I felt very confident using the system.	5-point Likert scale
SUS10	I needed to learn a lot of things before I could get going with this system.	5-point Likert scale

Table 3.8: SUS Questions: Operation Task.

3.2.3 NASA-TLX Results

The NASA-TLX evaluated the perceived workload during the NeuroMix Operation task. Key findings included:

- **NASA1 - Mental Demand**: Responses indicated low-to-moderate mental demands, suggesting the tasks were cognitively manageable for most participants.
- **NASA2 - Physical Demand**: Physical exertion was minimal, consistent with the expected nature of a mixed reality simulation system.
- **NASA3 - Temporal Demand**: The simulation's pace was generally adequate, allowing participants to complete tasks without feeling rushed.

Code	Question	Answer Type
NASA1	How mentally demanding was the task?	10-point Likert scale
NASA2	How physically demanding was the task?	10-point Likert scale
NASA3	How hurried or rushed was the pace of the task?	10-point Likert scale
NASA4	How successful were you in accomplishing what you were asked to do?	10-point Likert scale
NASA5	How hard did you have to work to accomplish your level of performance?	10-point Likert scale
NASA6	How insecure, discouraged, irritated, stressed, and annoyed were you?	10-point Likert scale

Table 3.9: NASA Task Load Index (TLX) Questions: Operation Task.

3.2.4 TAM Results

The TAM measured the application's acceptance and perceived value. Feedback from participants included:

- **Perceived Usefulness**: Participants largely agreed that the system enhanced their control over and efficiency in the simulated neurosurgical procedures (TAM-PU1 and TAM-PU2).
- **Efficiency and Productivity**: Users noted that the application improved productivity and reduced time needed compared to traditional methods (TAM-PU5, TAM-PU6).
- **User Satisfaction**: Overall, participants found the system effective for achieving EVD neurosurgical goals, affirming its value as a simulation tool (TAM-PU14).

The results reflect positively on the NeuroMix Operation module's usability, task load management, and technological acceptance, indicating that it can be a valuable tool for neurosurgical simulation training.
All tests result can be viewed at & .

Code	Question	Answer Type
TAM-PU1	Doing the task (i.e. simulating the EVD procedure) without the application would be challenging.	5-point Likert scale
TAM-PU2	Utilizing the application gives me better control over the simulated EVD procedure.	5-point Likert scale
TAM-PU3	Using the application enhances my ability to simulate the EVD procedure.	5-point Likert scale
TAM-PU4	The application addresses my specific needs for simulating the EVD procedure.	5-point Likert scale
TAM-PU5	Learning with the application saves me time when mastering simulating the EVD procedure.	5-point Likert scale
TAM-PU6	The system/application allows me to simulate the EVD procedure more efficiently.	5-point Likert scale
TAM-PU7	The application supports critical aspects of the EVD procedure simulation process.	5-point Likert scale
TAM-PU8	Learning from the application enables me to achieve better results than traditional methods for mastering the EVD procedure simulation.	5-point Likert scale
TAM-PU9	Using the application reduces the time I spend on less effective software for simulating the EVD procedure.	5-point Likert scale
TAM-PU10	Learning from the application enhances my proficiency in simulating the EVD procedure.	5-point Likert scale
TAM-PU11	Using the application improves the quality of my skills in simulating the EVD procedure.	5-point Likert scale
TAM-PU12	Using the application increases my overall productivity in mastering the EVD procedure simulation.	5-point Likert scale
TAM-PU13	Using the application simplifies the process of simulating the EVD procedure.	5-point Likert scale
TAM-PU14	Overall, I find the system/application valuable for simulating the EVD procedure.	5-point Likert scale

Table 3.10: TAM-PU Questions: Operation Task.

Code	Question	Answer Type
TAM-PE1	I often find the interface of the application confusing when simulating the EVD procedure.	5-point Likert scale
TAM-PE2	I make mistakes frequently when using the application to simulate the EVD procedure.	5-point Likert scale
TAM-PE3	Interacting with the application can be frustrating during the simulation of the EVD procedure.	5-point Likert scale
TAM-PE4	I need to refer to the experimenters' guidance frequently when using the application to simulate the EVD operation.	5-point Likert scale
TAM-PE5	Interacting with the application demands a significant amount of mental effort during the simulation of the EVD operation.	5-point Likert scale
TAM-PE6	I find it easy to recover from errors encountered while using the system/application for simulating the EVD operation.	5-point Likert scale
TAM-PE7	The application's interface is rigid and inflexible when it comes to simulating the neurosurgical procedure.	5-point Likert scale
TAM-PE8	I find it easy to achieve the specific simulated neurosurgical goals using the application.	5-point Likert scale
TAM-PE9	The application sometimes behaves unpredictably during the simulation of the EVD operation.	5-point Likert scale
TAM-PE10	I consider the application user-friendly for simulating the EVD operation.	5-point Likert scale
TAM-PE11	My interaction with the application is straightforward to understand when simulating the EVD operation.	5-point Likert scale
TAM-PE12	It is easy for me to remember how to perform tasks using the application for simulating the EVD operation.	5-point Likert scale
TAM-PE13	The application provides helpful guidance while I'm simulating the EVD operation.	5-point Likert scale
TAM-PE14	Overall, I find the application easy to use for mastering simulating the EVD operation.	5-point Likert scale

Table 3.11: TAM-PE Questions: Operation Task.

3.3 Discussion and Future Work

The current study on NeuroMix represents a pilot investigation into the potential of using MR technologies for neurosurgical training. The results are promising, but several avenues for future development and experimentation can expand the scope and functionality of the system to enhance both its usability and clinical relevance.

3.3.1 Expanding User Testing

One primary direction for future work involves expanding the testing of NeuroMix to include a larger and more diverse pool of participants. While the initial pilot study provides valuable insights, increasing the number of test subjects across varying levels of neurosurgical experience can offer a more comprehensive understanding of the system's effectiveness and usability. Moreover, engaging different demographics and skill levels could provide deeper insights into how NeuroMix can be adapted for use in different training environments, from medical students to experienced neurosurgeons.

3.3.2 Integrating Automated Tracking for 3D Model Alignment

Currently, the process of aligning the virtual model with the physical setup is done manually, which can introduce user-dependent variability and limit the precision of the training environment. Future work could explore the integration of automated tracking systems to align the 3D model with the real-world anatomy more accurately. Technologies like optical tracking or electromagnetic sensors can facilitate this integration, ensuring that the virtual and physical models align dynamically in real time. This feature would not only improve the accuracy of simulations but also enhance the overall user experience by reducing manual input requirements.

3.3.3 Testing with Physical 3D Printed Models

Another valuable addition to future testing is the inclusion of physical 3D-printed anatomical models alongside the virtual simulations. This semi-realistic testing environment would allow users to experience tactile feedback, further enhancing the realism of the training scenario. Such an approach could bridge the gap between purely digital simulations and real-world practice, providing a more holistic training experience. By integrating a physical model, the system could simulate the physical dynamics of tool interactions, such as resistance during cannula insertion, thus adding another layer of depth to the training.

3.3.4 Enhancing User Experience and System Usability

User experience (UX) remains a critical area for improvement. Feedback from the initial usability tests indicated some complexity and learning challenges for new users, suggesting that future iterations of NeuroMix should include more intuitive interfaces and additional in-system guidance. Simplifying navigation, incorporating voice commands, and implementing customizable user controls could all contribute to a smoother user experience. Additionally, a streamlined onboarding process, potentially including step-by-step tutorials directly within the mixed reality environment, can help users become proficient with minimal outside assistance.

3.3.5 Realistic Physical Simulations

To complement the MR-based simulations, future development could incorporate more advanced physical simulations. For example, simulating forces encountered during cannula insertion, such as tissue resistance, could improve the realism of the experience. Integrating haptic feedback devices could facilitate this, allowing users to feel the physical resistance in real-time, which is crucial for developing surgical skills. By enhancing the tactile component, the system can more effectively mimic real-world conditions, aiding in skill acquisition and reinforcing procedural knowledge.

Conclusions

To recap what has been done in the NeuroMix project before reaching the final conclusions:

3.4 Objectives and Context

NeuroMix was developed to enhance neurosurgical training using MR technologies for EVD surgeries. Currently, the product is still in the development phase and requires improvements to stabilize the system, especially for use with standalone HMD devices such as the Quest 3. The primary goal was to make neurosurgical training more accessible and less reliant on expensive tools such as cadavers or traditional neuronavigation systems. NeuroMix also aims to bridge the gap between current simulation technologies and the growing need for more practical and interactive training for future neurosurgeons.

3.5 Technological Development

The project was developed using the Unity game engine and the Meta Quest 3 headset. This mixed reality device was chosen for its portability and its ability to provide immersive experiences without requiring external hardware, making the system more accessible to a wide range of users. Unity was chosen not only for its versatility but also for its large developer community, which offers support and additional resources to continuously improve the application.

3.6 NeuroMix Features

3.6.1 Realistic Simulation of Intracranial Procedures

NeuroMix offers an immersive simulation of cannula insertion, allowing users to understand the spatial and dimensional aspects of the procedure in a virtual environment. This simulation is designed to replicate the real difficulties that surgeons might face during procedures, providing them with an opportunity to develop and refine their manual skills in a safe and controlled environment.

3.6.2 Interactive Annotations

The system allows direct annotation of DICOM images through the headset, integrating these annotations with the 3D model. This feature enhances interaction with medical data and facilitates understanding of anatomical relationships. Interactive annotations also enable more effective collaboration among different members of the medical team, as information can be shared and analyzed collectively.

3.6.3 Advanced Visualization Features

NeuroMix integrates volumetric DICOM data with 3D anatomical models, enhancing spatial awareness during surgical planning and execution. The ability to switch from an opaque to a transparent view allows surgeons to simultaneously visualize external and internal structures, providing a comprehensive understanding of anatomy and the positioning of instruments during surgery.

3.7 Evaluation and Results

The system was evaluated using the SUS, NASA-TLX, and the TAM, which showed a high level of acceptance and usability from neurosurgery residents who participated in the pilot project. The results indicate that NeuroMix not only facilitates skills acquisition but also reduces reliance on traditional cadaver-based training. The residents reported that the immersive experience improved their understanding of anatomical structures and provided a valuable opportunity to practice challenging situations in a safe and repeatable environment.

3.8 Future Prospects

It has been proposed to expand the number of participants in the tests and to integrate new features, such as haptic feedback and automatic alignment of 3D models, to further improve the realism of the simulations and the precision of alignment during training. Haptic feedback, in particular, could provide a tactile sensation during instrument manipulation, thereby improving practical training and making the experience even closer to reality. Additionally, integrating artificial intelligence models is planned to adapt the difficulty level of simulations according to user skills, offering a personalized and progressive learning path.

3.9 Final thoughts

This thesis suggests that NeuroMix could be a valuable tool to improve neurosurgical training, addressing some of the limitations of traditional methods. The system has shown potential to improve the accessibility of neurosurgical training, reducing reliance on costly and hard-to-find resources such as cadavers. The pilot tests conducted with neurosurgery residents has shown a high level of acceptance and good effectiveness in acquiring practical skills. NeuroMix thus positions itself as a valuable complement to traditional methods, with the potential to make surgical training more modern, interactive, and adaptable to the individual needs of students.

In the future, NeuroMix could represent a viable option in neurosurgical training, especially if further improvements such as haptic feedback and the ability to automatically align 3D models with real anatomical data are integrated. These developments could help provide more accurate and practical training, contributing to reducing surgical complications. The future success of NeuroMix will depend on the ability to integrate these advanced features, improving the quality and effectiveness of the simulations and ensuring an increasingly immersive and realistic experience.

NeuroMix could become a sustainable and advanced alternative for neurosurgical training if system stability is improved and further developments are implemented, particularly to ensure full compatibility with standalone HMD devices like the Meta Quest 3 or similar. In this way, it could contribute to patient safety and improve the efficiency of medical practice. Moreover, the integration of artificial intelligence technologies and the expansion of collaboration features could make NeuroMix an essential tool for the continuous training of surgeons, allowing them to gain experience in an immersive and risk-free environment, with the possibility of sharing and analyzing experiences with other professionals in the field.

Appendix A

NeuroMIX_Operation

4 risposte

Pubblica i dati di analisi

Demograghic question

Please enter your Participant ID:

4 risposte

0-1

0-2

0-3

0-4

Please specify your exact age in years:

4 risposte

32

27

29

28

Please provide the name of your country and city of residence.

4 risposte

Italy Bologna

Italy-Faenza

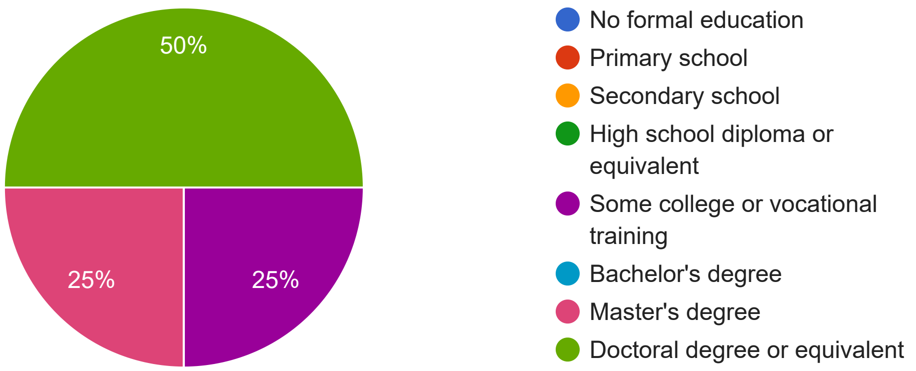
Italia Pesaro

italy

Please select your highest level of education completed from the options below:

Copia

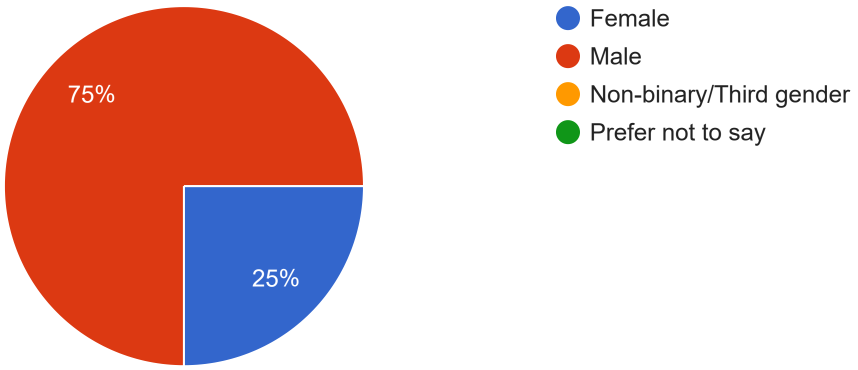
4 risposte



What is your gender?

Copia

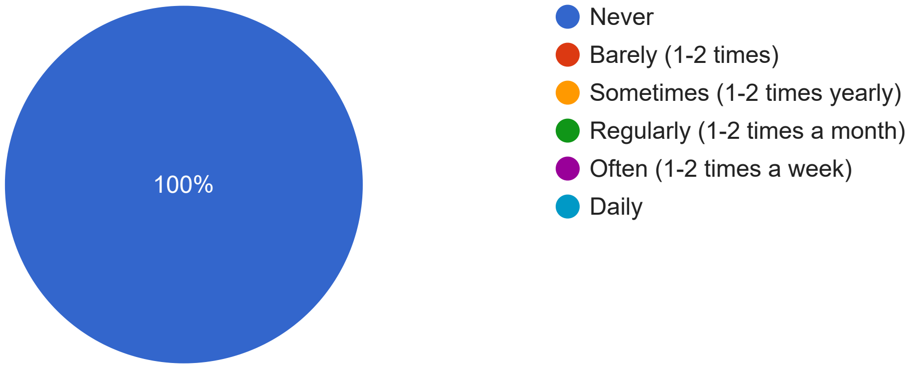
4 risposte



How often do you use Mixed Reality applications (e.g. for games) ?

Copia

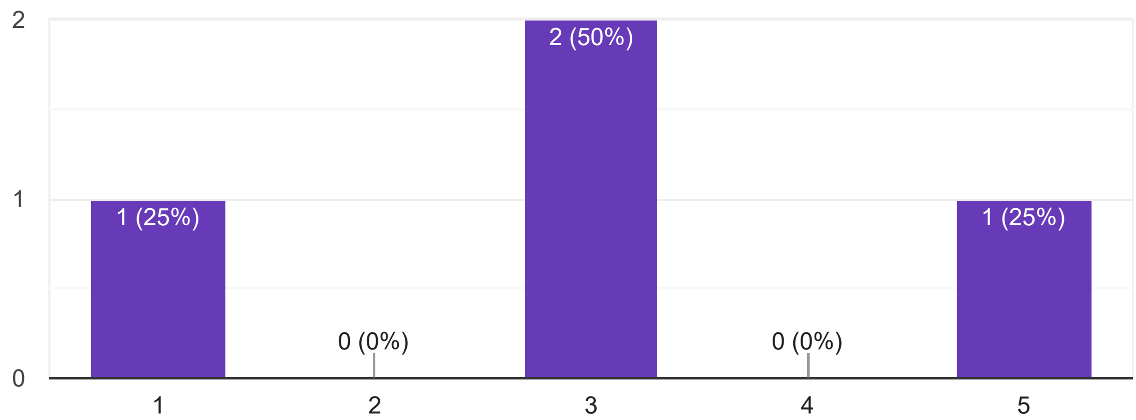
4 risposte



How confident are you with neurosurgical procedures requiring the insertion of a catheter?

Copia

4 risposte

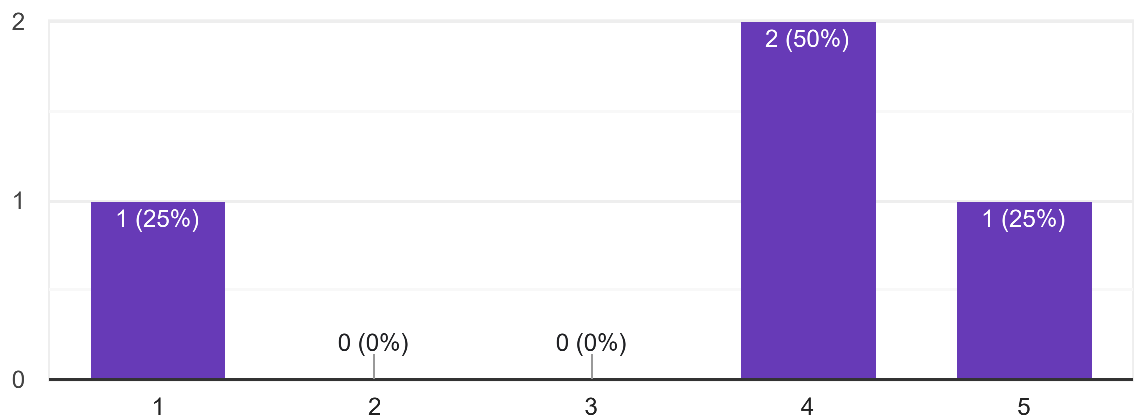


The System Usability Scale (SUS)

SUS1 - I think that I would like to use this system frequently.

Copia

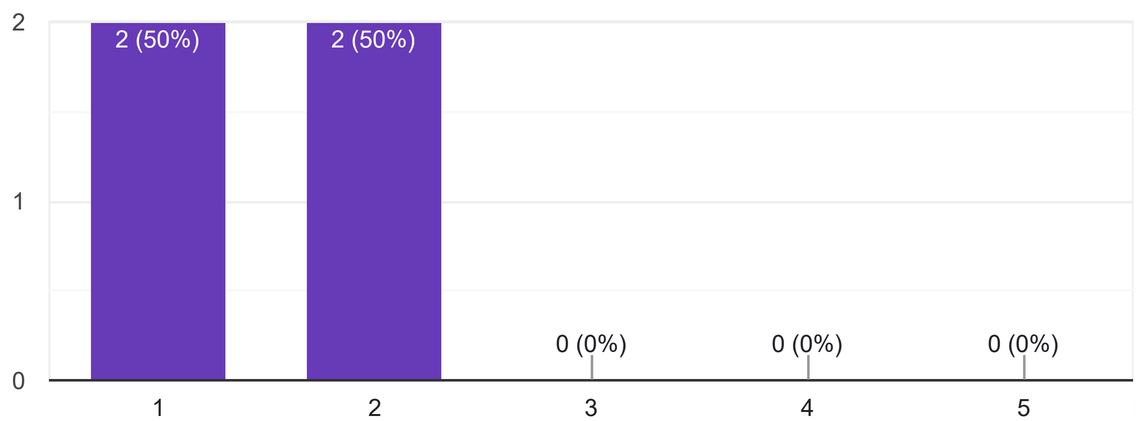
4 risposte



SUS2 - I found the system unnecessarily complex.

Copia

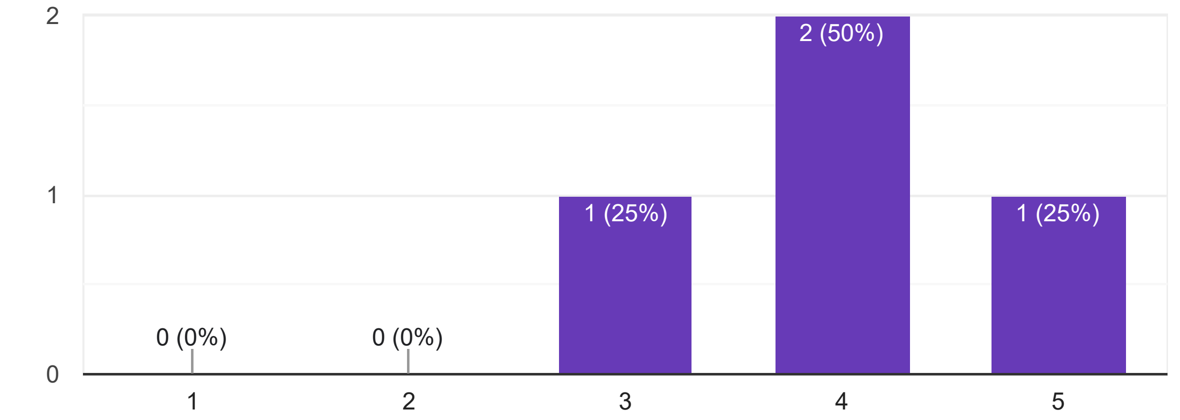
4 risposte



SUS3 - I thought the system was easy to use.

Copia

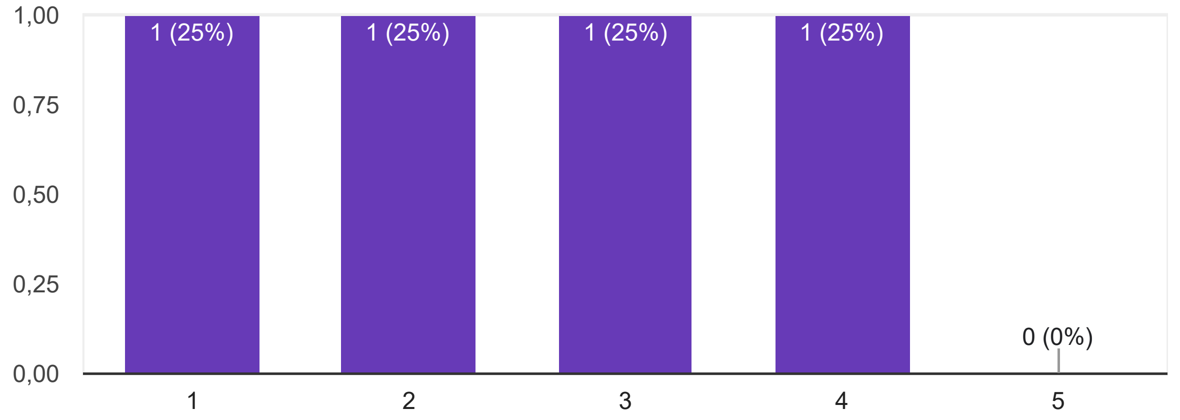
4 risposte



SUS4 - I think that I would need the support of a technical person to be able to use this system.

Copia

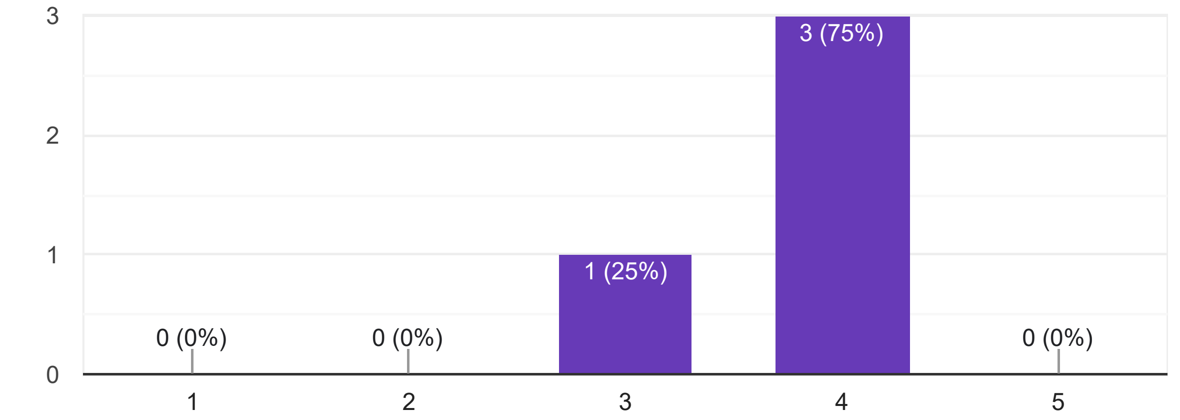
4 risposte



SUS5 - I found the various functions in this system were well integrated.

Copia

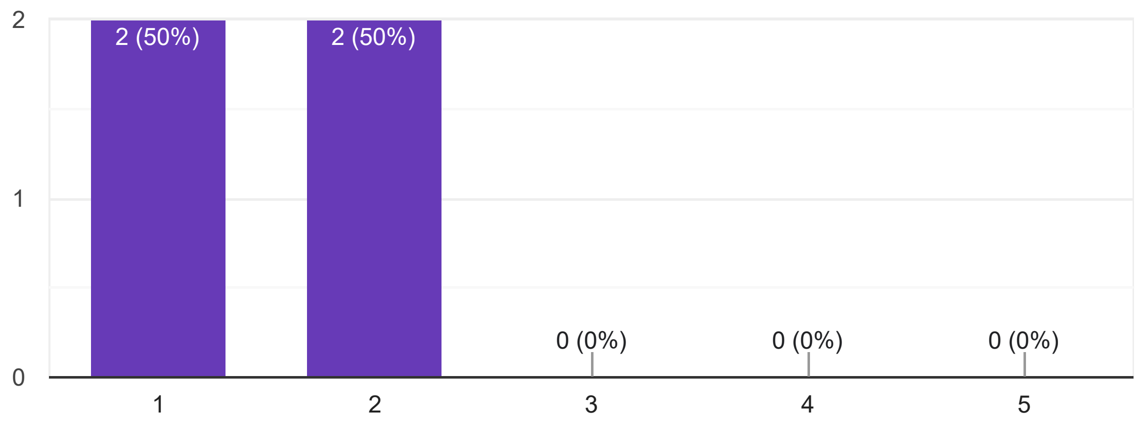
4 risposte



SUS6 - I thought there was too much inconsistency (e.g. the buttons are not always in the same position, etc...) in this system.

Copia

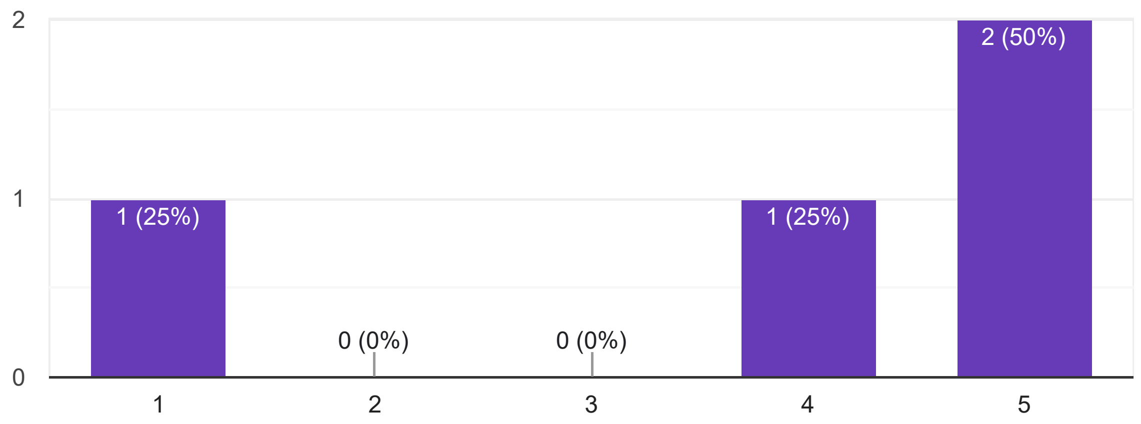
4 risposte



SUS7 - I would imagine that most people would learn to use this system very quickly.

Copia

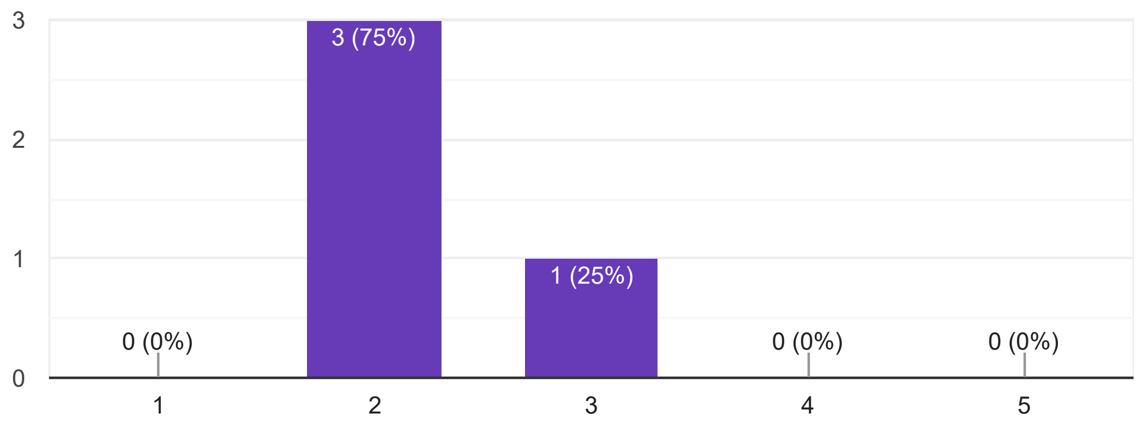
4 risposte



SUS8 - I found the system very cumbersome to use.

Copia

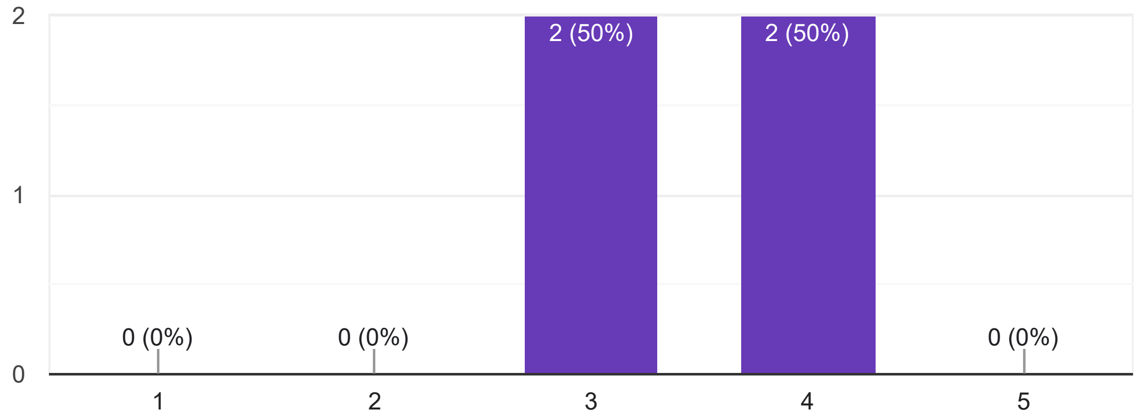
4 risposte



SUS9 - I felt very confident using the system.

Copia

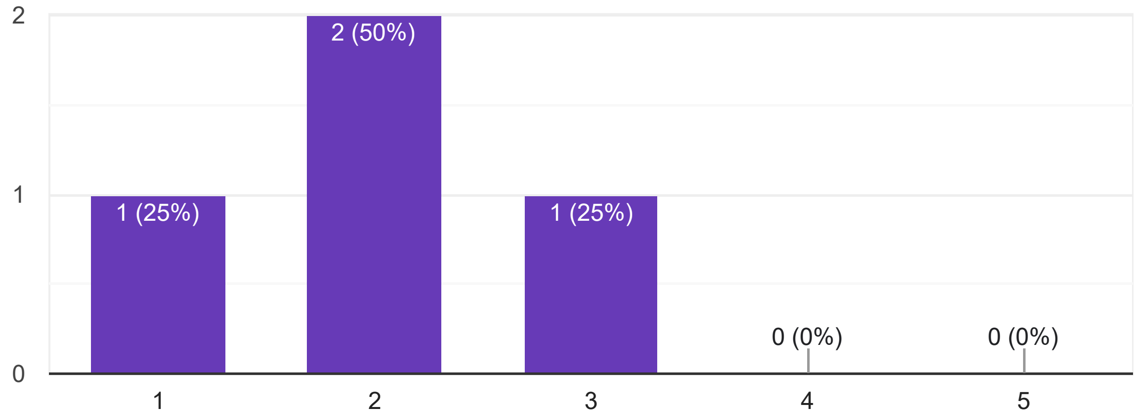
4 risposte



SUS10 - I needed to learn a lot of things before I could get going with this system.

Copia

4 risposte

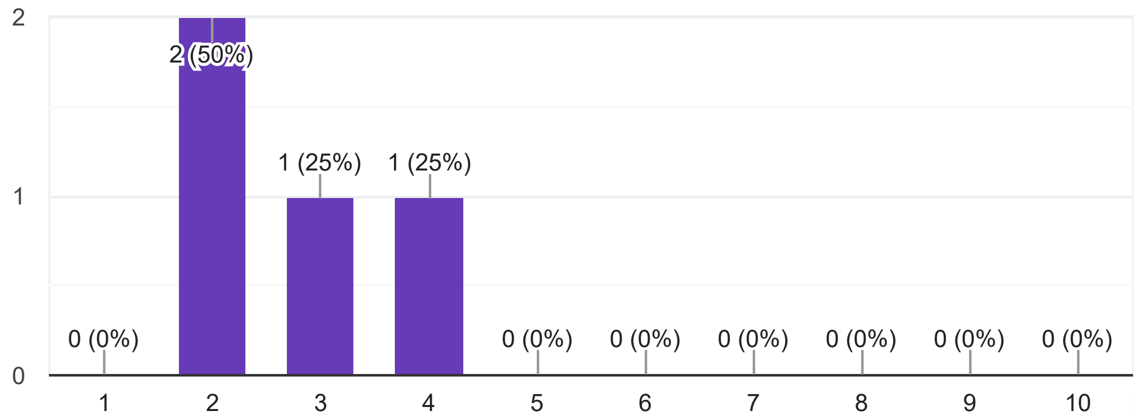


NASA Task Load Index

NASA1 - How mentally demanding was the task?

Copia

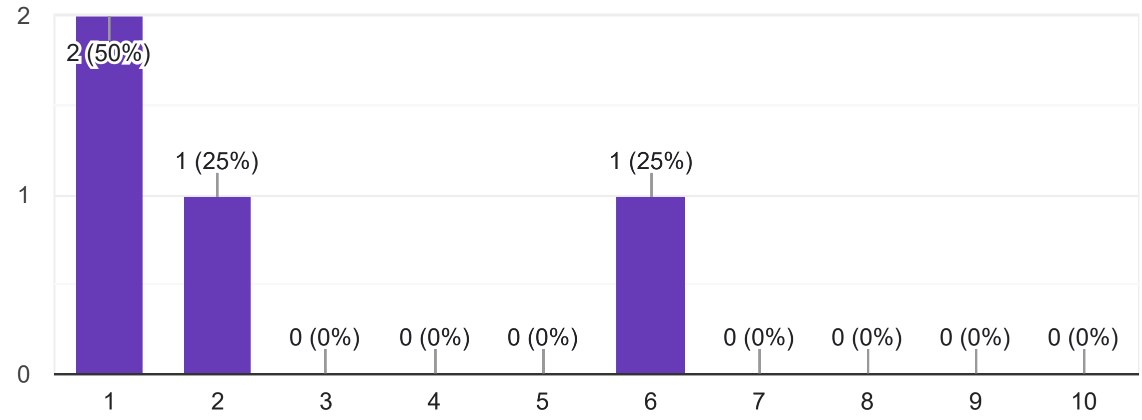
4 risposte



NASA2 - How physically demanding was the task?

Copia

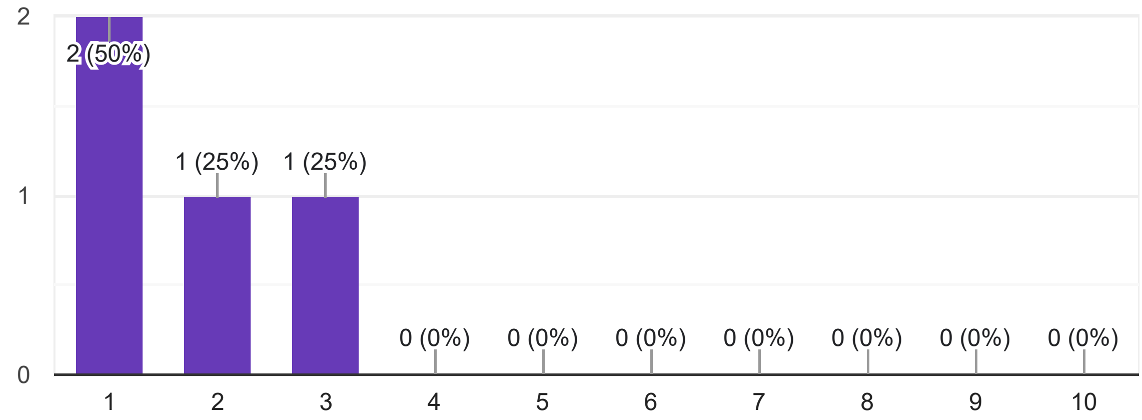
4 risposte



NASA3 - How hurried or rushed was the pace of the task?

Copia

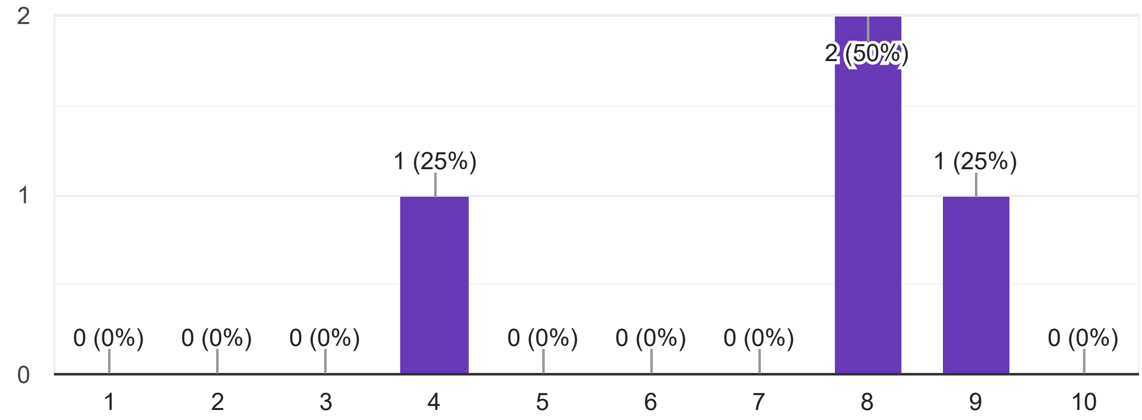
4 risposte



NASA4 - How successful were you in accomplishing what you were asked to do?

Copia

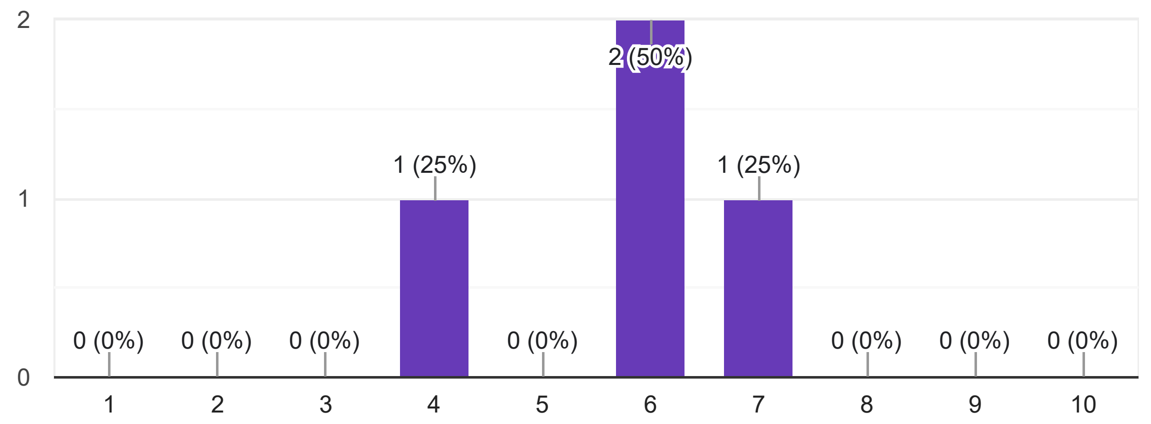
4 risposte



NASA5 - How hard did you have to work to accomplish your level of performance?

Copia

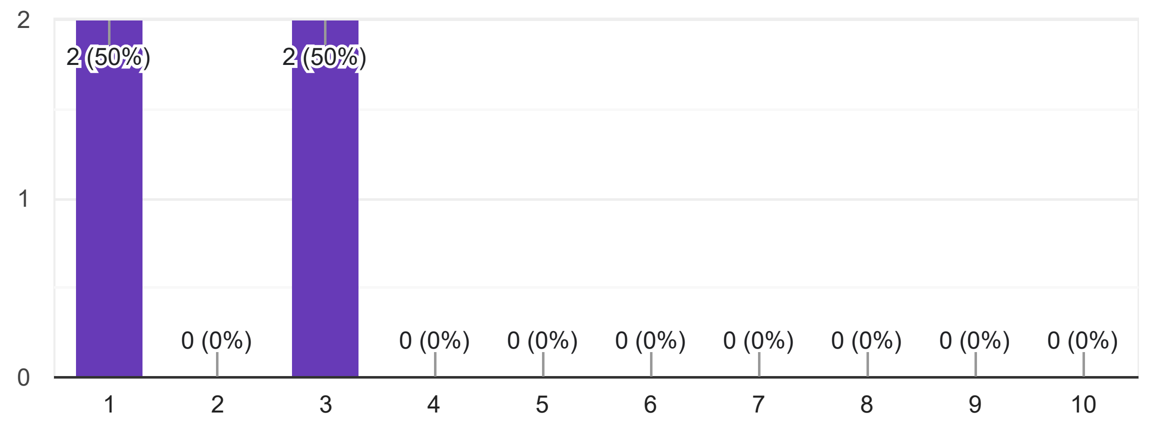
4 risposte



NASA6 - How insecure, discouraged, irritated, stressed, and annoyed were you?

Copia

4 risposte

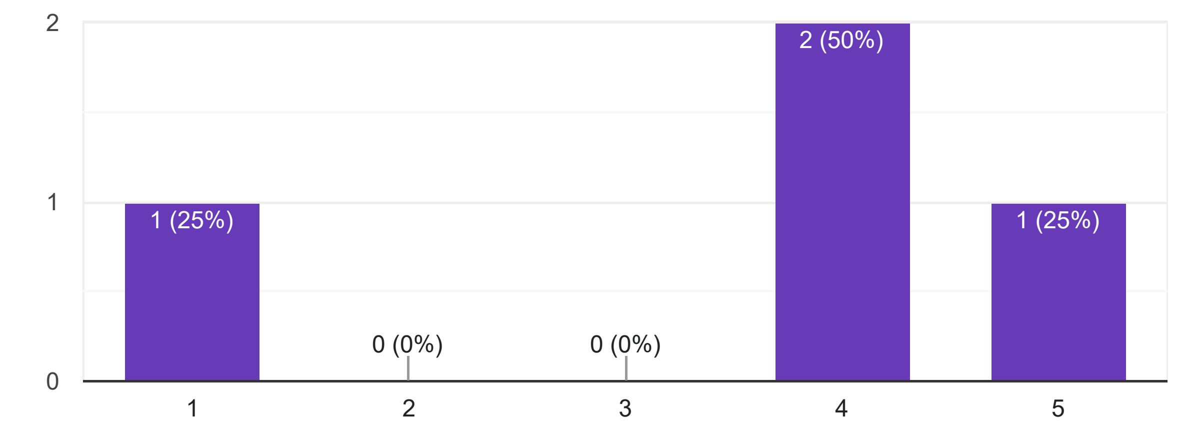


TAM - Technology Acceptance Model

TAM-PU1 - Doing the task (i.e. simulating the specific neurosurgical procedure) without the application would be challenging.

Copia

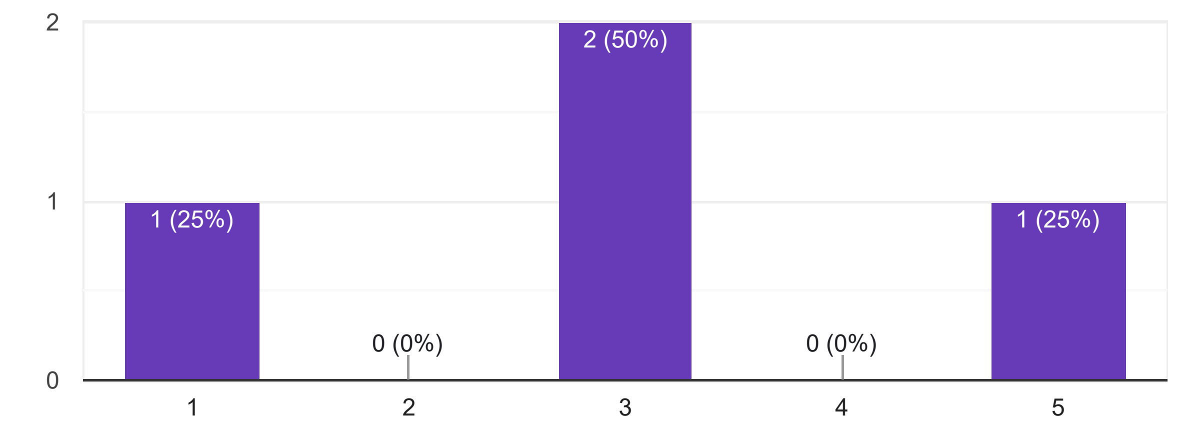
4 risposte



TAM-PU2 - Utilizing the application gives me better control over the simulated specific neurosurgical procedure.

Copia

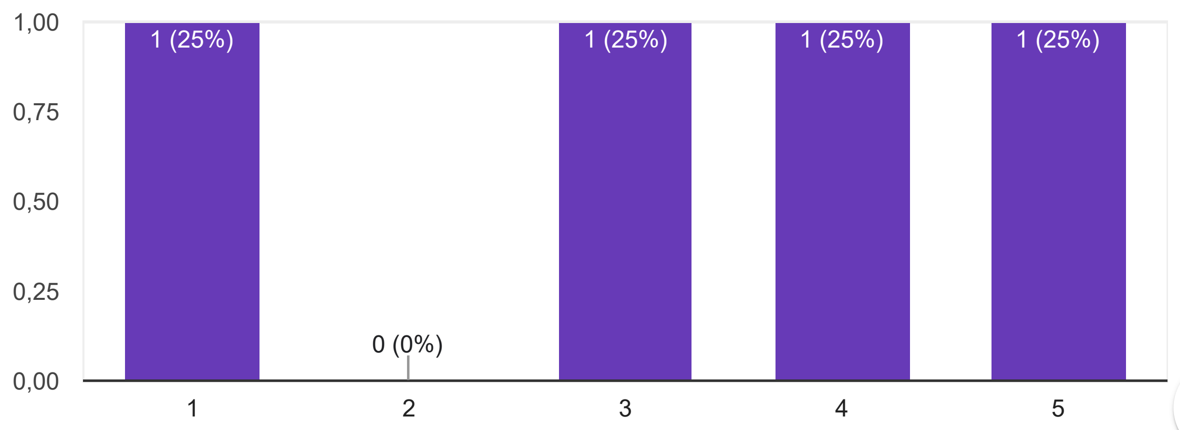
4 risposte



TAM-PU3 - Using the application enhances my ability to simulate the specific neurosurgical procedure.

Copia

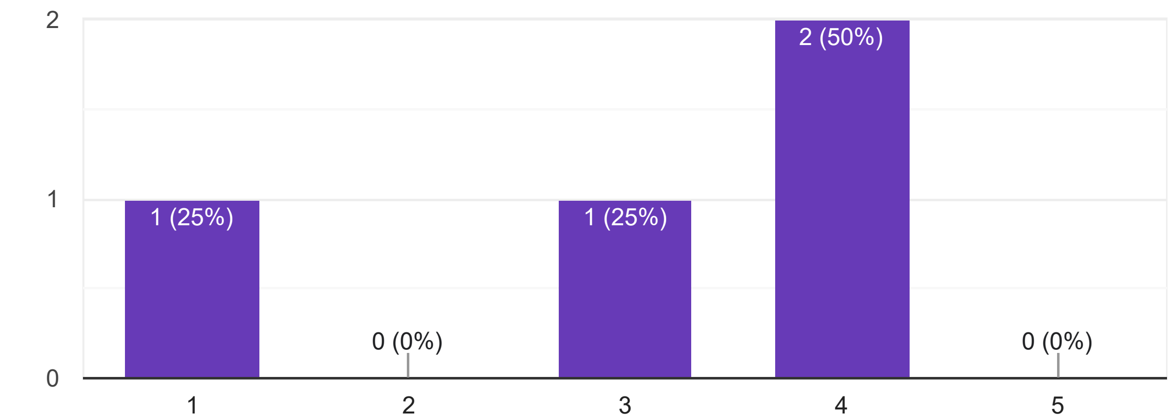
4 risposte



TAM-PU4 - The application addresses my specific needs for simulating the specific neurosurgical procedure.

Copia

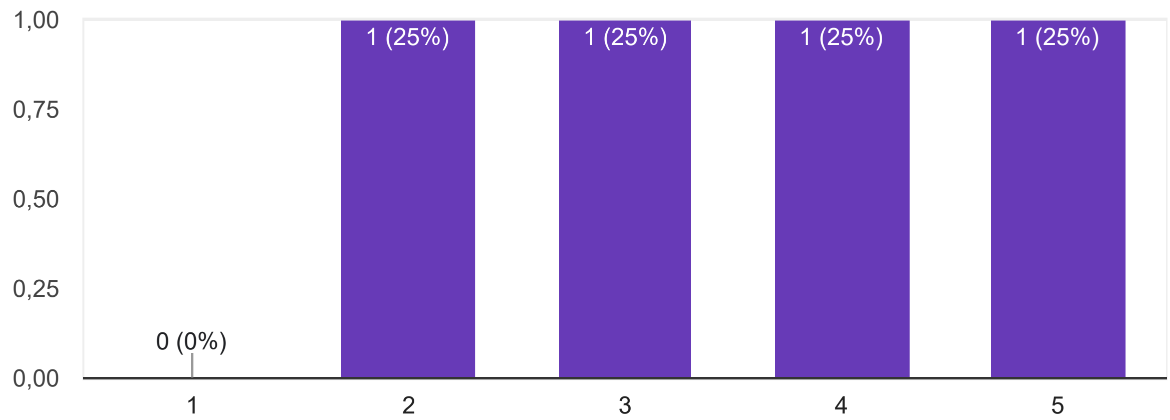
4 risposte



TAM-PU5 - Learning with the application saves me time when mastering simulating the specific neurosurgical procedure.

Copia

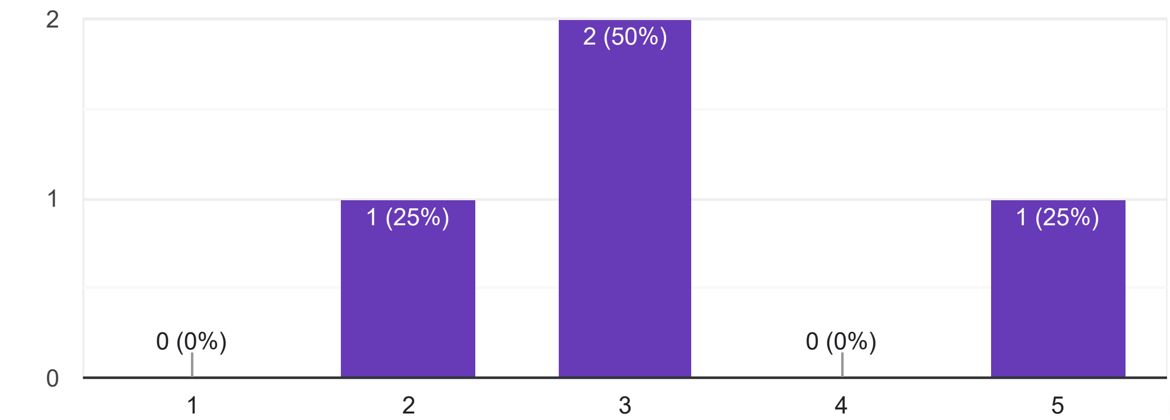
4 risposte



TAM-PU6 - The system/application allows me to simulate the specific neurosurgical procedure more efficiently.

Copia

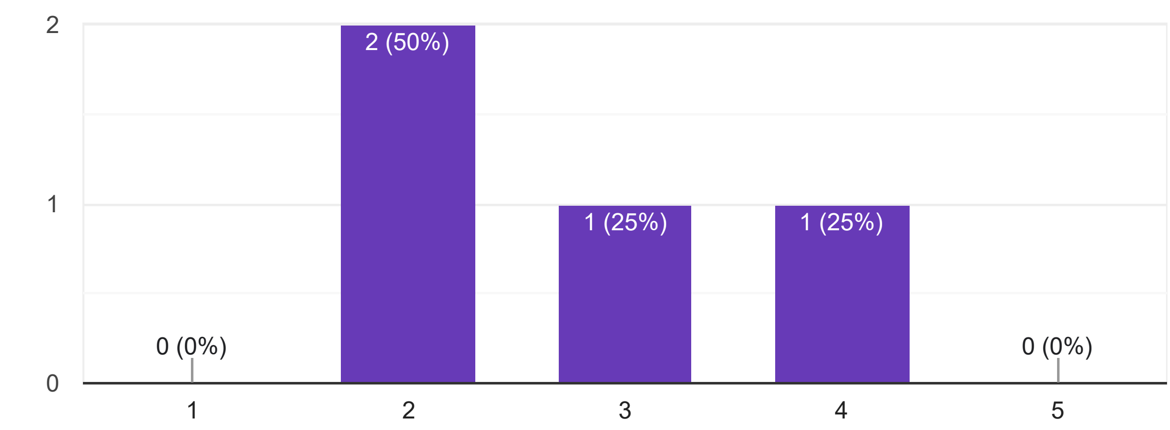
4 risposte



TAM-PU7 - The application supports critical aspects of the specific neurosurgical procedure simulation process.

Copia

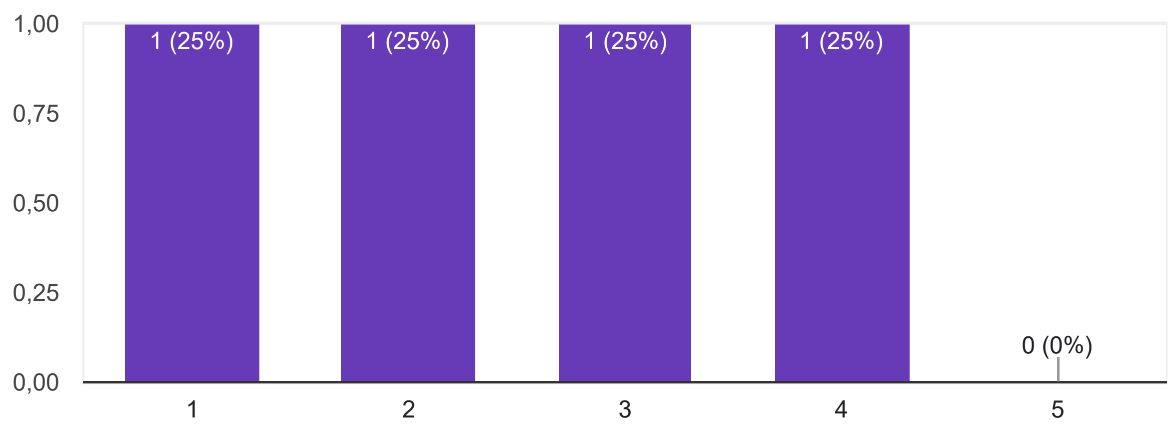
4 risposte



TAM-PU8 - Learning from the application enables me to achieve better results than traditional methods for mastering the specific neurosurgical procedure simulation.

Copia

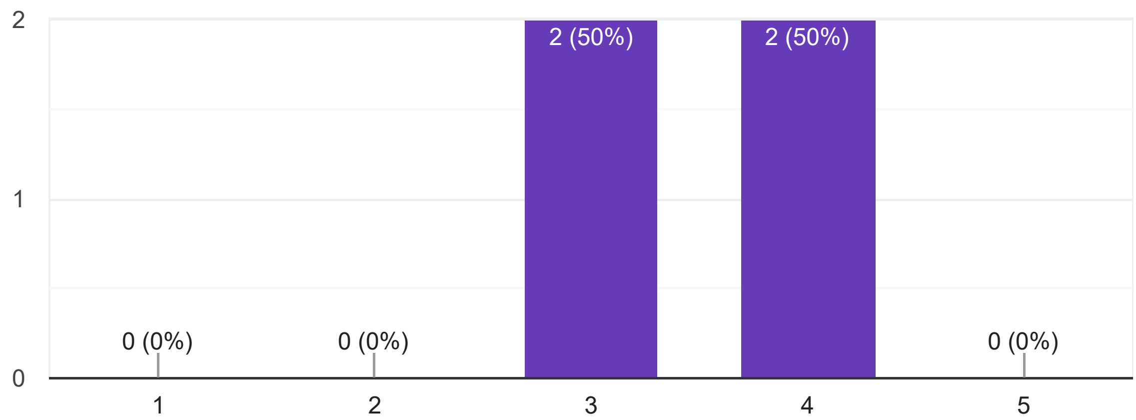
4 risposte



TAM-PU9 - Using the application reduces the time I spend on less effective software for simulating the specific neurosurgical procedure.

Copia

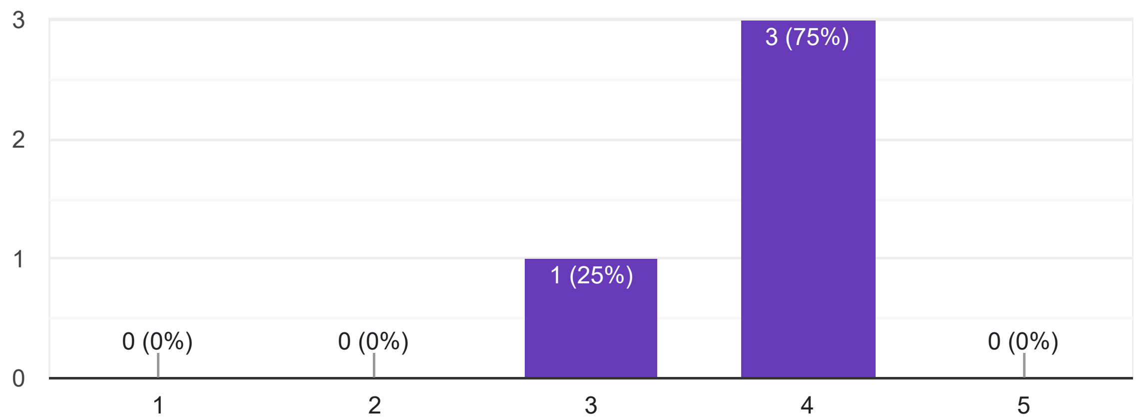
4 risposte



TAM-PU10 - Learning from the application enhances my proficiency in simulating the specific neurosurgical procedure.

Copia

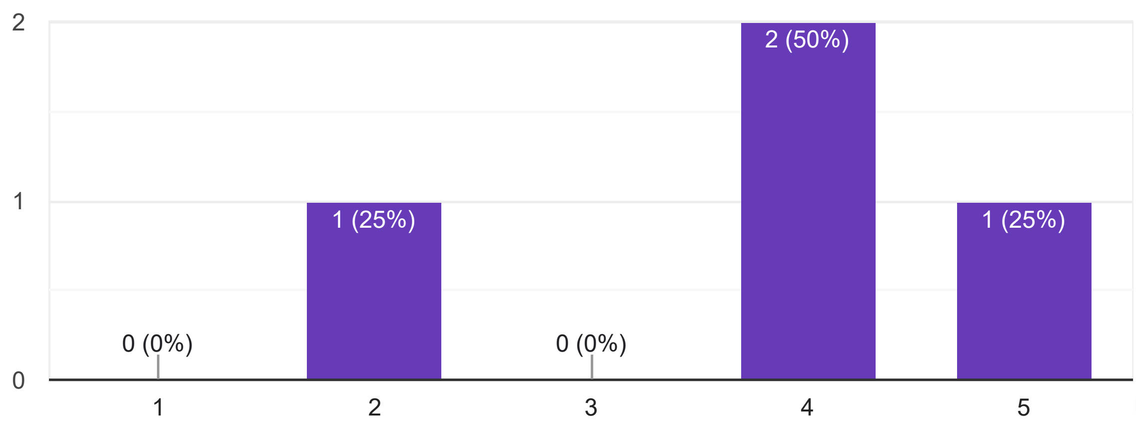
4 risposte



TAM-PU11 - Using the application improves the quality of my skills in simulating the specific neurosurgical procedure.

Copia

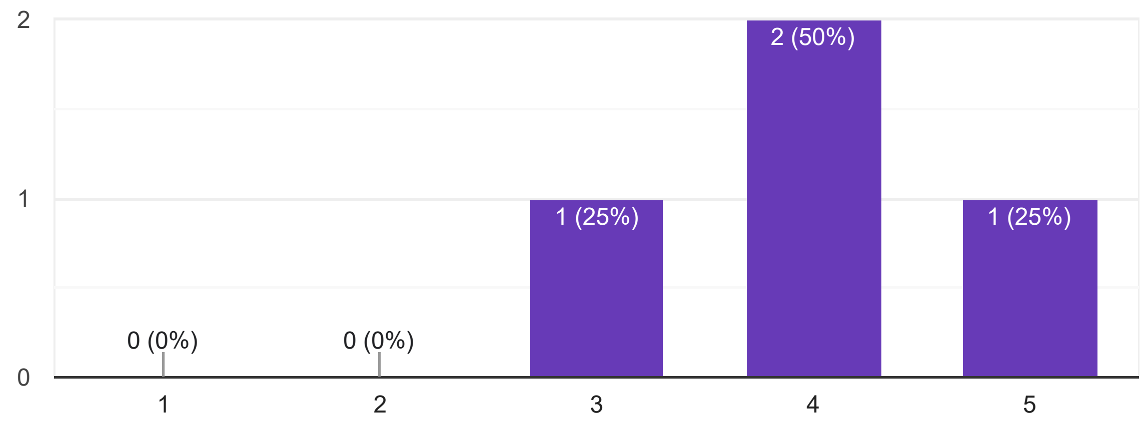
4 risposte



TAM-PU12 - Using the application increases my overall productivity in mastering the specific neurosurgical procedure simulation.

Copia

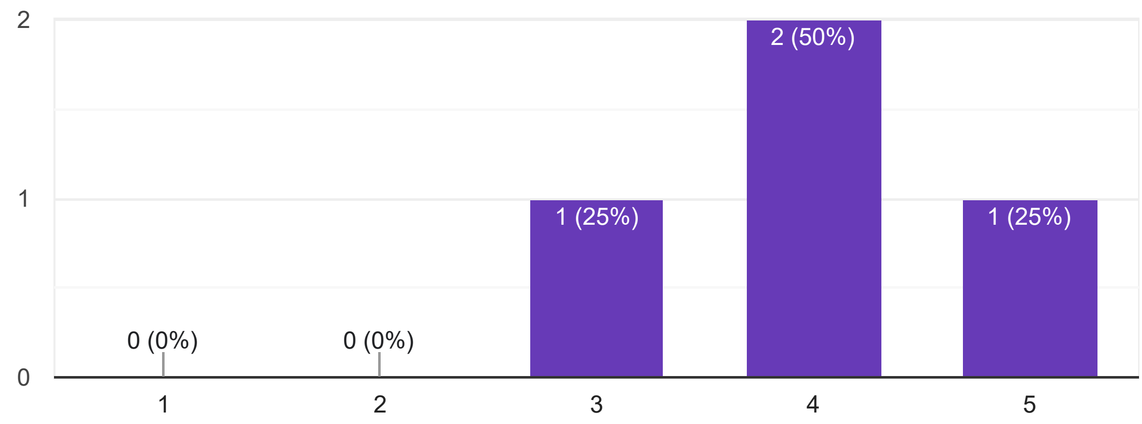
4 risposte



TAM-PU13 - Using the application simplifies the process of simulating the specific neurosurgical procedure.

Copia

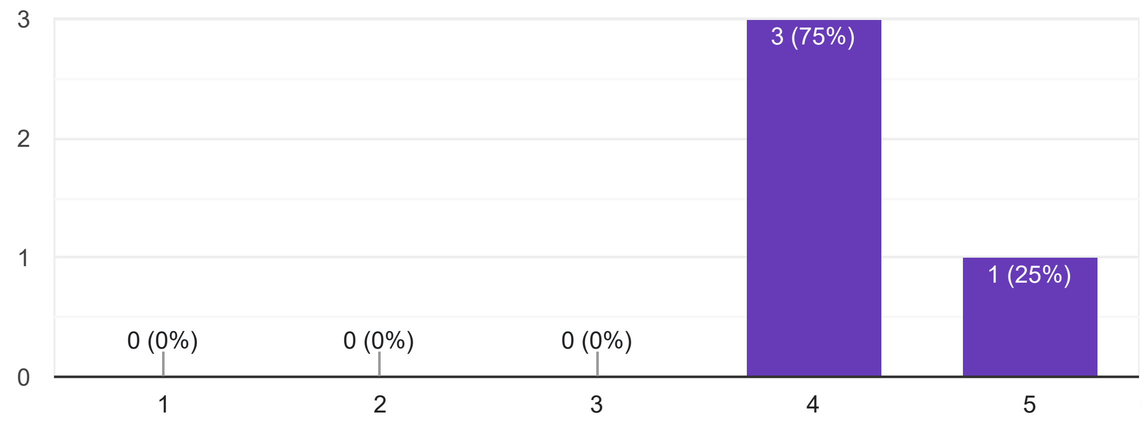
4 risposte



TAM-PU14 - Overall, I find the system/application valuable for simulating the specific neurosurgical procedure.

Copia

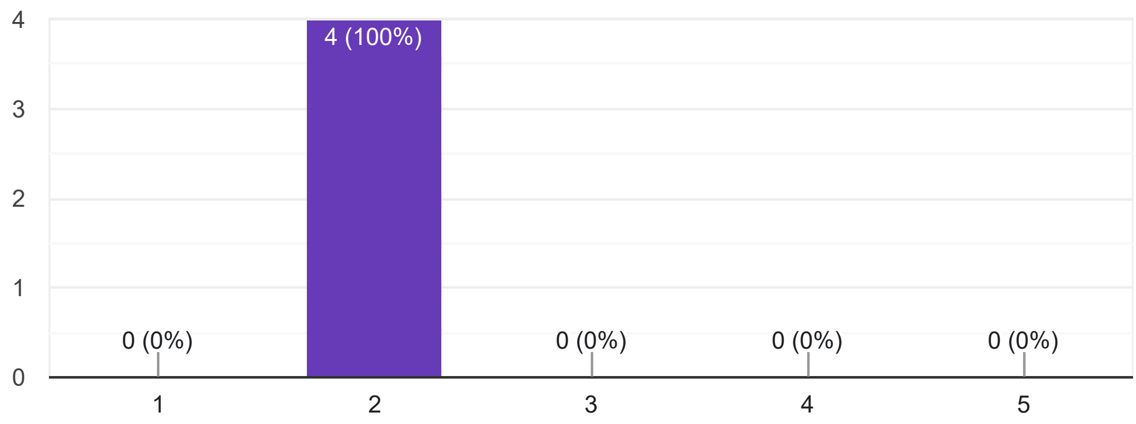
4 risposte



TAM-PE1 - I often find the interface of the application confusing when simulating the specific neurosurgical procedure.

Copia

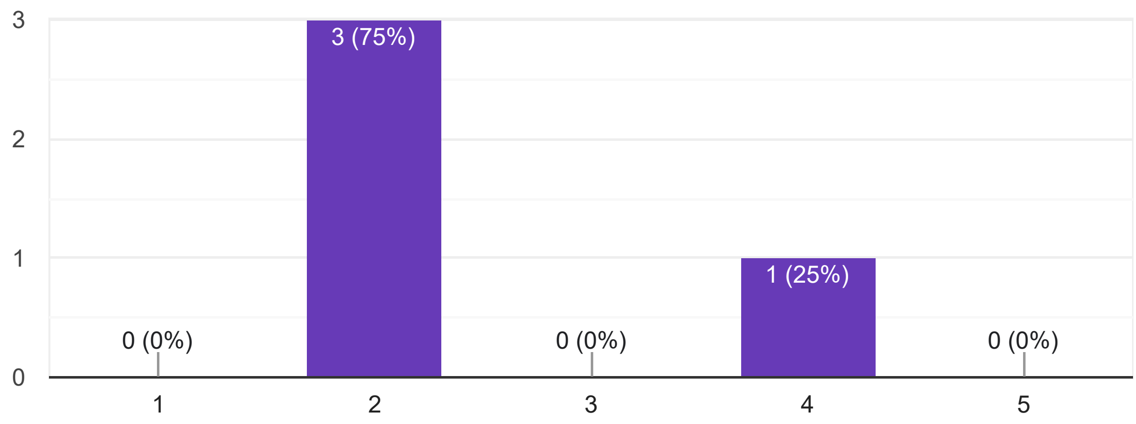
4 risposte



TAM-PE2 - I make mistakes frequently when using the application to simulate the specific neurosurgical procedure.

Copia

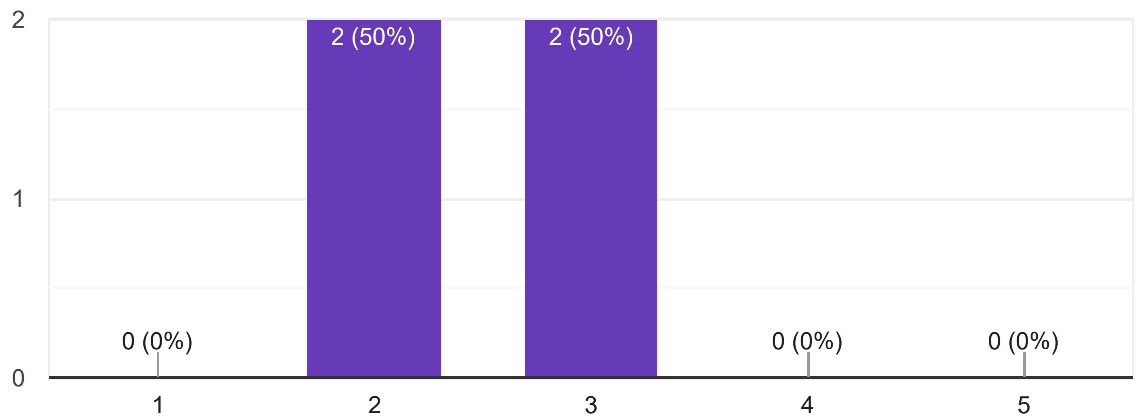
4 risposte



TAM-PE3 - Interacting with the application can be frustrating during the simulation of the specific neurosurgical procedure.

Copia

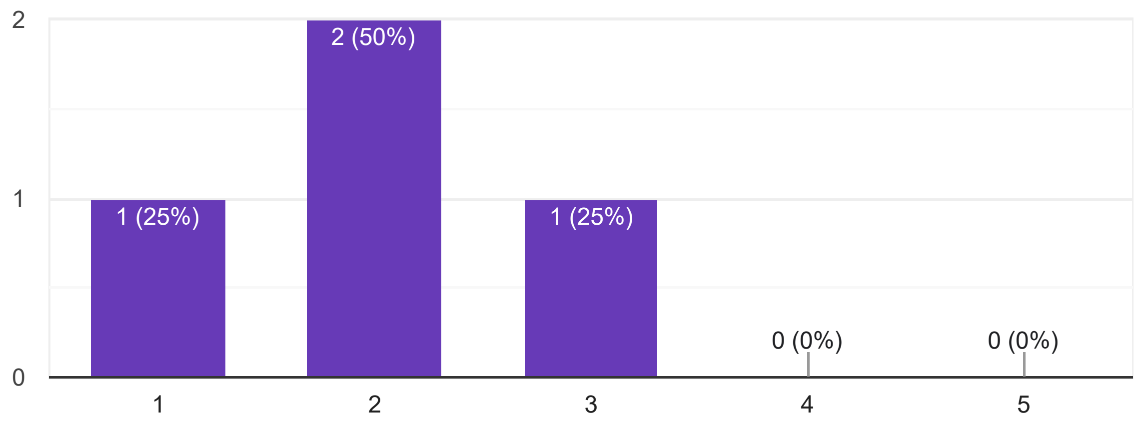
4 risposte



TAM-PE4 - I need to refer to the experimenters' guidance frequently when using the application to simulate the specific neurosurgical operation.

Copia

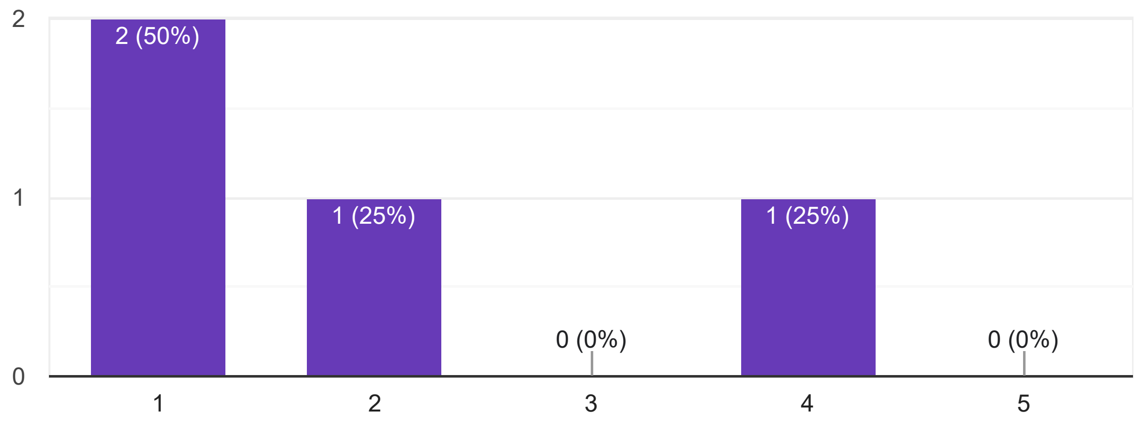
4 risposte



TAM-PE5 - Interacting with the application demands a significant amount of mental effort during the simulation of the specific neurosurgical operation.

Copia

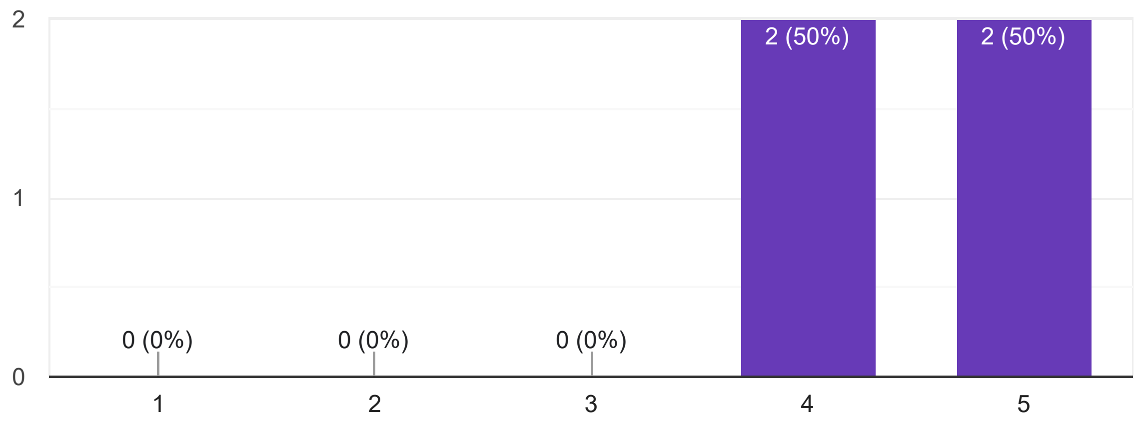
4 risposte



TAM-PE6 - I find it easy to recover from errors encountered while using the system/application for simulating the specific neurosurgical operation.

Copia

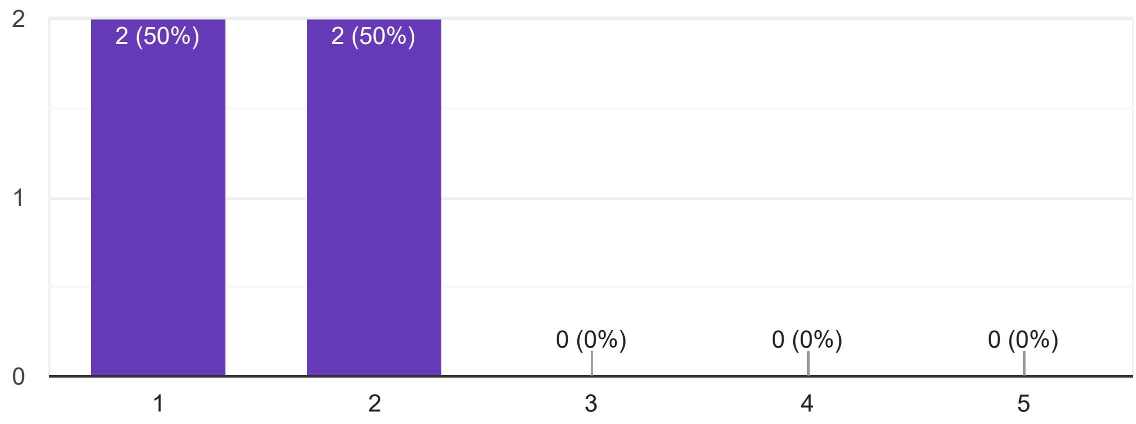
4 risposte



TAM-PE7 - The application's interface is rigid and inflexible when it comes to simulate the neurosurgical procedure.

Copia

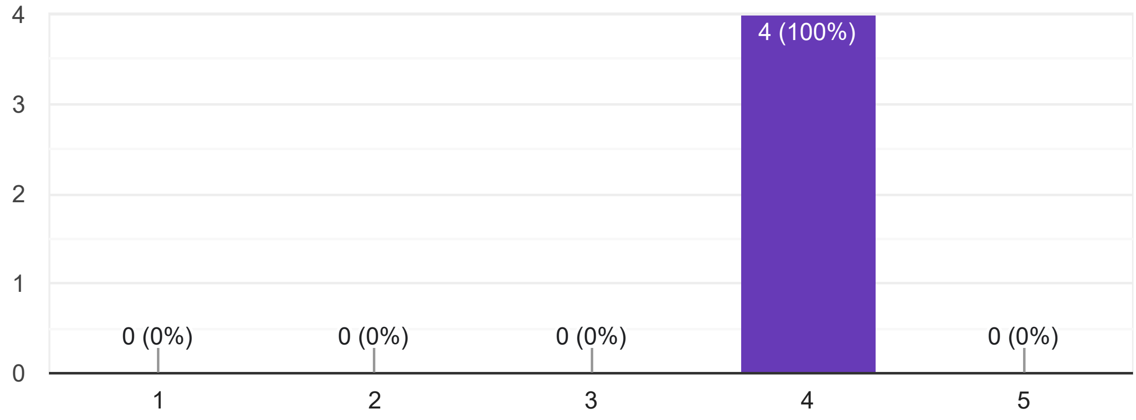
4 risposte



TAM-PE8 - I find it easy to achieve the specific simulated neurosurgical goals using the application.

Copia

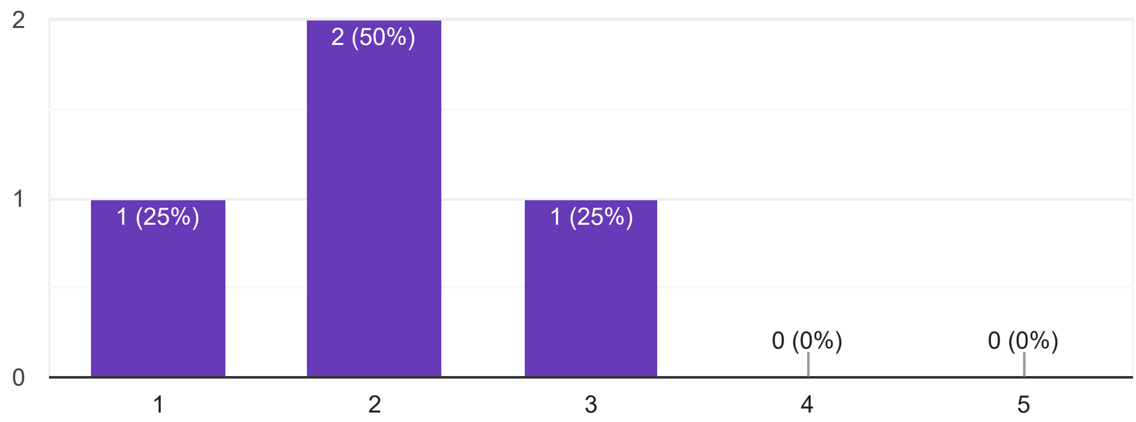
4 risposte



TAM-PE9 - The application sometimes behaves unpredictably during the simulation of the specific neurosurgical operation.

Copia

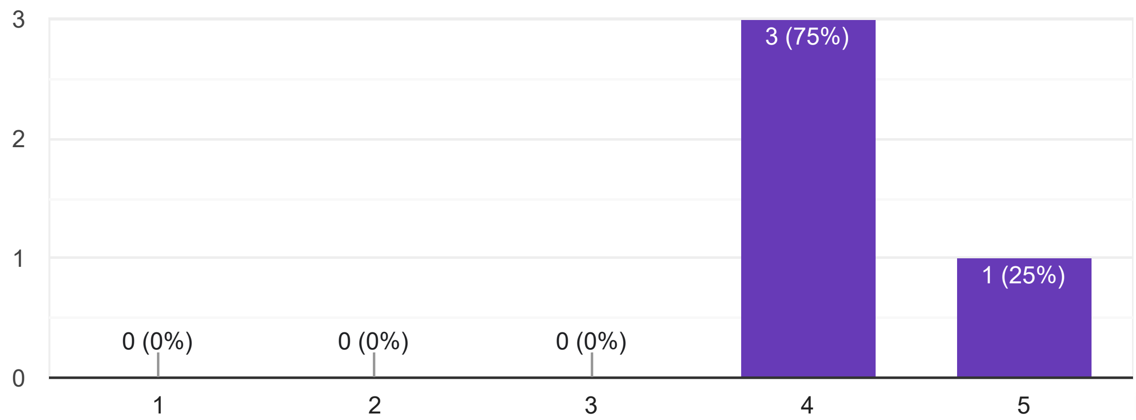
4 risposte



TAM-PE10 - I consider the application user-friendly for simulating the specific neurosurgical operation.

Copia

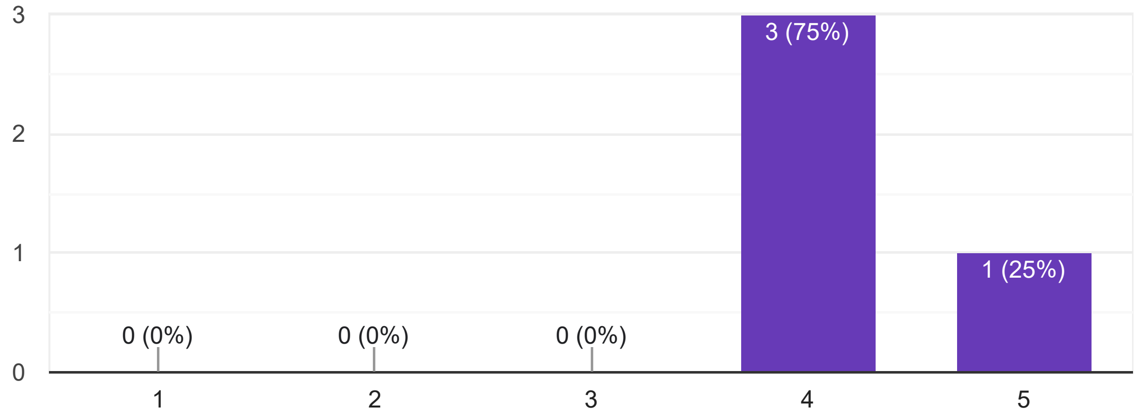
4 risposte



TAM-PE11 - My interaction with the application is straightforward to understand when simulating the specific neurosurgical operation.

Copia

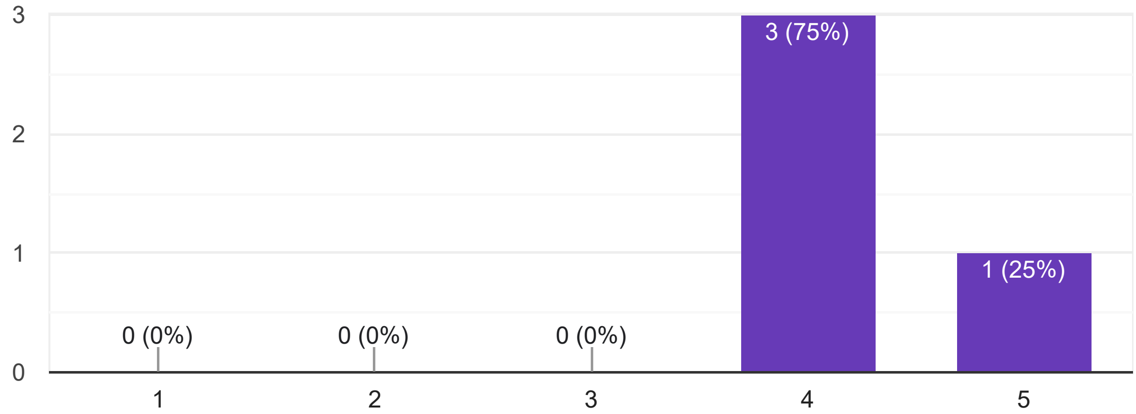
4 risposte



TAM-PE12 - It is easy for me to remember how to perform tasks using the application for simulating the specific neurosurgical operation.

Copia

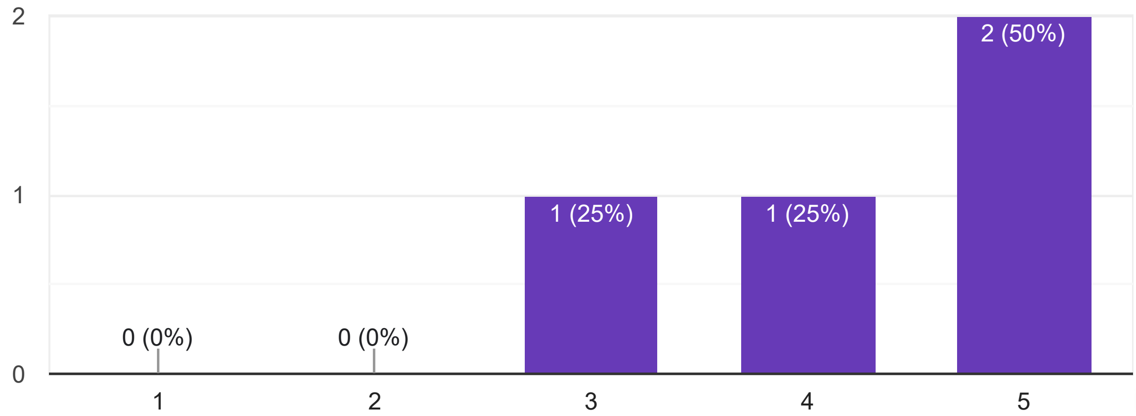
4 risposte



TAM-PE13 - The application provides helpful guidance while I'm simulating the specific neurosurgical operation.

Copia

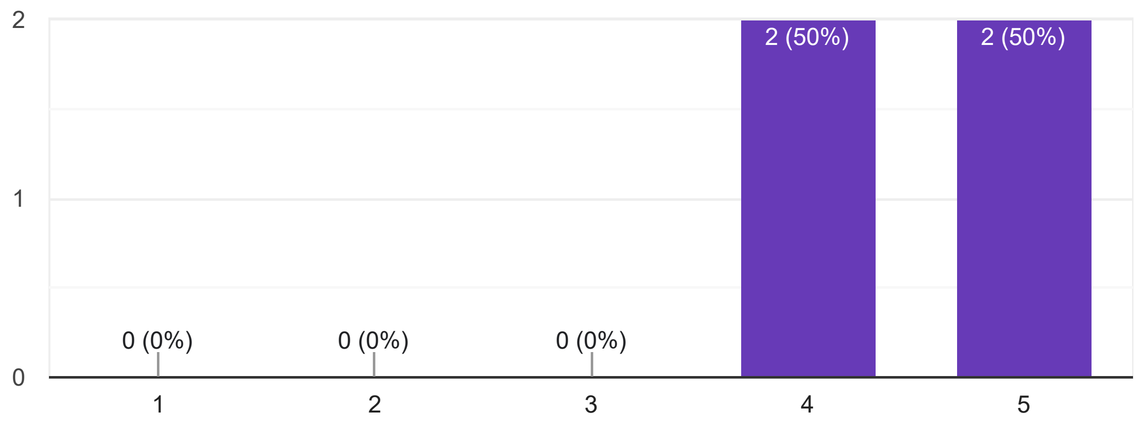
4 risposte



TAM-PE14 - Overall, I find the application easy to use for mastering simulating the specific neurosurgical operation.

Copia

4 risposte



Appendix B

NeuroMIX_Visualization

4 risposte

Pubblica i dati di analisi

Demograghic question

Please enter your Participant ID:

4 risposte

0-1

0-2

0-3

0-4

Please specify your exact age in years:

4 risposte

32

27

29

28

Please provide the name of your country and city of residence.

4 risposte

Italy Bologna

Italy - Faenza

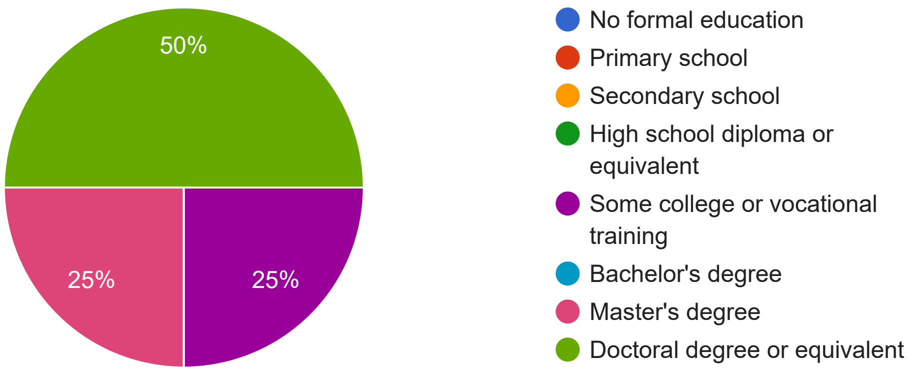
Italia Pesaro

italy

Please select your highest level of education completed from the options below:

Copia

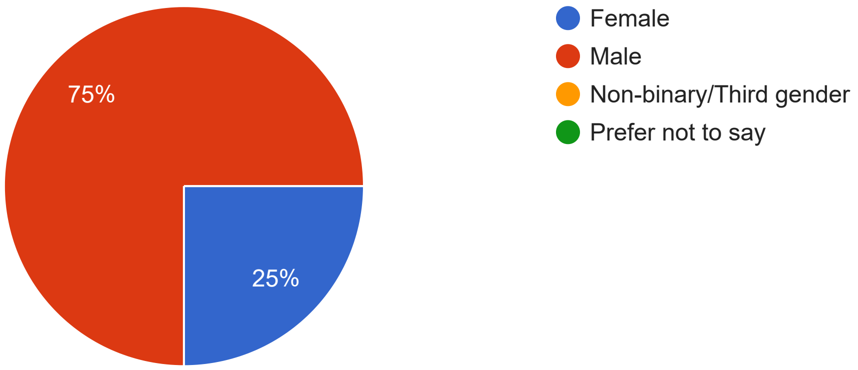
4 risposte



What is your gender?

Copia

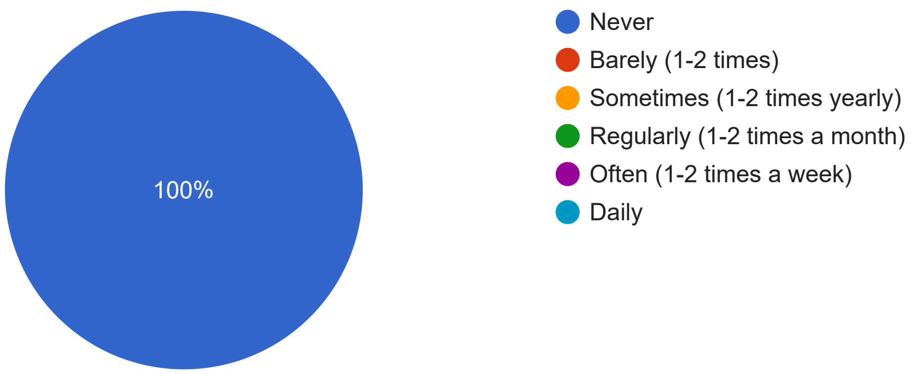
4 risposte



How often do you use Mixed Reality applications (e.g. for games) ?

Copia

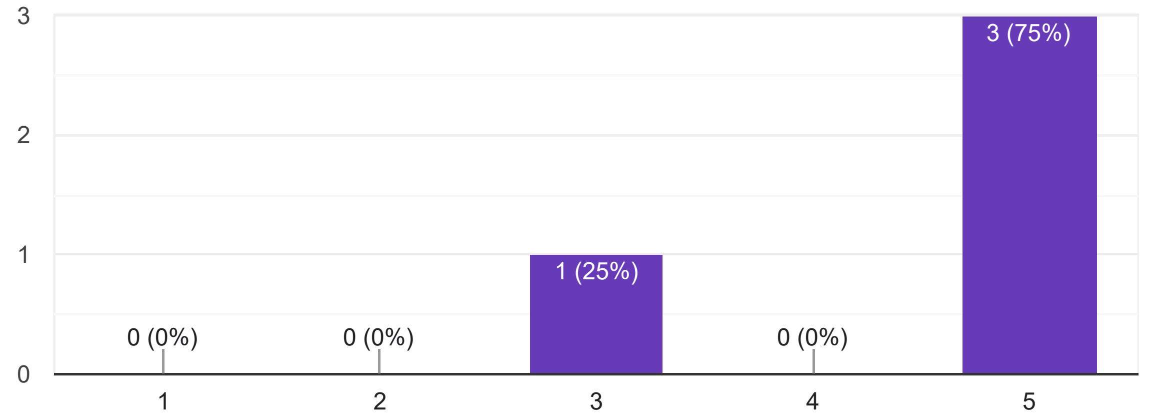
4 risposte



How confident are you with reading DICOM images?

Copia

4 risposte

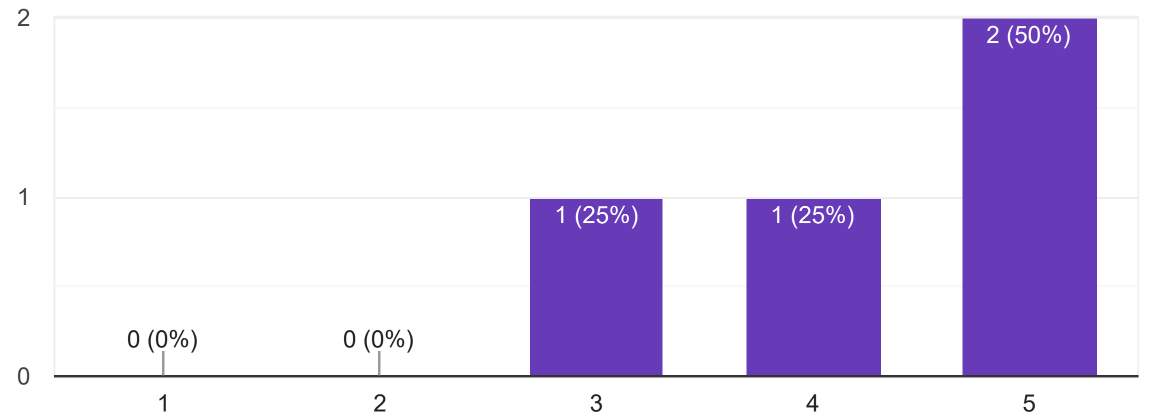


The System Usability Scale (SUS)

SUS1 - I think that I would like to use this system frequently.

Copia

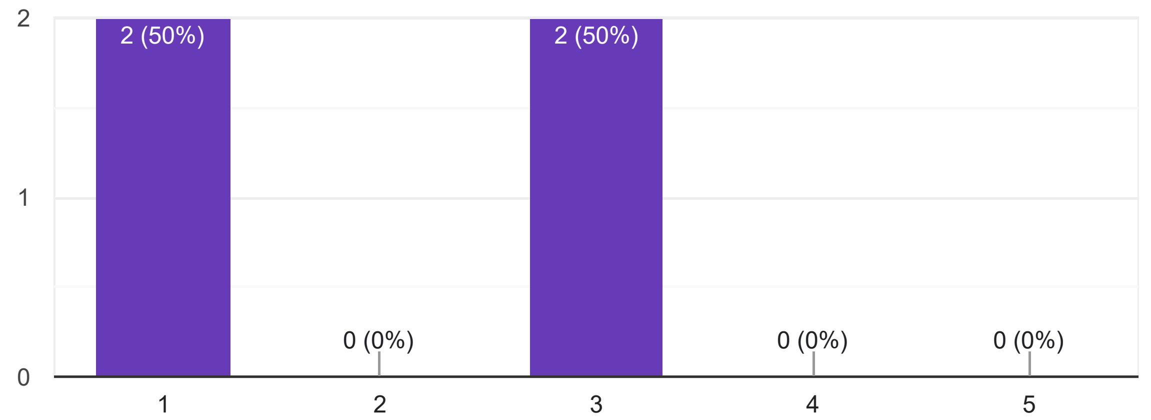
4 risposte



SUS2 - I found the system unnecessarily complex.

Copia

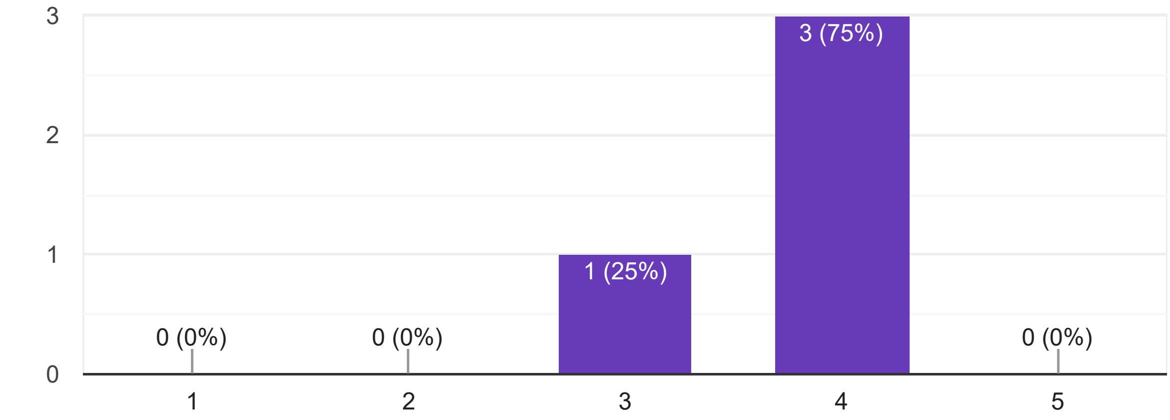
4 risposte



SUS3 - I thought the system was easy to use.

Copia

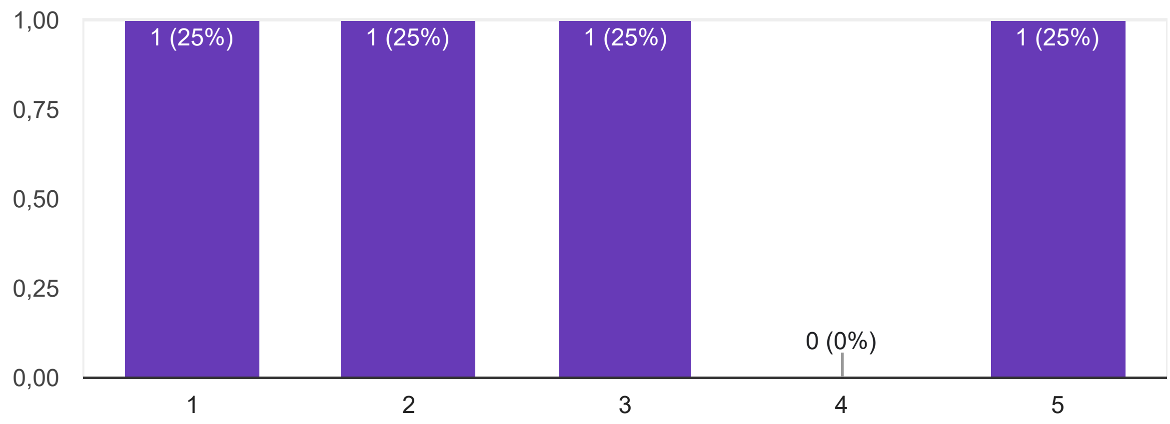
4 risposte



SUS4 - I think that I would need the support of a technical person to be able to use this system.

Copia

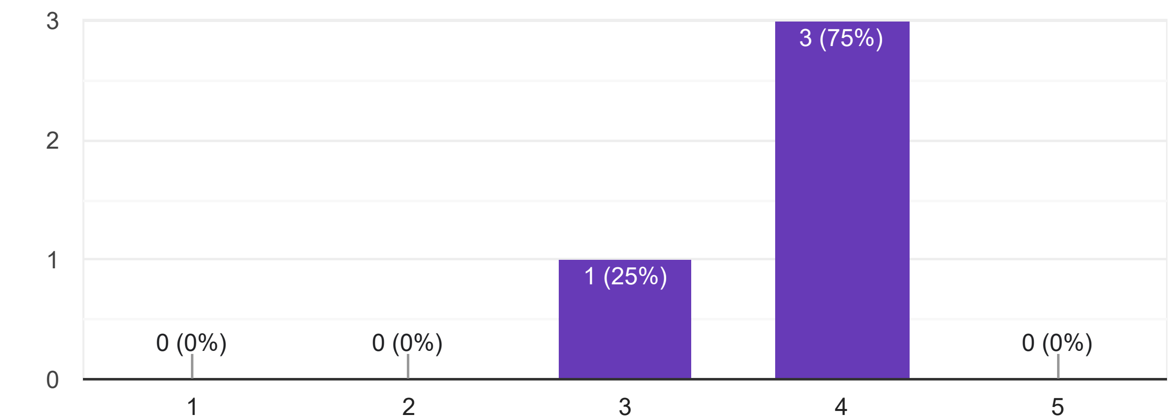
4 risposte



SUS5 - I found the various functions in this system were well integrated.

Copia

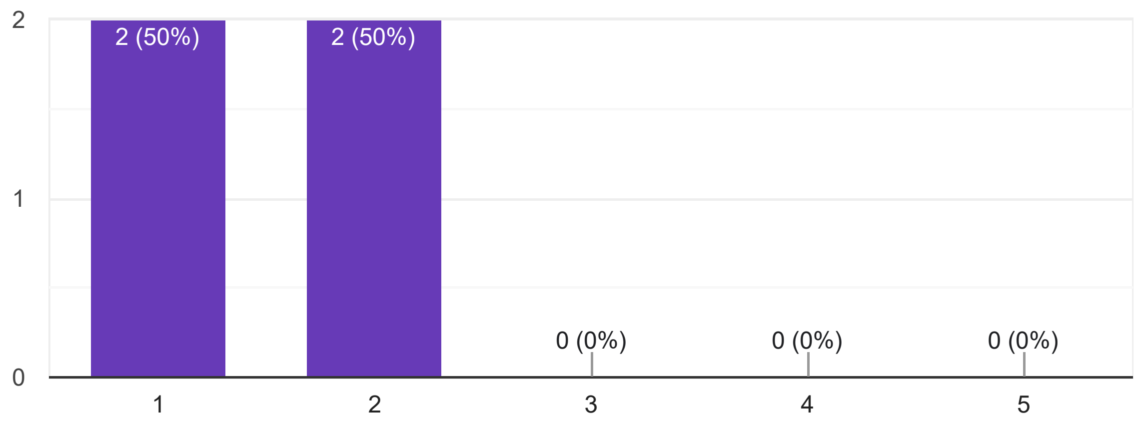
4 risposte



SUS6 - I thought there was too much inconsistency (e.g. the buttons are not always in the same position, etc...) in this system.

Copia

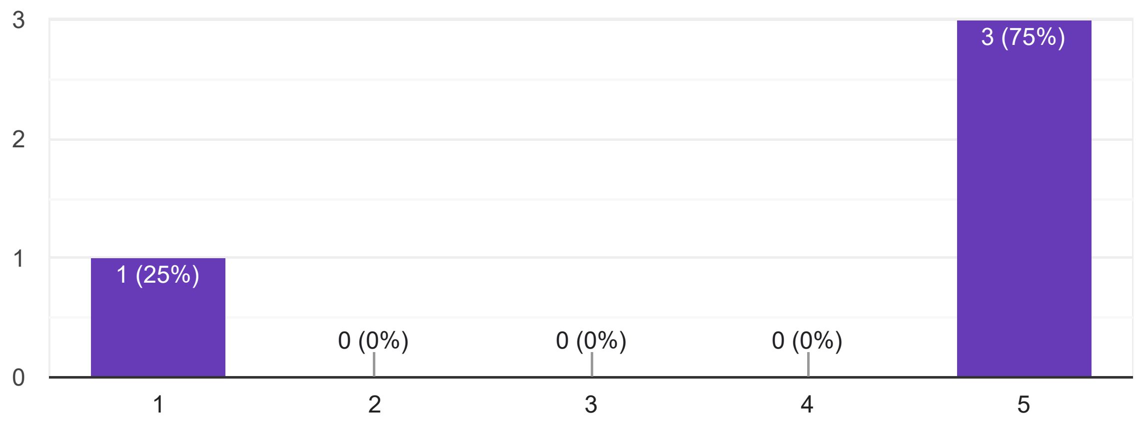
4 risposte



SUS7 - I would imagine that most people would learn to use this system very quickly.

Copia

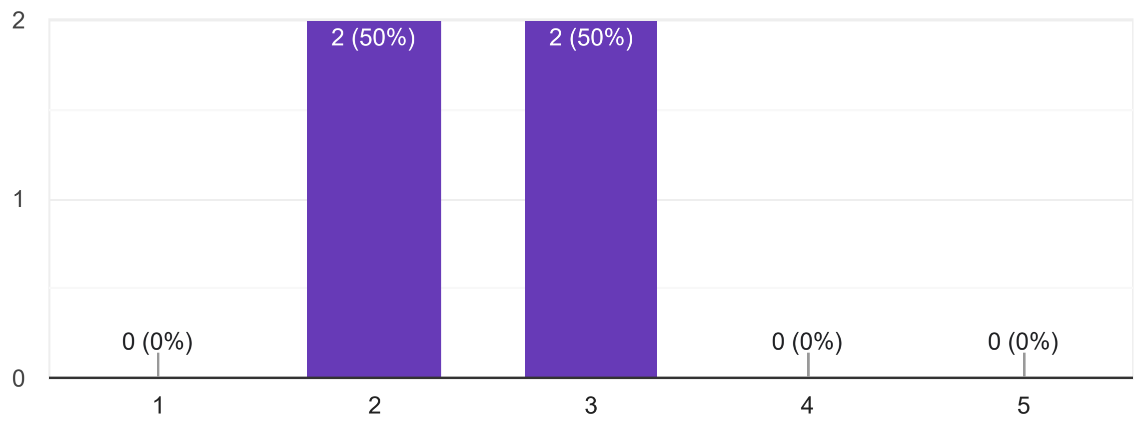
4 risposte



SUS8 - I found the system very cumbersome to use.

Copia

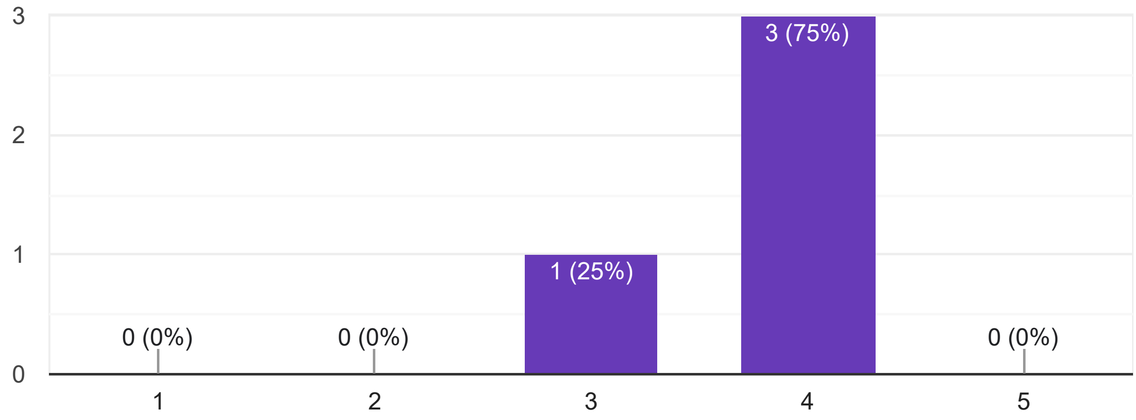
4 risposte



SUS9 - I felt very confident using the system.

Copia

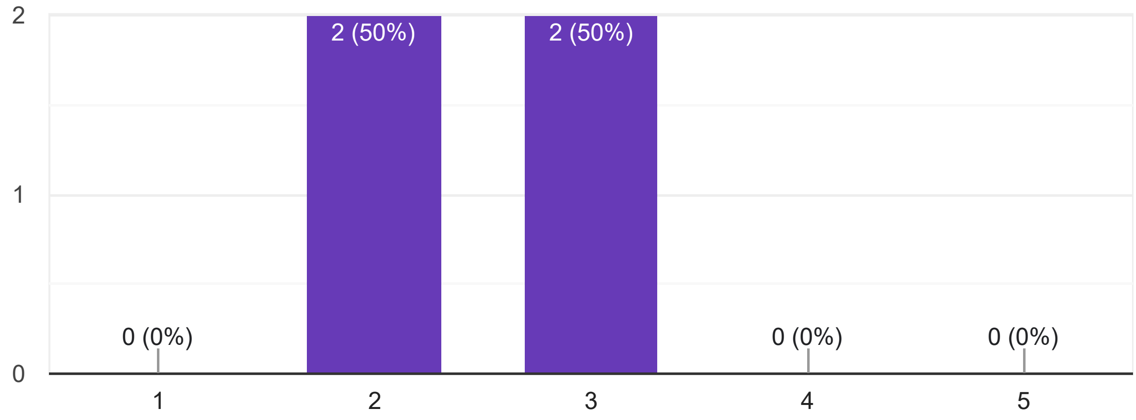
4 risposte



SUS10 - I needed to learn a lot of things before I could get going with this system.

Copia

4 risposte

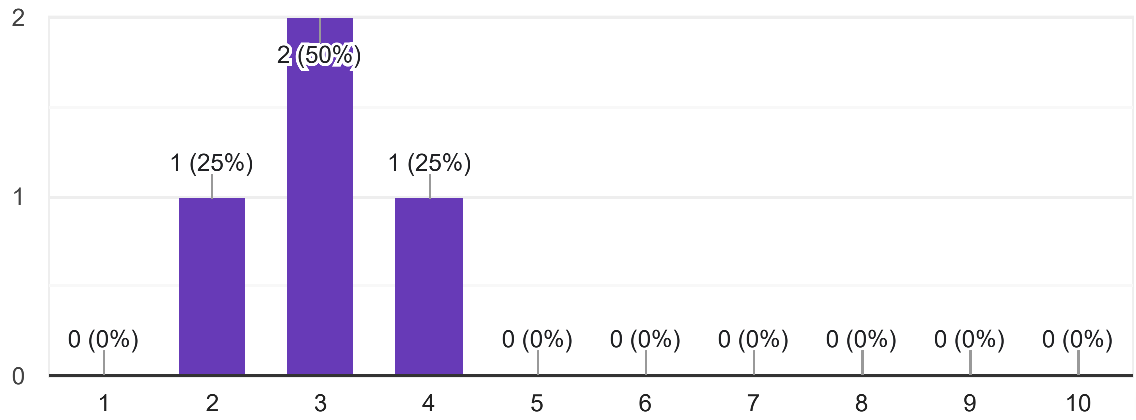


NASA Task Load Index

NASA1 - How mentally demanding was the task?

Copia

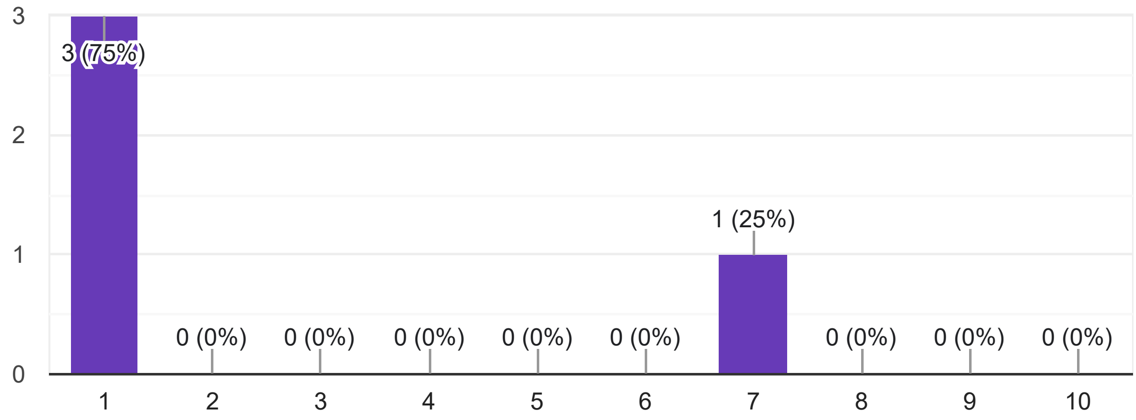
4 risposte



NASA2 - How physically demanding was the task?

Copia

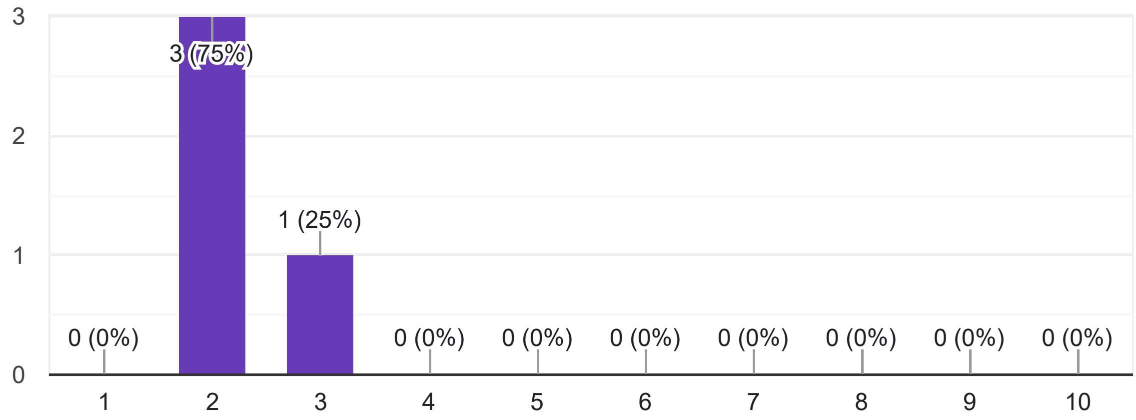
4 risposte



NASA3 - How hurried or rushed was the pace of the task?

Copia

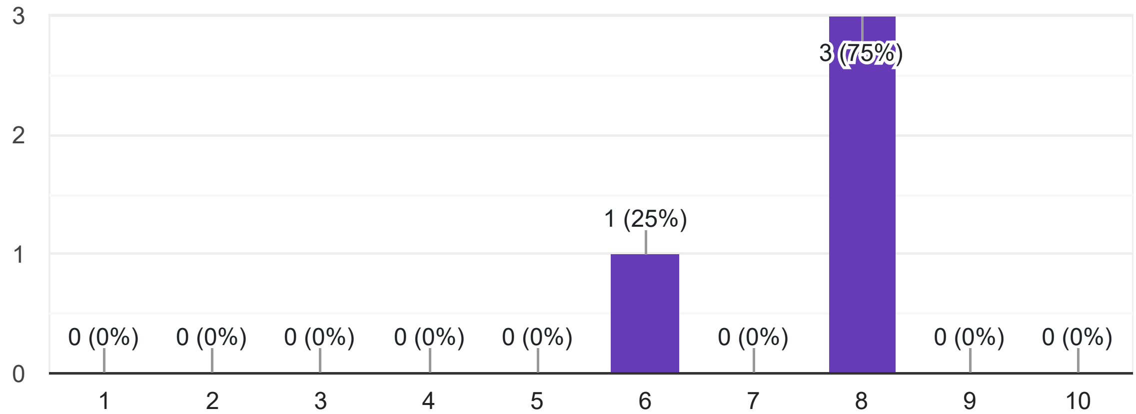
4 risposte



NASA4 - How successful were you in accomplishing what you were asked to do?

Copia

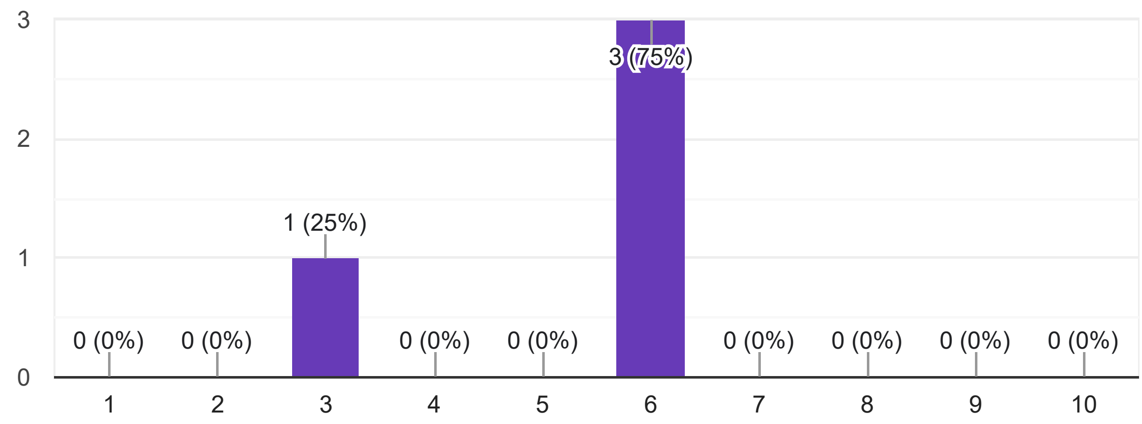
4 risposte



NASA5 - How hard did you have to work to accomplish your level of performance?

Copia

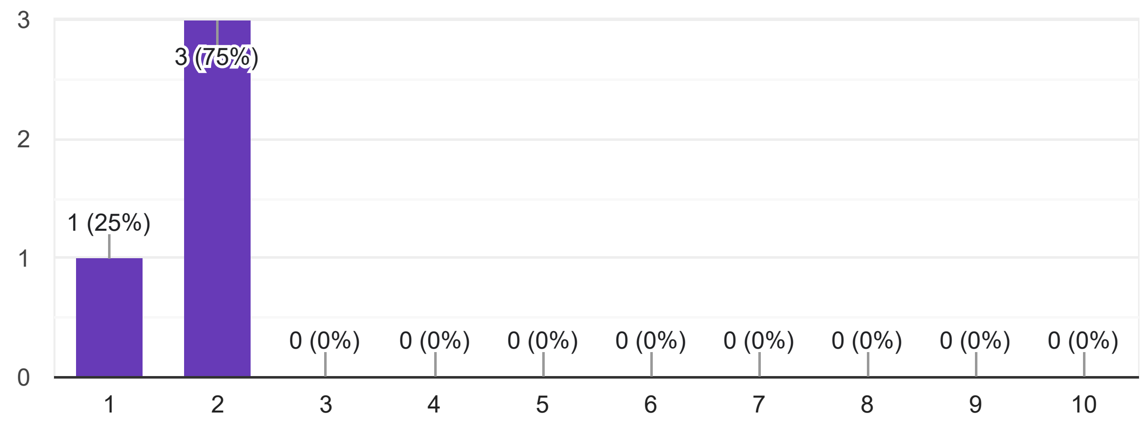
4 risposte



NASA6 - How insecure, discouraged, irritated, stressed, and annoyed were you?

Copia

4 risposte

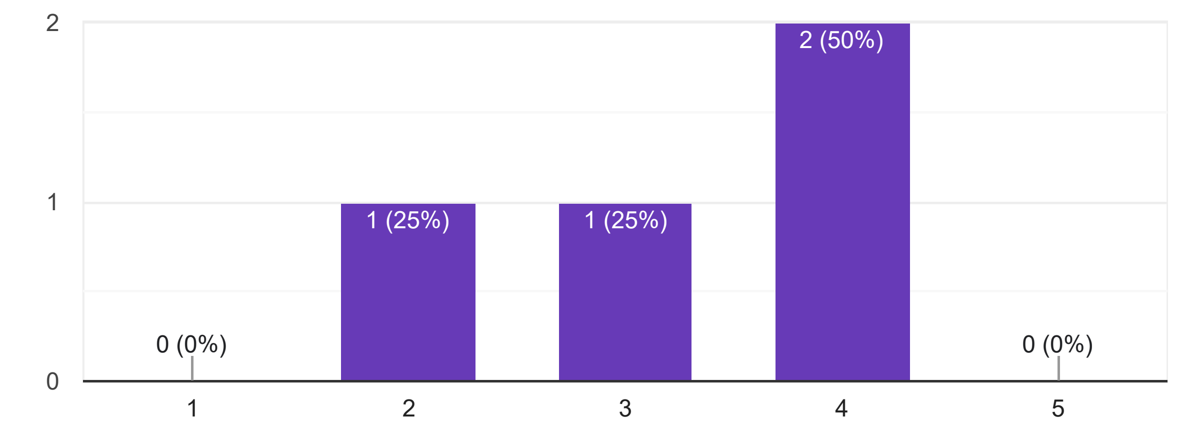


TAM - Technology Acceptance Model

TAM-PU1 - Doing the task (i.e. finding the blue target point on all three axes DICOM images) without the application would be challenging.

Copia

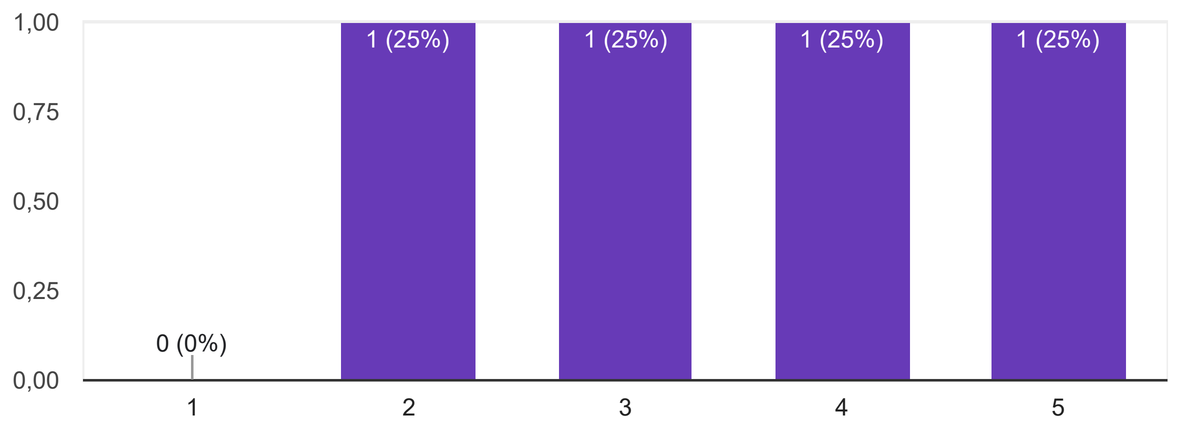
4 risposte



TAM-PU2 - Utilizing the application gives me better control over the manipulation of DICOM images.

Copia

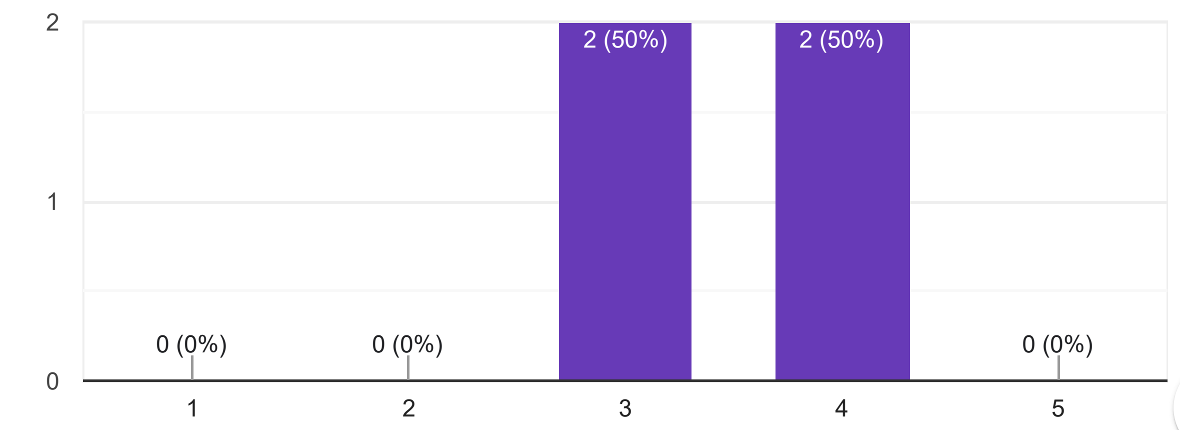
4 risposte



TAM-PU3 - Using the application enhances my ability to manipulate DICOM images.

Copia

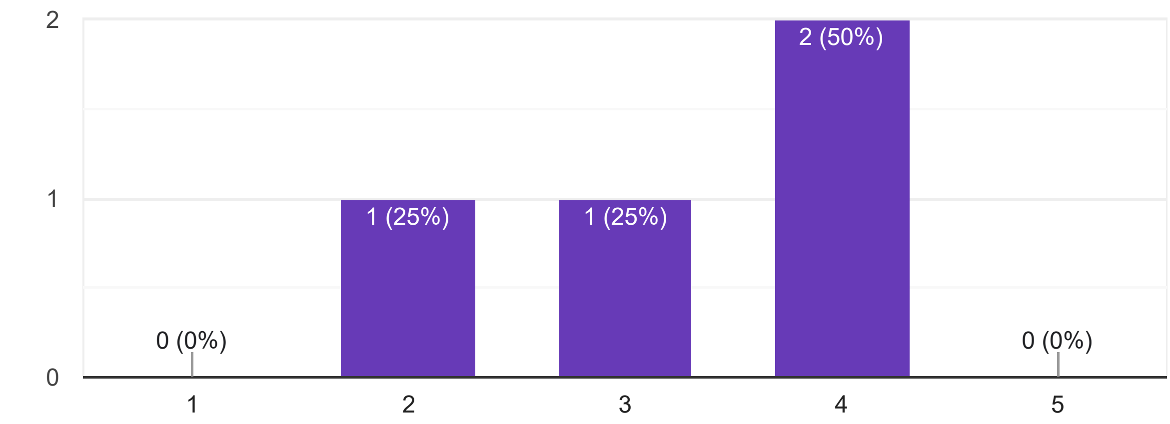
4 risposte



TAM-PU4 - The application addresses my specific needs for manipulating DICOM images.

Copia

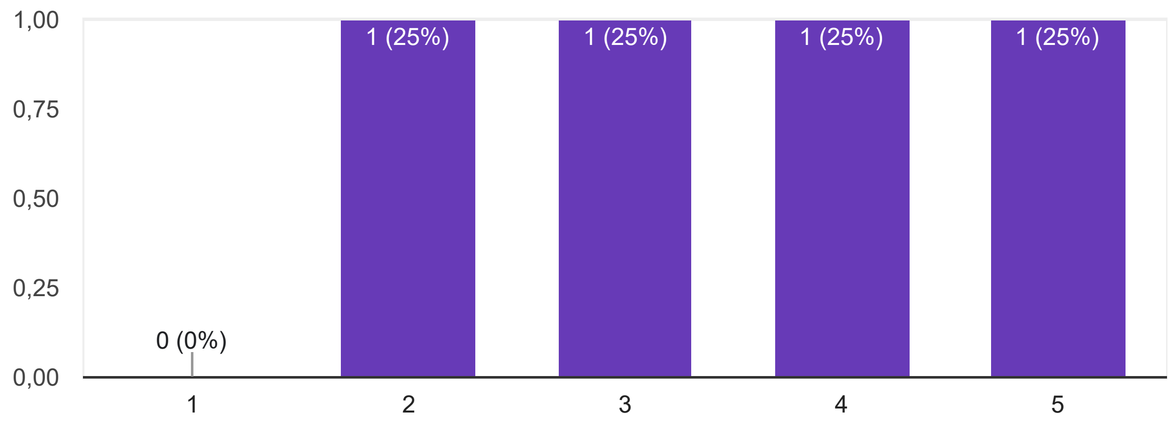
4 risposte



TAM-PU5 - Learning with the application saves me time when mastering manipulating the DICOM images.

Copia

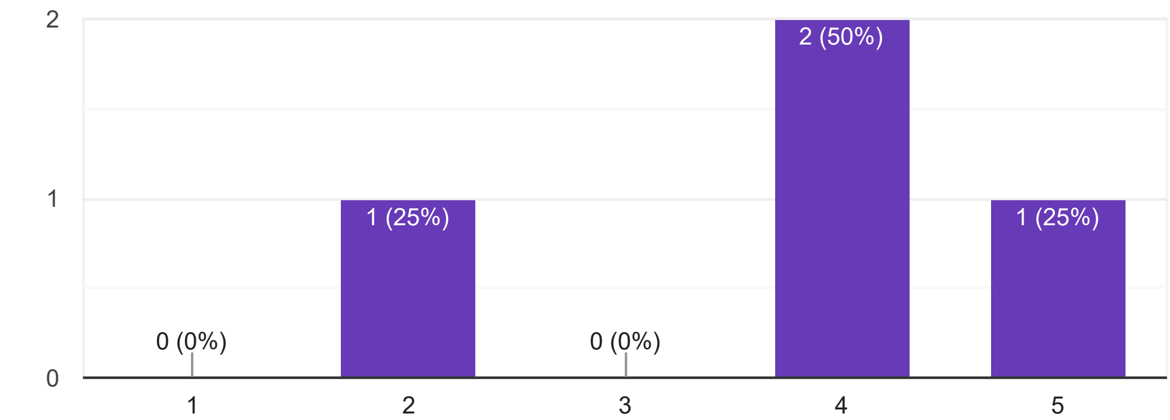
4 risposte



TAM-PU6 - The system/application allows me to manipulate DICOM images more efficiently.

Copia

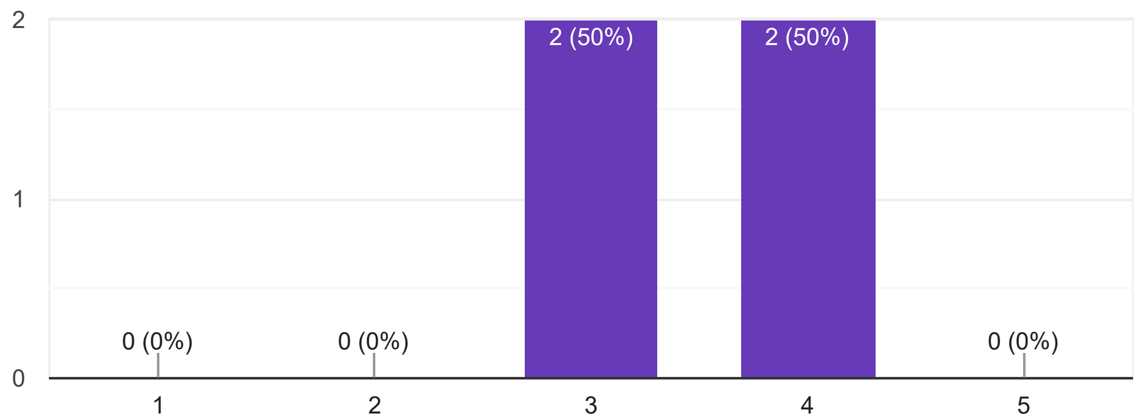
4 risposte



TAM-PU7 - The application supports critical aspects of the DICOM images manipulation process.

Copia

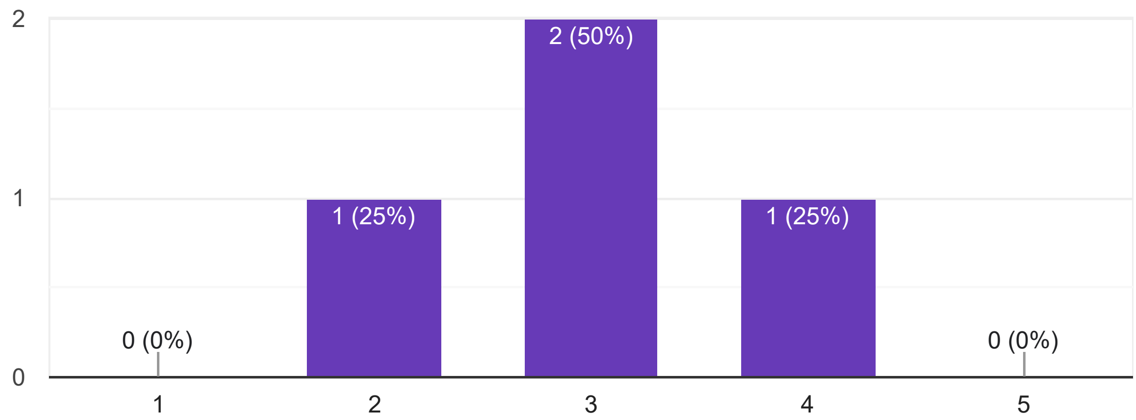
4 risposte



TAM-PU8 - Learning from the application enables me to achieve better results than traditional methods for mastering DICOM images manipulations.

Copia

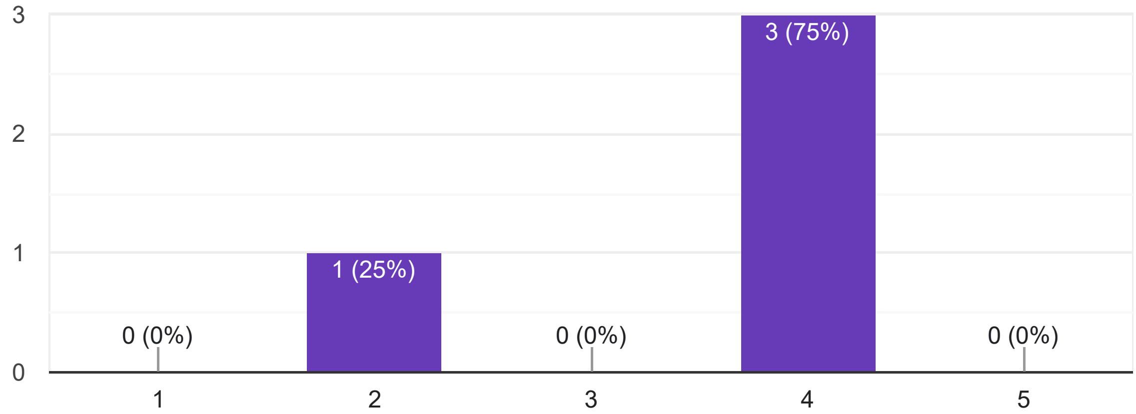
4 risposte



TAM-PU9 - Using the application reduces the time I spend on less effective software for DICOM manipulation images.

Copia

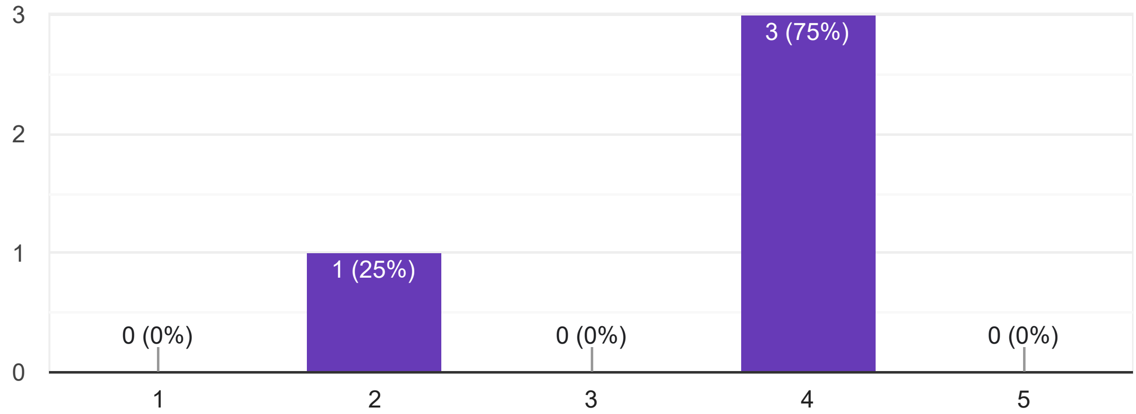
4 risposte



TAM-PU10 - Learning from the application enhances my proficiency in manipulating DICOM images.

Copia

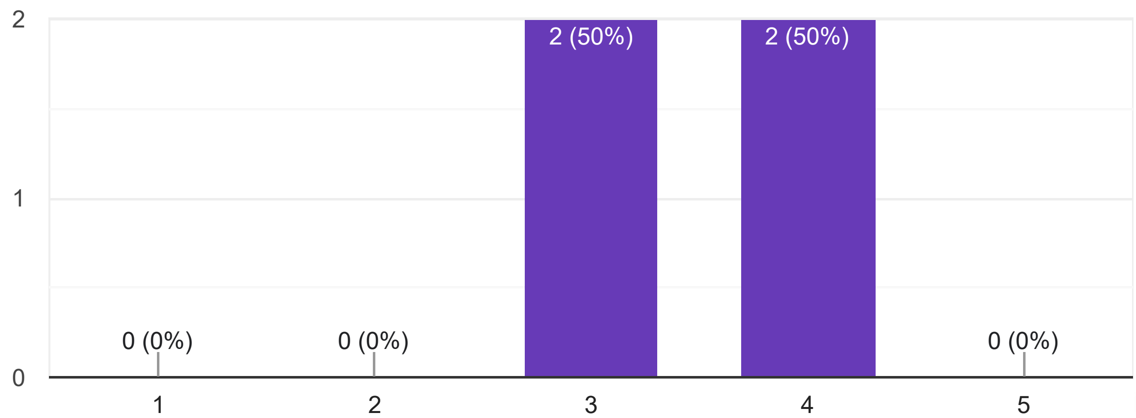
4 risposte



TAM-PU11 - Using the application improves the quality of my skills in DICOM images manipulation.

Copia

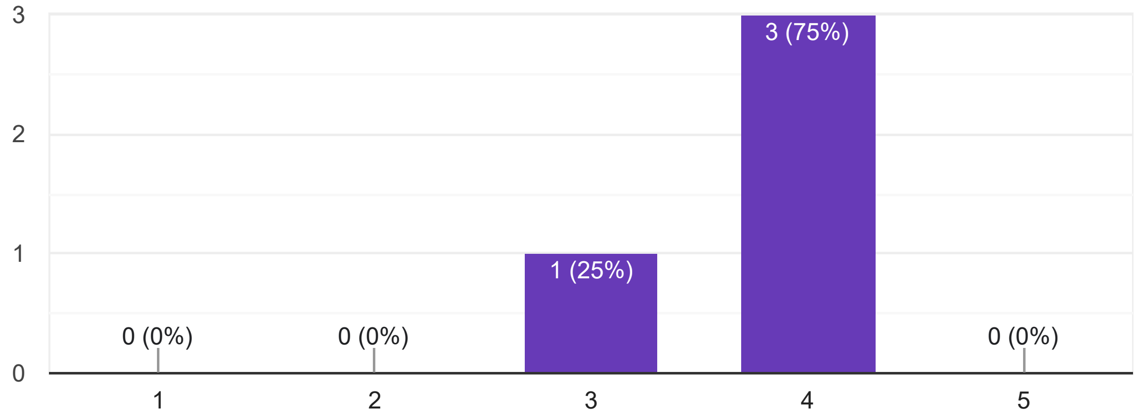
4 risposte



TAM-PU12 - Using the application increases my overall productivity in mastering manipulation of DICOM images.

Copia

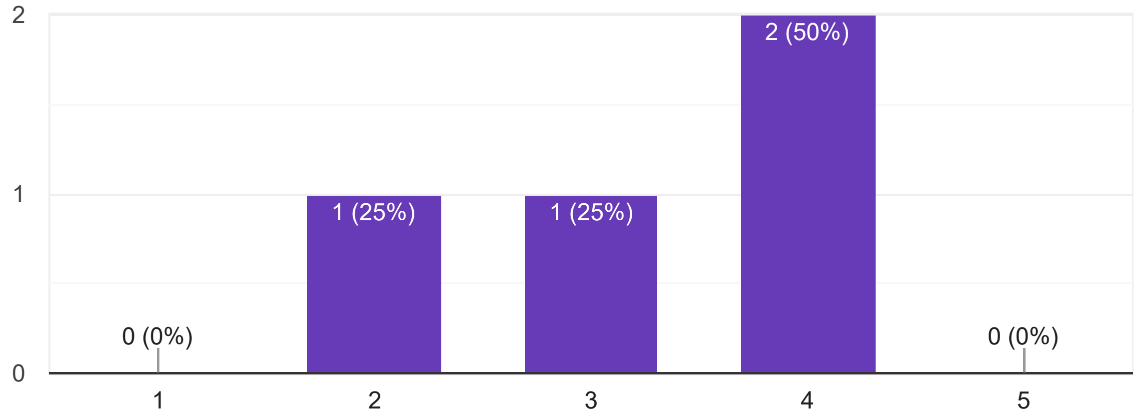
4 risposte



TAM-PU13 - Using the application simplifies the process manipulating DICOM images.

Copia

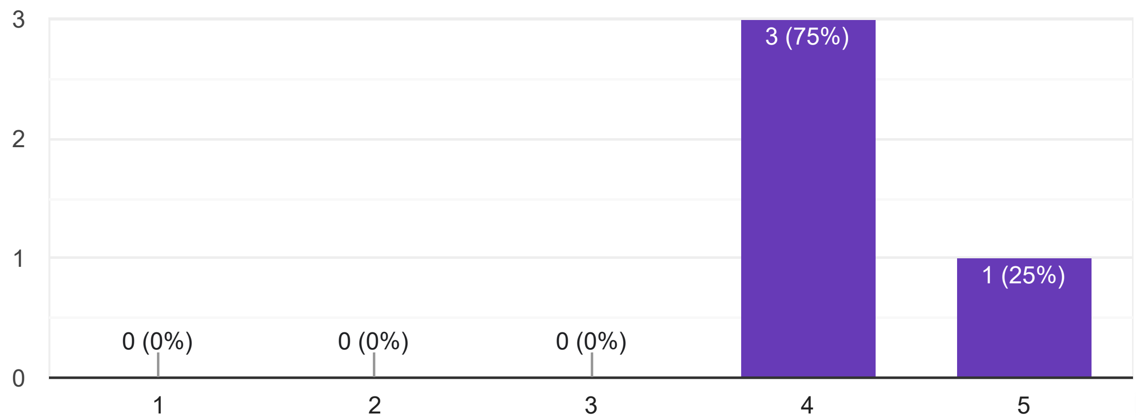
4 risposte



TAM-PU14 - Overall, I find the system/application valuable for manipulating DICOM images.

Copia

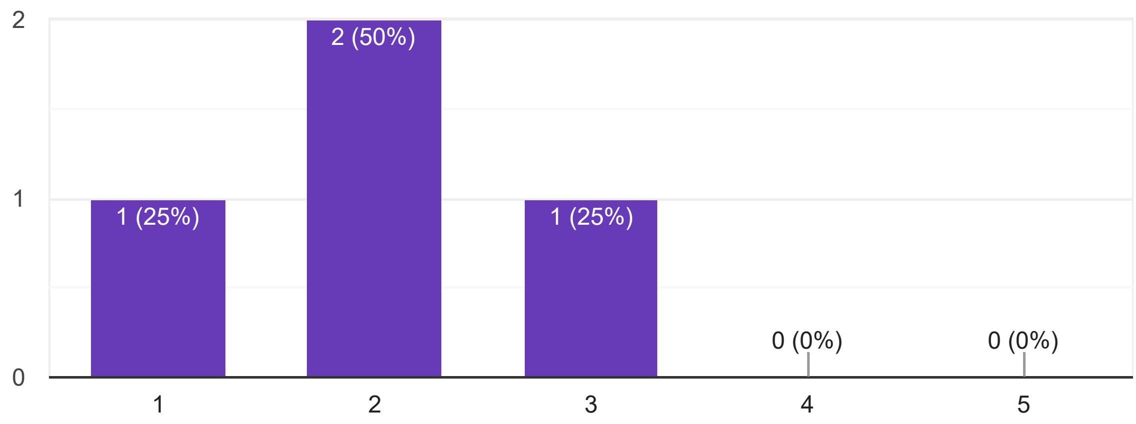
4 risposte



TAM-PE1 - I often find the interface of the application confusing when manipulating DICOM images.

Copia

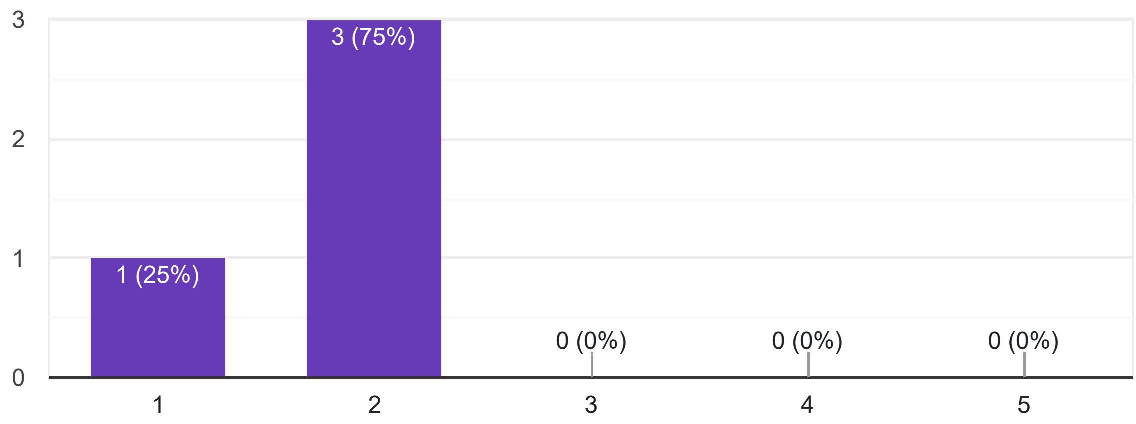
4 risposte



TAM-PE2 - I make mistakes frequently when using the application to manipulate DICOM images.

Copia

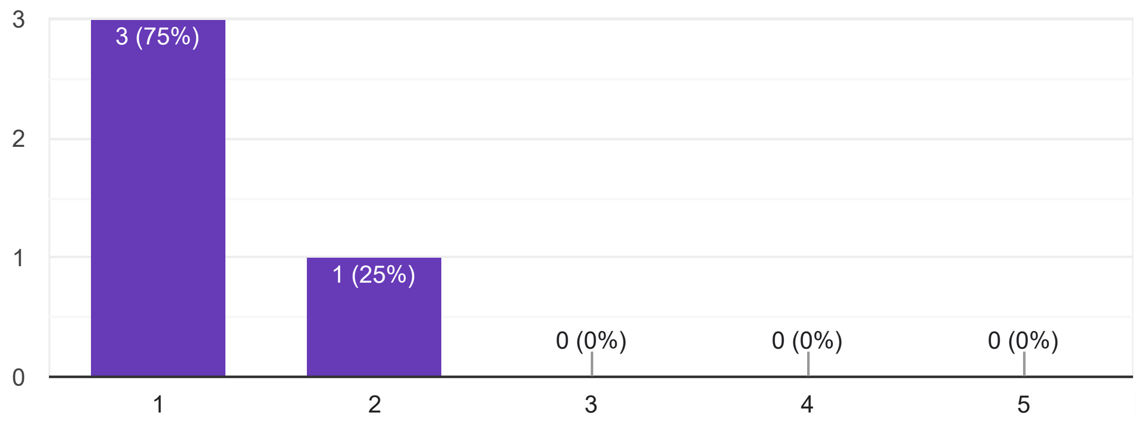
4 risposte



TAM-PE3 - Interacting with the application can be frustrating during my DICOM manipulation process.

Copia

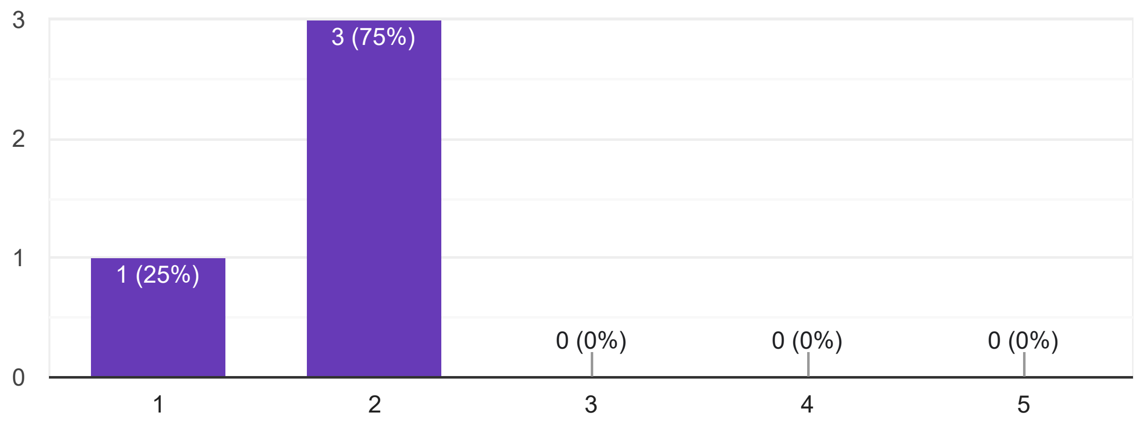
4 risposte



TAM-PE4 - I need to refer to the experimenters' guidance frequently when using the application to manipulate DICOM images.

Copia

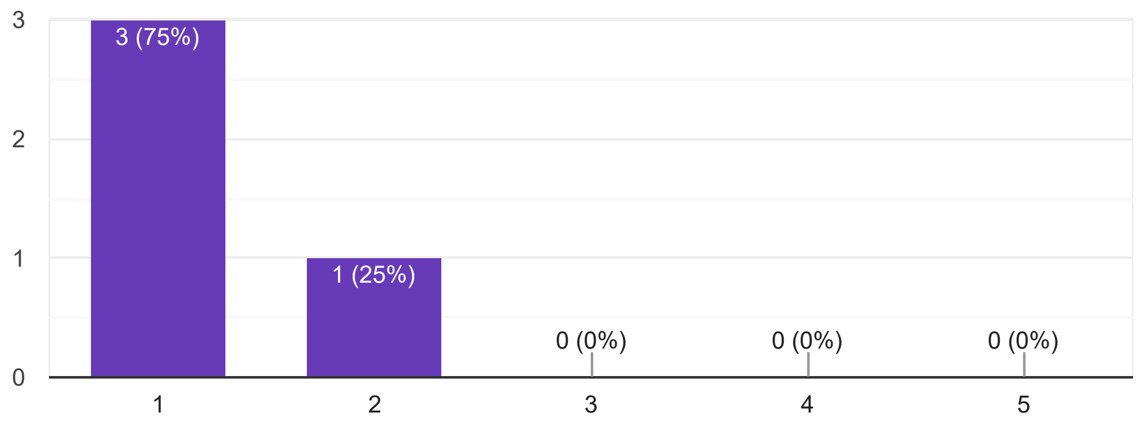
4 risposte



TAM-PE5 - Interacting with the application demands a significant amount of mental effort during DICOM images manipulation.

Copia

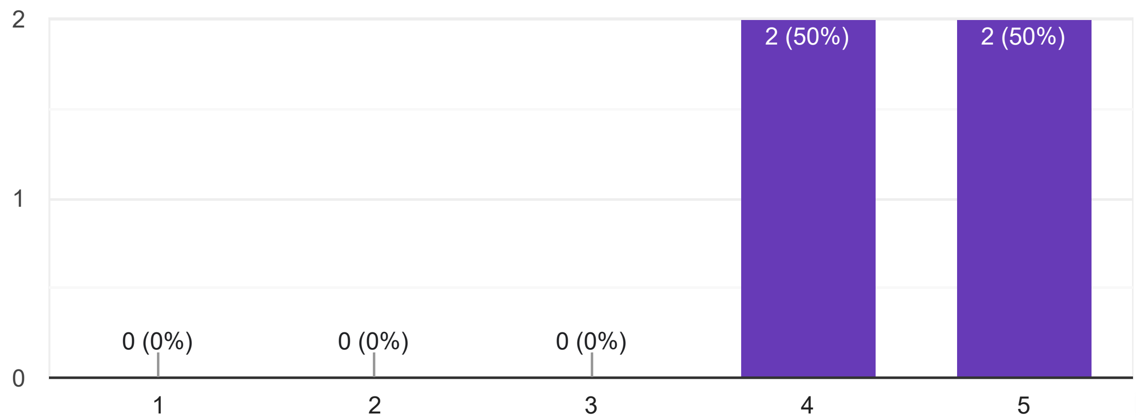
4 risposte



TAM-PE6 - I find it easy to recover from errors encountered while using the system/application for DICOM images manipulation.

Copia

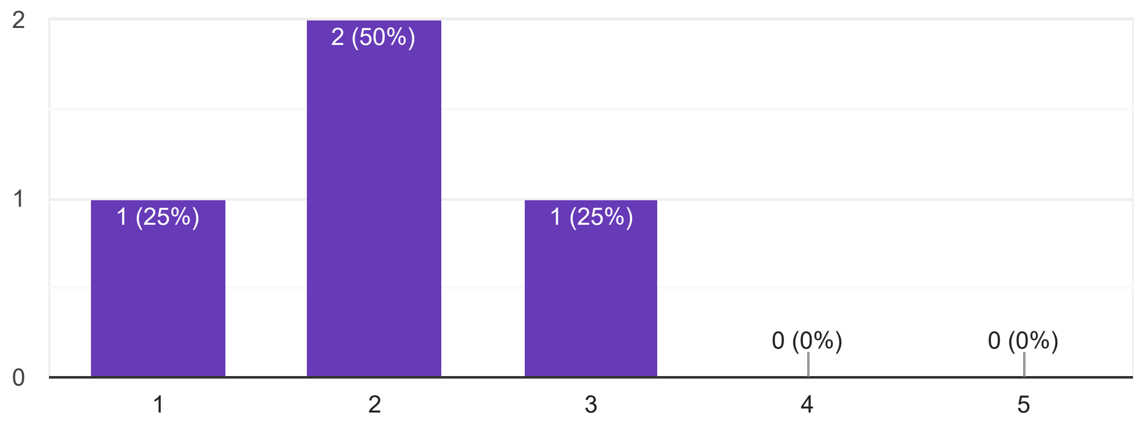
4 risposte



TAM-PE7 - The application's interface is rigid and inflexible when it comes to manipulate DICOM images.

Copia

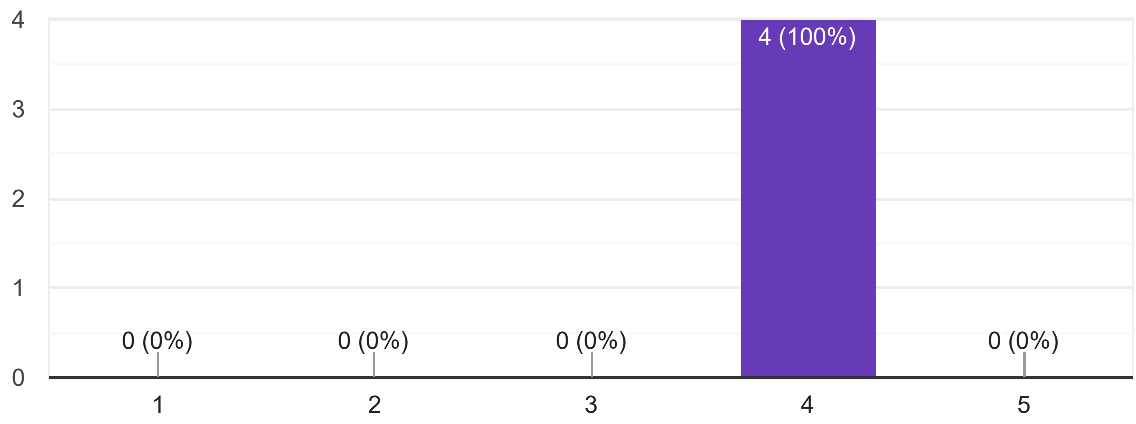
4 risposte



TAM-PE8 - I find it easy to achieve my DICOM images manipulation goals using the application.

Copia

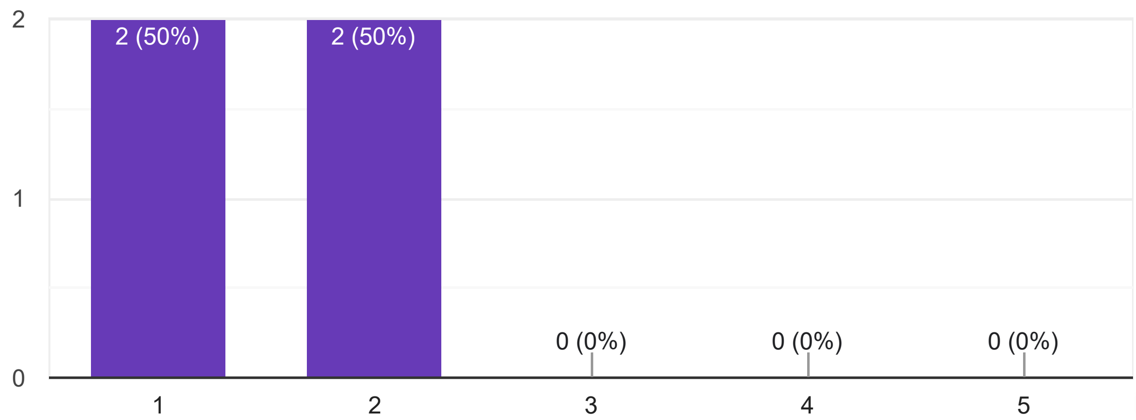
4 risposte



TAM-PE9 - The application sometimes behaves unpredictably during my DICOM images manipulation sessions.

Copia

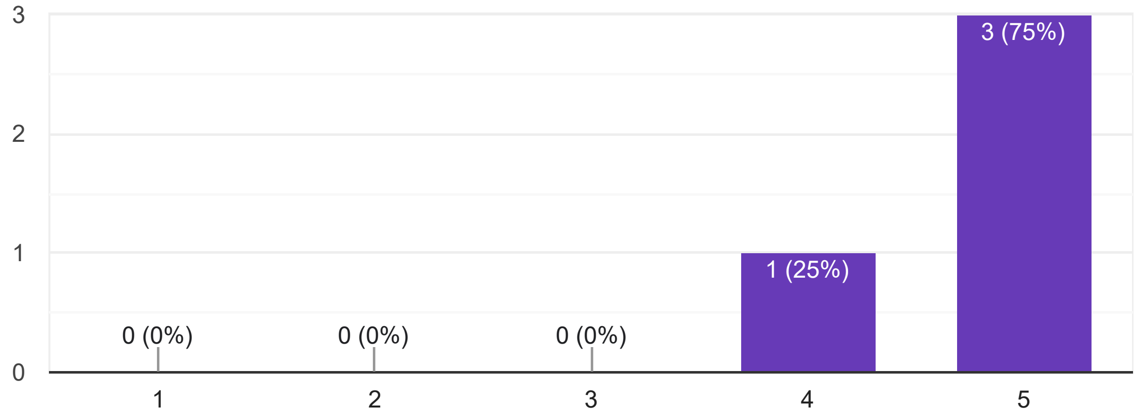
4 risposte



TAM-PE10 - I consider the application user-friendly for manipulating DICOM images.

Copia

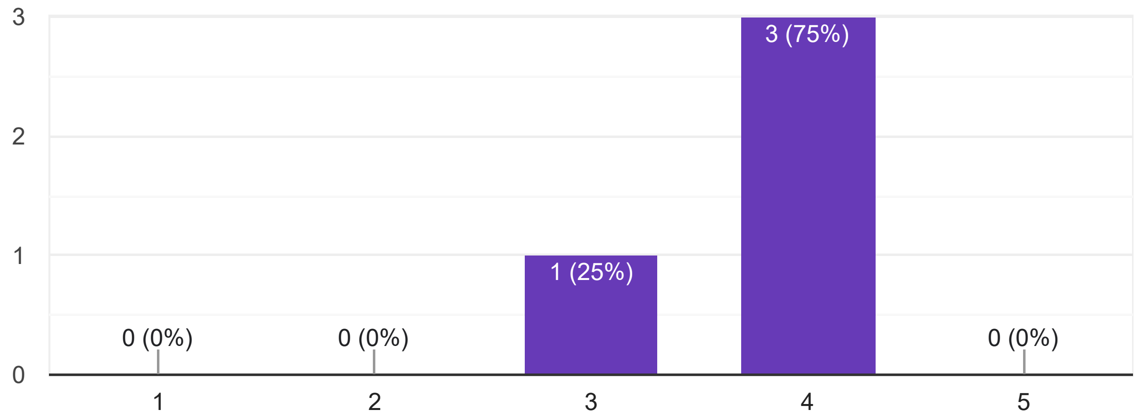
4 risposte



TAM-PE11 - My interaction with the application is straightforward to understand when manipulating DICOM images.

Copia

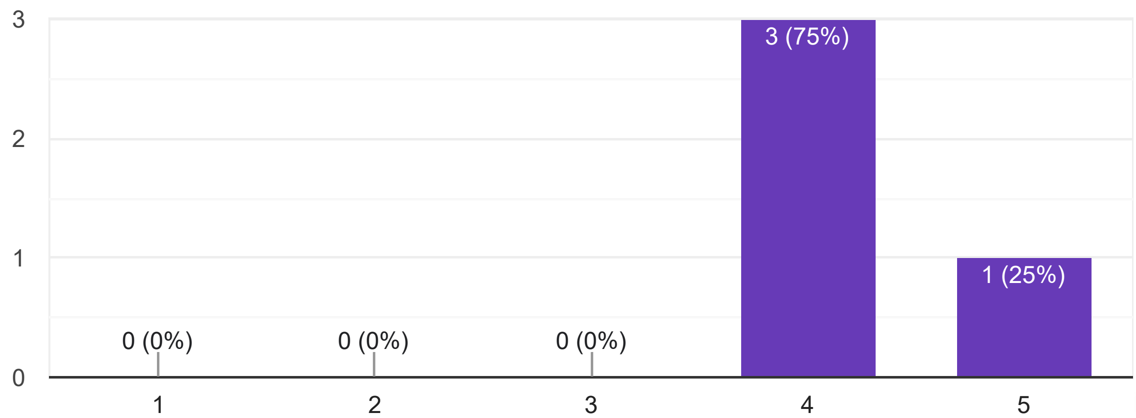
4 risposte



TAM-PE12 - It is easy for me to remember how to perform tasks using the application for manipulating DICOM images.

Copia

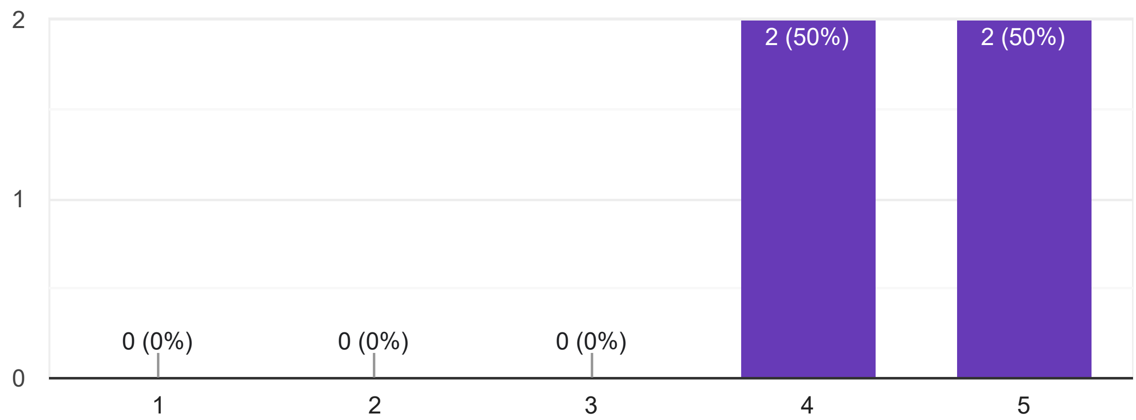
4 risposte



TAM-PE13 - The application provides helpful guidance while I'm manipulating DICOM images.

Copia

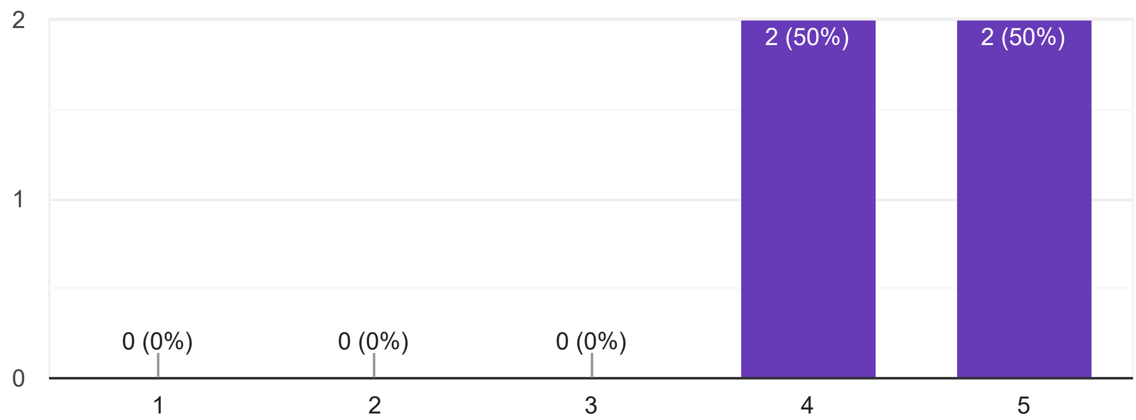
4 risposte



TAM-PE14 - Overall, I find the application easy to use for mastering manipulating DICOM images.

Copia

4 risposte



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PS: PISSSSSSCCCCCCCCCIIIIINNNNNNNAAAAAAAA!!!!!