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**INVESTIGATION OF THE POSSIBILITIES OF USING A LOW-COST THREE-DIMENSIONAL  
VISUALIZATION DEVICE TO SUPPORT RADIOLOGICAL DIAGNOSIS**

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**INVESTIGATION OF THE POSSIBILITIES OF USING A LOW-COST THREE-DIMENSIONAL VISUALIZATION DEVICE TO SUPPORT RADIOLOGICAL DIAGNOSIS**

This dissertation has been submitted in partial fulfillment of the requirements for the degree of Master of Computer Science, of the Computer Science Graduate Program, School of Technology of the Pontifical Catholic University of Rio Grande do Sul.

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*“The greatest glory in living lies not in  
never falling, but in rising every time  
we fall.” (Nelson Mandela)*

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# INVESTIGAÇÃO DAS POSSIBILIDADES DE USO DE DISPOSITIVO DE VISUALIZAÇÃO TRIDIMENSIONAL DE BAIXO CUSTO PARA APOIAR O DIAGNÓSTICO RADIOLÓGICO

## RESUMO

A radiologia é uma área da medicina focada em examinar corpos humanos em busca de anormalidades, sendo assim uma das áreas mais importantes quando profissionais da saúde querem diagnosticar patologias clínicas. Apesar da sua popularidade, especialistas desse campo ainda enfrentam problemas ao diagnosticar, como iluminação externa e má postura ao sentar-se. Esses problemas são em sua maioria causadas pelo uso de computadores tradicionais de mesa, e a realidade virtual surgiu como uma possível solução para isso. Com sua capacidade de bloquear estímulos visuais externos e imergir os usuários em ambientes virtuais criados e manipulados por computadores, tem sido estudada e provou trazer benefícios para a área. Neste trabalho foi desenvolvido um aplicativo de realidade virtual que roda apenas em dispositivos móveis e permite que profissionais da área de radiologia executem as duas tarefas mais comuns durante o processo de diagnóstico radiológico: *windowing* e *scrolling*. O objetivo deste estudo foi avaliar uma abordagem de visualização imersiva e estereoscópica de imagens médicas na tentativa de solucionar os problemas enfrentados pelos profissionais no momento do diagnóstico. Para isso, foi aplicado um total de 6 questionários diferentes com os testadores, sendo 3 *ad hoc* e 3 tradicionais na literatura. Os resultados sugerem que o aplicativo desenvolvido foi bem-sucedido porque os usuários avaliaram a ferramenta como "boa o suficiente". Além disso, as pesquisas indicaram que é necessário um baixo esforço para utilizar a aplicação desenvolvida. Sugestões de melhoria também foram mencionadas pelos candidatos. Alguns afirmaram que a qualidade da imagem utilizada é muito baixa para um diagnóstico real, portanto, recomenda-se melhorar a qualidade da imagem. Outros comentaram que o conjunto de controles é complexo e, portanto, é aconselhável torná-lo mais semelhante aos *softwares* comuns usados na área.

**Palavras-chave:** realidade virtual, radiologia, dispositivo móvel, *scrolling*, *windowing*

# INVESTIGATION OF THE POSSIBILITIES OF USING A LOW-COST THREE-DIMENSIONAL VISUALIZATION DEVICE TO SUPPORT RADIOLOGICAL DIAGNOSIS

## ABSTRACT

Radiology is a field from medicine in which human bodies are examined for abnormalities, and such area is one of the most important ones when professionals want to diagnose clinical pathologies. Despite that popularity, experts still need to face a variety of problems when diagnosing, such as external illumination and bad sitting posture. Virtual reality emerged as a candidate solution for that. With its ability to block external visual stimuli and immerse users in virtual environments created and manipulated by computers, it has been recently studied and proven to bring benefits to the field. Most studies, however, deploy their solution in traditional desktop computers exclusively, leaving some room for exploration for other platforms, such as smartphones. In this work we developed a virtual reality application that runs on smartphones only and allows professionals from the radiology field to execute the two most common tasks when diagnosing: windowing and scrolling. Our objective was to evaluate an immersive and stereoscopic visualization approach of medical images as an attempt to solve the issues faced by professionals when they are doing radiological diagnosis. To do so, we applied a total of 6 different surveys with our subjects, 3 being *ad hoc* and 3 being traditional in the literature. The results suggest that our application was successful because our testers evaluated our tool as "good enough". In addition to that, the surveys indicated that a low effort is required to use our app. Suggestions for improvement were also mentioned by the subjects. Some stated that the quality of the used image is too low for a real diagnosis, thus improving the image quality is recommended. Others commented that the set of controls are complex, and therefore making it more similar to commonly used software of the field is advised.

**Keywords:** virtual reality, radiology, smartphone, scrolling, windowing

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## 1. INTRODUCTION

Radiology is medical discipline in which human bodies are examined for abnormalities (den Boer et al., 2018), and such area is one of the most important ones when professionals want to diagnose clinical pathologies (Izard et al., 2018). Although radiology is widely used in many different medicine specialties, doctors still face some issues when performing the diagnosis process because special rooms are required for that, and many external factors can interfere with the diagnosis process and the result, such as external light and monitor saturation (Samei et al., 2005; Sousa et al., 2017).

A candidate technology to reduce these problems is the virtual reality (VR). VR has proved to bring many benefits for a variety of different areas (Tori & Hounsell, 2020) mainly due to its ability to block external visual stimulus and to create a safe and controlled virtual environment (VE). Within such spaces, users are free to explore the environment and perform actions with no risk of injuring any person. In fact, the use of VEs allows developers to create applications with multiple purposes, such as training and learning (Tori & Hounsell, 2020).

In the radiology field, VR has been used by doctors for multiple reasons. Making preoperative decisions (Xu et al., 2020), training through simulations (Park et al., 2014), learning with immersive 3D structures (Izard et al., 2018) and diagnosing (see Subsection 3.3.1) are among the possibilities of use. In addition to that, VR has also been used to treat MRI-related anxiety in patients (Liszio et al., 2020) and teaching them about their health or treatment (Han et al., 2019; Sutherland et al., 2018).

In this study we performed literature review in the radiology field and discovered that VR is mostly used in that area with traditional desktop computers, followed by Cave Automatic Virtual Environment (CAVE), Head-Mounted Display (HMD) and smartphones. Even though smartphones are widely available and have been becoming very powerful in the last 5 years (Steed & Julier, 2013), they are still a very little explored platform in the deployment of VR radiology solutions.

Therefore, we decided to delve into that area to fill a gap in the literature. To do so, we created an immersive VR application that runs in smartphones and allows professionals to perform the two most common operations in the field: scrolling and windowing (Wirth et al., 2018). After developing 4 versions of the app with the guidance of an expert from the area, we tested it out with two types of professionals in the radiology field: radiologists (RA) and

medical physicists (MP). Figure 1 depicts the final version of our application tested by professionals running on a smartphone.



Figure 1 – The final mobile version of our application<sup>1</sup>

Source: The authors

Finally, we applied a survey with our testers to collect data from them. **Our objective was to evaluate an immersive and stereoscopic visualization approach of medical images** as an attempt to solve the issues faced by professionals when they are doing radiological diagnosis.

Based on the results of our questionnaire, we could see that radiologists struggled more than medical physicists in all features. We also observed that our application was apparently not simple to use, even though both groups had years of experience with visualization software and video games. Despite all these facts, most testers still rated our tool as “good enough” and expressed excitement for the future versions of our application as they stated it can bring benefits to the radiology field.

Lastly, users also mentioned that our application can be improved by increasing the quality of the rendered 3D model and adjusting the input system to match other common visualization software of field. We believe that the outcomes of this study are a great start for future researchers to develop novel approaches.

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<sup>1</sup> <https://youtu.be/M0sCcJoNw24>



The rest of this document is organized as follows: this current Chapter 1, presented an introduction to our research. Chapter 2 introduces and characterizes the two main concepts of our study (virtual reality and radiology). Next, Chapter 3 presents the related work with the steps we took to perform a literature review in the area and the findings of it. Chapter 4 describes our proposed research for this work. Chapter 5 presents the development process in details of all the versions we created for our application, including the feedback received by the partnered expert. The user study with the details of the procedure, results and discussion are explored in Chapter 6. Lastly, Chapter 7 outlines the conclusion and final remarks for this work.

## 2. BACKGROUND

In this section we present the definition of virtual reality and the hardware needed to interact with a virtual environment. Furthermore, we define radiology and present the two main tasks performed in the area, these being windowing and scrolling.

### 2.1. Virtual reality

There are many definitions for virtual reality, some focusing more on technology, others in user's perception. Tori et al. (2006) defined VR as an advanced user interface to access applications running on computers, having real-time visualization and movement in three-dimensional environments and interaction with elements in it as features.

The authors (Tori et al., 2006) also mentioned that beyond the visualization itself, the user experience in VR can be enhanced by the stimulation of other senses, such as touch and hearing. Jerald (2015) defended that VR can be experienced in an interactive way as it was real although being defined as a digital environment computationally generated.

In both definitions, a software is required to create the immersive world, also known as virtual environment, and to develop the interactions in it. Moreover, a hardware is necessary to do the immersion and the interaction.

Regarding virtual environment, it is an artificial world created by computers that can give the observer a sense of "being there" (presence) in the environment. Various input devices are needed to interact with the VE or manipulate the world, such as cursor keys, joystick, or head tracker. The artificial space can be presented visually on a desktop display, a head-mounted display, or on one or more projection displays, sometimes combined with (spatialized) audio, haptic feedback, and sometimes even scents or thermal cues (Kort et al., 2003).

With the development of these types of media, the potential to provide viewers with an accurate representation of nonmediated experience has increased significantly (Kort et al., 2003). These mediated environments are thus able to provoke responses and behavior similar to those portrayed in real environments (Lombard, 1995).

There are any many other types of VEs for a great variety of purposes rather than entertaining, such as therapy, education, data visualization, etc. Some of them do not present a realistic environment because being close to reality may not be necessary to achieve the goal of the application.

Regarding the VR hardware, there is a great variety of input devices that helps users to communicate with the VR system. Some examples of such devices are trackers, electronic gloves, 3D mouse devices, keyboard, joystick, voice recognizers, etc. (Tori et al., 2006). The screens are treated as output sensorial elements involving more than the vision, such as audio and haptic displays.

Thanks to the advance of the gaming and entertainment industry (e.g.: movie theaters, amusement parks, videogames, etc.), the technology to interact with VR became more common and accessible to the public. Google Cardboard (Google, n.d.b), Sony VR (Sony, n.d.b), HTC Vive (HTC Corporation, n.d.) and Oculus Rift (Meta, n.d.) are among the most famous hardware in the area, some being simpler and others being more advanced. All of them depend on a processor unit, such as computers, smartphones, etc., to generate the images, and only Google Cardboard relies exclusively on a smartphone as a screen because it does not have its own display. Figure 2 presents these VR devices.



Figure 2 – VR devices. (a) Google Cardboard, (b) Sony VR, (c) HTC Vive and (d) Oculus Rift

Source: The authors

Recent advances in mobile graphics have given modern smartphones capabilities which surpass the desktop systems of just a few years ago (Steed & Julier, 2013). In 2014, Google introduced the concept of “Cardboard VR” - VR headsets costing just a few dollars and working with most modern mobile phones (Google, n.d.b). Whilst they are not intended to compete in the market with offerings such as Oculus Rift or HTC Vive, the ultra-low cost

makes them attractive to those who may not otherwise consider entering the VR market (Powell et al., 2016).

## **2.2. Radiology**

Radiology is a medical discipline in which images visualizing human bodies are examined for abnormalities (den Boer et al., 2018) and radiological studies are undoubtedly one of the most important resources when diagnosing different clinical pathologies, and it is used in different medical specialties (Izard et al., 2018).

It is remarkable that medical images which are inherently 3D in nature are mostly visualized in clinical practice by physicians and radiology technicians (Locuson et al., 2015) in reading rooms (Wirth et al., 2018), using multiple 2D displays among 1D or 2D input media (Card et al., 1990). Therefore, clinicians have to deal with the presence of external factors, such as external lights and screen color saturation when diagnosing, which might interfere with the process and the results (Samei et al., 2005; Sousa et al., 2017). Besides, the interpretation of these images is considered a highly complex task since medical images are not self-explanatory (Drew et al., 2013; van der Gijp et al., 2014).

When reading 3D images, radiologists need to view and scroll through a substantial number of image slices (a slice is a single 2D image of a cross section of the human body (den Boer et al., 2018)) and manipulate that image in such a manner that abnormalities become visible (den Boer et al., 2018). The two main volumetric imaging techniques performed to do so are called windowing and scrolling (Wirth et al., 2018).

Windowing is one of the most popular image postprocessing operations used by both technologists and radiologists alike to change the contrast and brightness of an image (Seeram, 2016) to highlight irregularities (den Boer et al., 2018). Figure 3 presents the results of a windowing process.

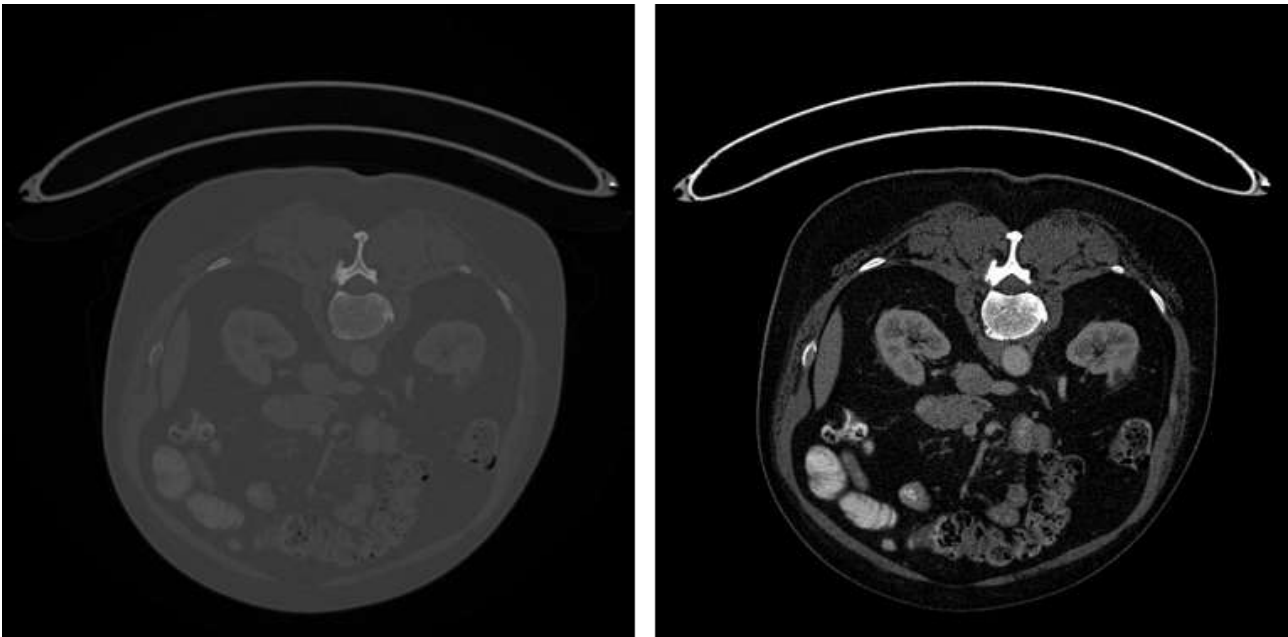


Figure 3 – A mammographic image before (left) and after (right) a windowing process

Source: adapted from Roth et al. (2016)

On the other hand, scrolling is the act of browsing through image slices in a volumetric image (den Boer et al., 2018), usually done by using the wheel on a computer mouse (Taoka et al., 2009), requiring large amounts of wheel manipulations to observe large numbers of images on a daily basis (Taoka et al., 2009). Figure 4 shows an example of scrolling on a 3D image, presenting three different image slices from the abdomen of a human patient, in the axial<sup>2</sup> viewing direction.

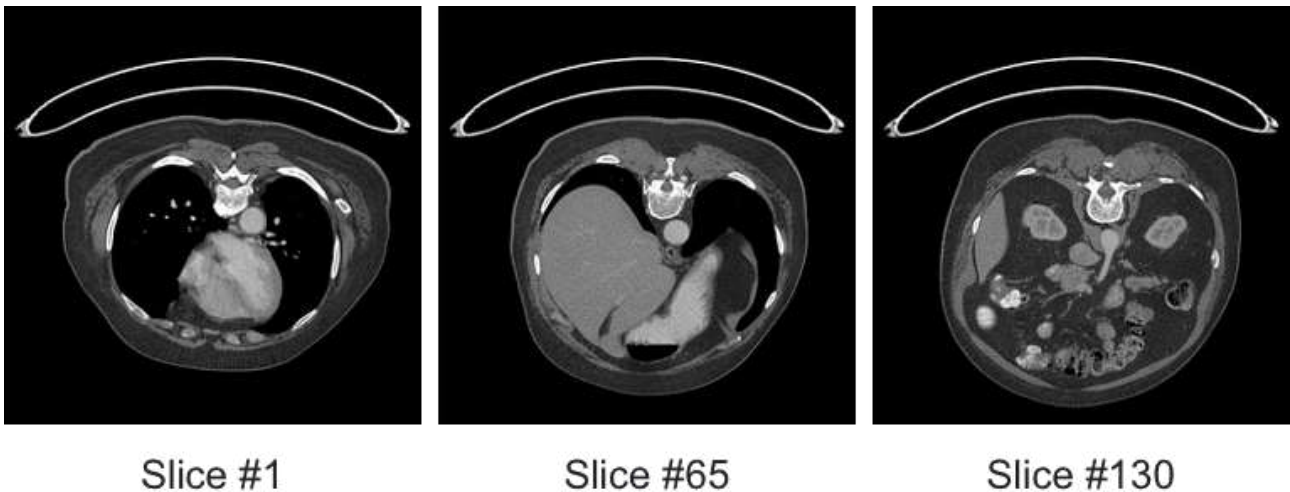


Figure 4 – Image display of abdominals in axial viewing direction

Source: adapted from Roth et al. (2016)

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<sup>2</sup> The axial viewing direction is the view taken from the head to the foot of the patient.

### 3. RELATED WORK

McCarthy and Uppot (2019) defend that the past years has shown a tremendous increase in the availability and use of virtual reality and augmented reality hardware. The researchers (McCarthy & Uppot, 2019) also state these devices typically take the form of headsets that can be used to either block out external visual stimuli (VR) or overlay graphics in a real-world environment (AR). The use of VR technology brings many benefits to distinct areas. In the educational field, for example, people can access virtual laboratories and libraries and attend meetings to have some group activity (Tori & Hounsell, 2020).

Regarding the medical field, there are also advantages for utilizing VR environments. For instance, 3D correlation of imaging data from multiple platforms such as computed tomography (CT), magnetic resonance imaging (MRI), positron emission tomography (PET), etc. can be used to display redundant and complementary information, thus providing confidence and accuracy in diagnoses (Locuson et al., 2015).

Another important potential use for this technology in the medical area is to assist with learning new skills. Health-care workers have embraced VR by using it in a variety of areas, including surgical training (Seymour et al., 2002), preoperative planning (Juhnke et al., 2018), and intraoperative navigation assistance (van Oosterom et al., 2018). Besides, VR platforms for various surgical procedures have been available for many years now (Pelargos et al., 2017; Thomsen et al., 2017) and have shown to improve technical performance of surgical procedures (Nagendran et al., 2013). Moreover, VR and AR have the potential to offer patients a novel way to explore their medical condition. For example, one group of researchers has developed a tool that allows pediatric patients to view a personalized VR tour of their own endoscopy (HealthVoyager, n.d.). Incorporating such technology into patient education offers the potential to increase patient engagement and overall satisfaction with their medical care (McCarthy & Uppot, 2019).

In regard to medical data visualization, radiologists usually use workstations to see the medical data using three-dimensional visualization (Izard et al., 2018) in traditional 2D desktop displays (Sousa et al., 2017) (see Figure 5). Hence, inadequate ergonomic postures and, more importantly, improper room conditions can cause erroneous diagnostics when professionals examine such digital images using common displays (Samei et al., 2005). In fact, varying illumination, ambient light, and display luminance are known to distort the images, which are characteristically laden with complex and hard-to-read fine details (Sousa et al., 2017).



*Figure 5 – Radiology workstation*

Source: Wikimedia Commons (Belli, 2006)

Although the use of VR technology has shown to bring many benefits to the medical area, some barriers still need to be overcome to make it widely adopted. First, the price to acquire the VR technology is still high (McCarthy & Uppot, 2019) and it also needs powerful computers to run the programs (Belmustakov et al., 2018). Besides, novel systems and technologies are not easily accepted by clinicians (Sousa et al., 2017) and the use of VR might bring sensations of discomfort including nausea, headache, and dizziness (Elsayed et al., 2020).

Based on this scenario, the objective of this review is to determine and characterize the state-of-the-art on VR in radiology. To do so, we performed a systematic mapping study (Kitchenham et al., 2011; Kitchenham & Charters, 2007; Petersen et al., 2008) aimed at:

- discovering the uses, benefits and main barriers of VR in radiology;
- identifying gaps for future studies.

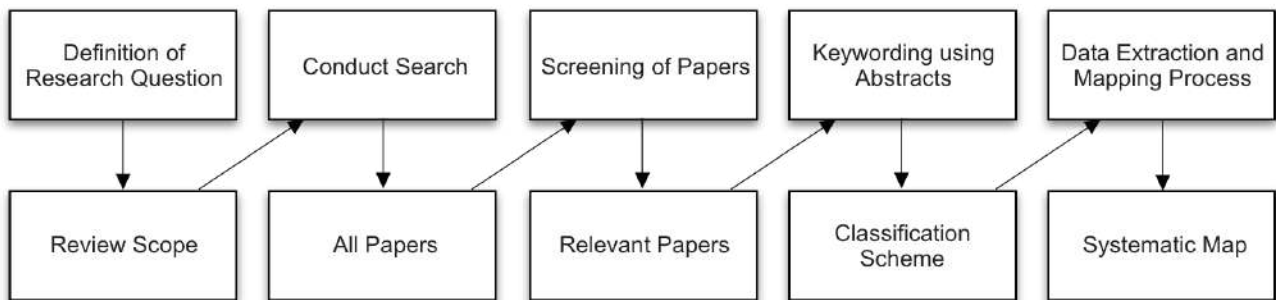
From an initial set of 329 papers, we have identified 24 primary studies worth analyzing from 6 individual scientific databases.

In addition to that, we also decided to look for commercial products in the field in order to analyze results from outside of the academic area. The intention was to bring a complementary discussion to the state-of-the-art found by the study. As a result, we came across 12 significant applications to the field.

### 3.1. Methodology

The goal of this study is to determine and characterize the state-of-the-art on VR in radiology. To do so, we conducted this systematic mapping following the recommendation from influential researchers in the software engineering area (Kitchenham et al., 2011; Kitchenham & Charters, 2007; Petersen et al., 2008). Figure 6 presents the steps we took to perform the systematic mapping study and the following subsections detail the planning of each step of this study.

#### Process Steps



#### Outcomes

Figure 6 – Systematic map process

Source: Petersen et al. (2008)

#### 3.1.1 Research questions

In order to determine and characterize the state-of-the-art on VR in radiology, the following research questions were defined:

- RQ1: How is virtual reality used in radiology?
- RQ2: What are the benefits of using virtual reality in radiology?
- RQ3: What are the challenges of using virtual reality in radiology?

The purpose of RQ1 is to discover the ways VR has been used in radiology and its main techniques and applications. From the following questions (RQ2 and RQ3) we intend to analyze the benefits and the challenges of using VR in radiology in order to find out the reasons it is applied to radiology and the difficulties it may carry along.

#### 3.1.2 Data source and search strategy

After defining the research questions, we built up a general string based on Kitchenham and Charters (2007) guidelines to identify primary studies on electronic databases to answer the research questions. The general string used in this study was: “(virtual reality OR vr) AND (radiology)”.



Regarding the selection of databases, we chose the ones proposed by Kitchenham and Charters (2007). However, we replaced Inspec and EI Compendex for Engineering Village because the content from both databases is contained inside Engineering Village (Elsevier, n.d.a). We then added 3 more databases: ScienceDirect, which provides access to a large bibliographic database of scientific and medical publications (Elsevier, n.d.c), PubMed, a free resource supporting the search and retrieval of biomedical and life sciences literature with more than 30 million citations and abstracts of biomedical literature (PubMed, n.d.) and Scopus, the largest abstract and citation database of peer-reviewed literature (Elsevier, n.d.b). Finally, we removed Citeseer Library and Springer due to difficulties in using their search engines as the former did not allow us to search using separated words (e.g.: virtual reality) and the latter returned papers that do not match with our general search string.

About publication period, we decided to select papers from January 2014 to July 2021 in order to get the most recent works in the research area. We also only included papers that were accepted in journals, conferences, workshops, and symposia and were written in English. In addition to that, we excluded duplicated papers, literature only available in the form of abstracts or presentations and publication not related to the field of study. Table 1 summarizes the search strategy we used.

*Table 1 – Search strategy*

<b>Databases Searched</b>	IEEEExplore ACM Digital Library Engineering Village ScienceDirect Scopus PubMed
<b>Inclusion Criteria</b>	Available Online Written in English From January 2014 to July 2021 In: Journals / Conferences / Workshops / Symposia
<b>Exclusion Criteria</b>	Duplicated Papers Literature only available in the form of ab- stracts or presentations Publication not related to the content of vir- tual reality in radiology
<b>Search applied to</b>	Title Abstract Keywords

To start the process of finding primary studies, we performed an initial research on the selected databases using the general string and the inclusion criteria, which yielded 329 studies. Table 2 summarizes the number of papers returned from each database.

*Table 2 – Returned papers*

<b>Database</b>	<b># Papers</b>
IEEEExplore ( <a href="https://ieeexplore.ieee.org/">https://ieeexplore.ieee.org/</a> )	24
ACM Digital Library ( <a href="https://dl.acm.org/">https://dl.acm.org/</a> )	3
Engineering Village ( <a href="https://www.engineeringvillage.com/">https://www.engineeringvillage.com/</a> )	50
ScienceDirect ( <a href="https://www.sciencedirect.com/">https://www.sciencedirect.com/</a> )	41
Scopus ( <a href="https://www.scopus.com/">https://www.scopus.com/</a> )	168
PubMed ( <a href="https://pubmed.ncbi.nlm.nih.gov/">https://pubmed.ncbi.nlm.nih.gov/</a> )	43
<b>Total</b>	<b>329</b>

### 3.1.3 Screening of papers

After retrieving the papers from the databases, we organized them in a spreadsheet for the screening process. Table 3 shows the information collected from the 329 primary studies. We started the process by removing duplicated work, which excluded 71 items, leaving the spreadsheet with 258. Next, we applied the exclusion criteria defined in Section 3.1.2, eliminating 33 items from the spreadsheet, leaving it with 225. Lastly, we read the title, abstracts, and keywords of the remaining studies to see if they were relevant to answer the research question of this study. From 225 papers, we eliminated 153 items, leaving the spreadsheet with 72 studies to be fully analyzed.

*Table 3 – Spreadsheet information*

<b>Information</b>	<b>Description</b>
Databases	IEEEExplore, ACM DL, Engineering Village, ScienceDirect, Scopus, PubMed
Title	Paper title
Year	Publication year
Authors	List of authors
Type of forum	Journal, conference, workshop, symposium
Abstract	Paper abstract
Keywords	Paper keywords
Status 1	Duplicate
Status 2	Does not fit into criteria (see Subsection 3.1.2)
Status 3	Is relevant

### 3.1.4 Keywording, data extraction and mapping

As stated by Petersen et al. (2008), keywording is a way to reduce the time needed in developing the classification scheme and ensuring that the scheme takes the existing studies into account. It starts with reviewers reading abstracts and looking for keywords and concepts that reflect the contribution of the papers (Petersen et al., 2008). If meaningful keywords cannot be extracted from abstracts, reviewers can choose to look for them in the introduction and conclusion sections of the papers. The objective is to create a set of categories in which papers can be combined. Figure 7 depicts this process.

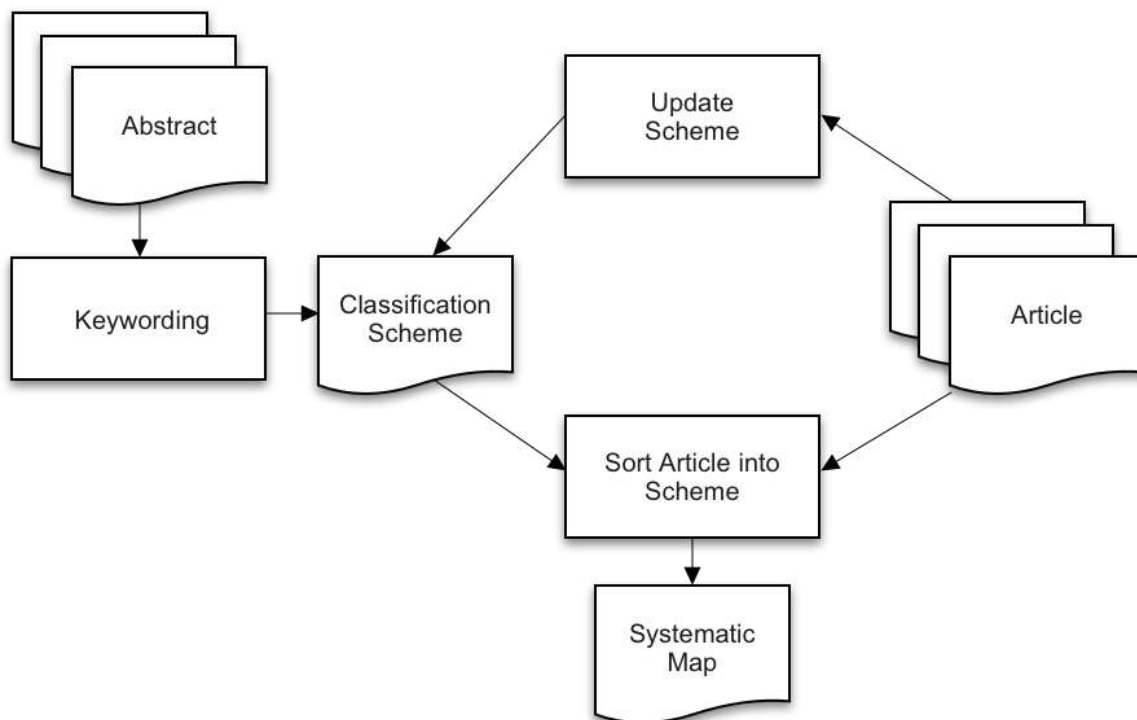


Figure 7 – Classification scheme workflow

Source: Petersen et al. (2008)

In order to sort the selected studies into the classification scheme, it was necessary to go over them. After reading the papers thoroughly, we noticed most of them, even though they contained the keyword “virtual reality” or “vr” in their abstracts, they neither treated it as an immersive environment, nor used it in radiology, nor had it as the main discussed topic, nor talked about HMD. Therefore, we removed a total of 48 studies from the selected papers, leaving our spreadsheet with 24 items.

In our study, three main categories were created to classify the studies, these being: contribution category, research type category and computer target category. Table 4 summarizes them. The contribution category describes the main contribution of the work to the area, and it was created from the keywords used on the keywording process. Furthermore, the research type category reflects the research approach used in the papers.

We chose an existing classification of research approaches by Wieringa et al. (2006) and added a new research type called "Overview Paper" to fit the papers that were only reviewing the available content of VR in radiology. Besides, the computer target category details the source of computational power in which the developed solutions aim to be deployed. To help in the organization of this study, we created three new columns in the spreadsheet to fit each category.

*Table 4 – Classification scheme*

<b>Category</b>	<b>Description</b>
<b>Contribution</b>	
Diagnostic Imaging	Describes the process of using VE for diagnostic imaging in radiology.
Medical Education	Explores the uses of VR in medical education such as surgical training.
Patient Care	Presents the uses of VR in patient treatments.
Interaction Technique	Details the interaction techniques in VE.
Tool	Software tools to help professionals employ VR in radiology.
<b>Research Type</b>	
Validation Research	Techniques investigated are novel and have not yet been implemented in practice. Techniques used are for example experiments, i.e., work done in the lab.
Evaluation Research	Techniques are implemented in practice and an evaluation of the technique is conducted. That means, it is shown how the technique is implemented in practice (solution implementation) and what are the consequences of the implementation in terms of benefits and drawbacks (implementation evaluation). This also includes identifying problems in the industry.
Solution Proposal	A solution for a problem is proposed. The solution can be either novel or a significant extension of an existing technique. The potential benefits and the applicability of the solution are shown by a small example or a good line of argumentation.
Philosophical Paper	A new way of looking at existing things by structuring the field in the form of a taxonomy or conceptual framework is sketched.
Opinion Paper	An opinion of somebody whether a certain technique is good or not, or how things should be done, is showed. The opinion does not rely on related work and research methodologies.
Experience Paper	An explanation on what and how something has been done in practice is presented. It must be the personal experience of the author.
Overview Paper	A summarization of the available content of a topic is depicted.
<b>Computer Target</b>	
Desktop	Traditional desktop computers.
Smartphone	Mobile devices.
HMD	Standalone head-mounted displays which do not rely upon a computer to provide real-time rendering.
CAVE	CAVE Automatic Virtual Environment is an immersive virtual reality environment made up of three rear-projection screens for walls and a down-projection screen for the floor (Cruz-Neira et al., 1993).

### 3.2. Results

The search process was carried out by following the process described in Figure 6. From an initial set of 329 papers identified through the search strategy, we have come across 72 primary studies, which were reduced to 24 after the data extraction process (see Subsection 3.1.4). The systematic map result is presented in Table 5.

Table 5 – Systematic map result

Author	Year	Research Type	Forum Type	Contribution	Computer Target
Venson et al.	2016	Evaluation Research	Conference	Diagnostic Imaging	Desktop/Smartphone
Sousa et al.	2017	Evaluation Research	Conference	Interaction Technique	Desktop
Klonig & Herrlich	2020	Evaluation Research	Conference	Diagnostic Imaging / Medical Education	N/A
Wirth et al.	2018	Evaluation Research	Symposium	Interaction Technique	Desktop
Liszio et al.	2020	Evaluation Research	Symposium	Patient Care	N/A
Venson et al.	2017	Evaluation Research	Journal	Diagnostic Imaging	Desktop/Smartphone
Nguyen et al.	2018	Evaluation Research	Journal	Diagnostic Imaging	Desktop
Han et al.	2019	Evaluation Research	Journal	Patient Care	HMD
Sapkaroski et al.	2019	Evaluation Research	Journal	Medical Education	Desktop
Sun et al.	2020	Evaluation Research	Journal	Patient Care	N/A
Locuson et al.	2015	Solution Proposal	Conference	Diagnostic Imaging	CAVE
Izard et al.	2018	Solution Proposal	Conference	Diagnostic Imaging	Desktop
Prange et al.	2018	Solution Proposal	Conference	Diagnostic Imaging	Desktop
Xu et al.	2020	Solution Proposal	Conference	Medical Education	Desktop
Knodel et al.	2018	Solution Proposal	Journal	Tool	CAVE
Alsofy et al.	2020	Solution Proposal	Journal	Diagnostic Imaging	N/A
Laas et al.	2021	Solution Proposal	Journal	Medical Education	N/A
Marescaux & Diana	2015	Overview Paper	Journal	Medical Education	Desktop
Belmustakov et al.	2018	Overview Paper	Journal	Medical Education	Desktop
Sutherland et al.	2018	Overview Paper	Journal	Diagnostic Imaging / Medical Education / Patient Care	Desktop/Smartphone
McCarthy & Uppot	2019	Overview Paper	Journal	Medical Education	Desktop/Smartphone
Elsayed et al.	2020	Overview Paper	Journal	Diagnostic Imaging / Medical Education / Patient Care	N/A
Ammanuel et al.	2019	Experience Paper	Journal	Tool	N/A
Abdelrazek et al.	2018	Opinion Paper	Journal	Diagnostic Imaging / Medical Education	N/A

Figure 8 presents the distribution of the primary studies according to the year they were published. We can see that the majority of the studies are recent. This could be a consequence of the popularization of VR equipment such as Oculus Rift, Gear VR and Google Cardboard. In 2018, it was estimated that some 12.4 million headsets were shipped worldwide, with this number forecast to increase to 68.9 million in 2022 (AR/VR headset hardware) (Locuson et al., 2015).

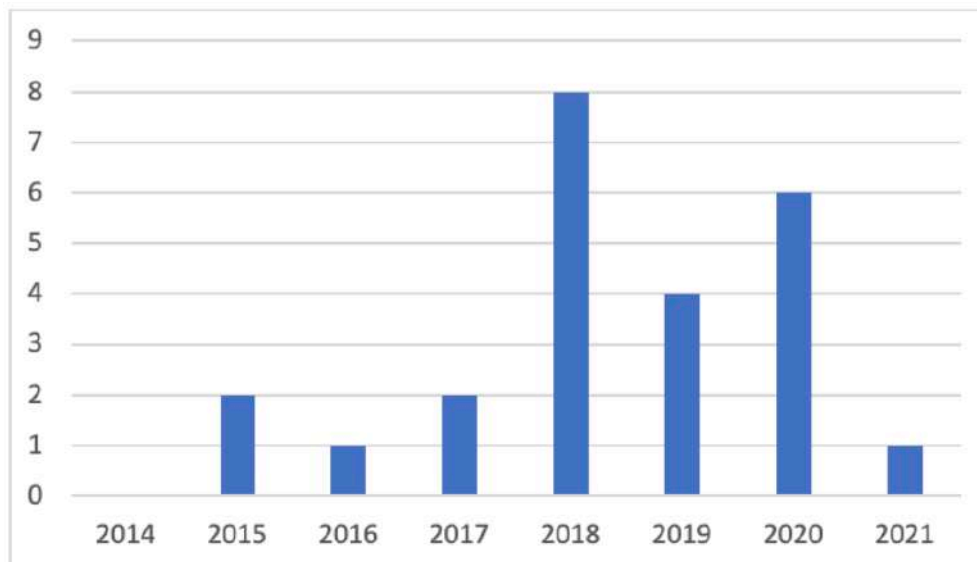
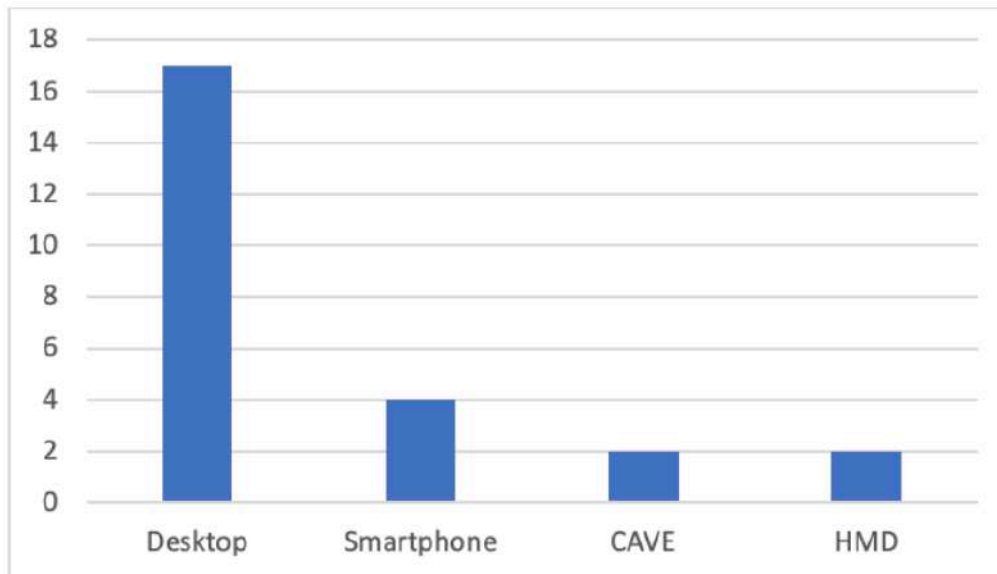


Figure 8 – Distribution of primary studies by year

Source: The authors

In Figure 9 we have the distribution of the studies according to their computer target category. It is clear that most papers aim traditional computers (desktop) as their main

research deployment target, leaving smartphone, CAVE and standalone HMD as possible gaps in the area for further solution development.



*Figure 9 – Distribution of primary studies by computer target*

Source: The authors

Figure 10 presents a bubble plot that combines the publication year with the research type and the contribution. Regarding the contribution, it is possible to see that the ones with the highest number of studies throughout the years are diagnostic imaging (DI), medical education (ME) and patient care (PC), with 2018 being the year with the greatest number of papers about DI. Besides, by combining these three major contributions with Table 5, we can see that DI is mainly published in both conferences and journals while ME and PC are mostly issued in journals. In addition to that, there seems to be a gap on interaction techniques and tools when it comes to the contribution.

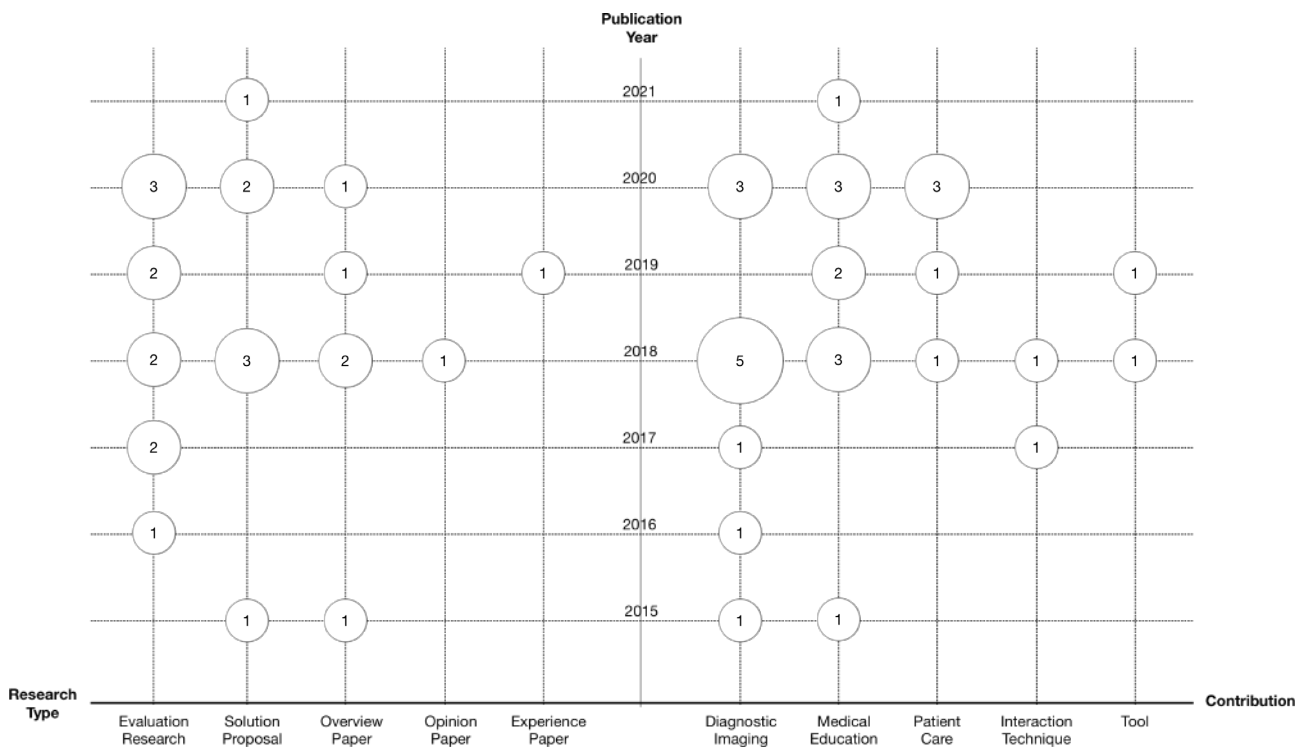
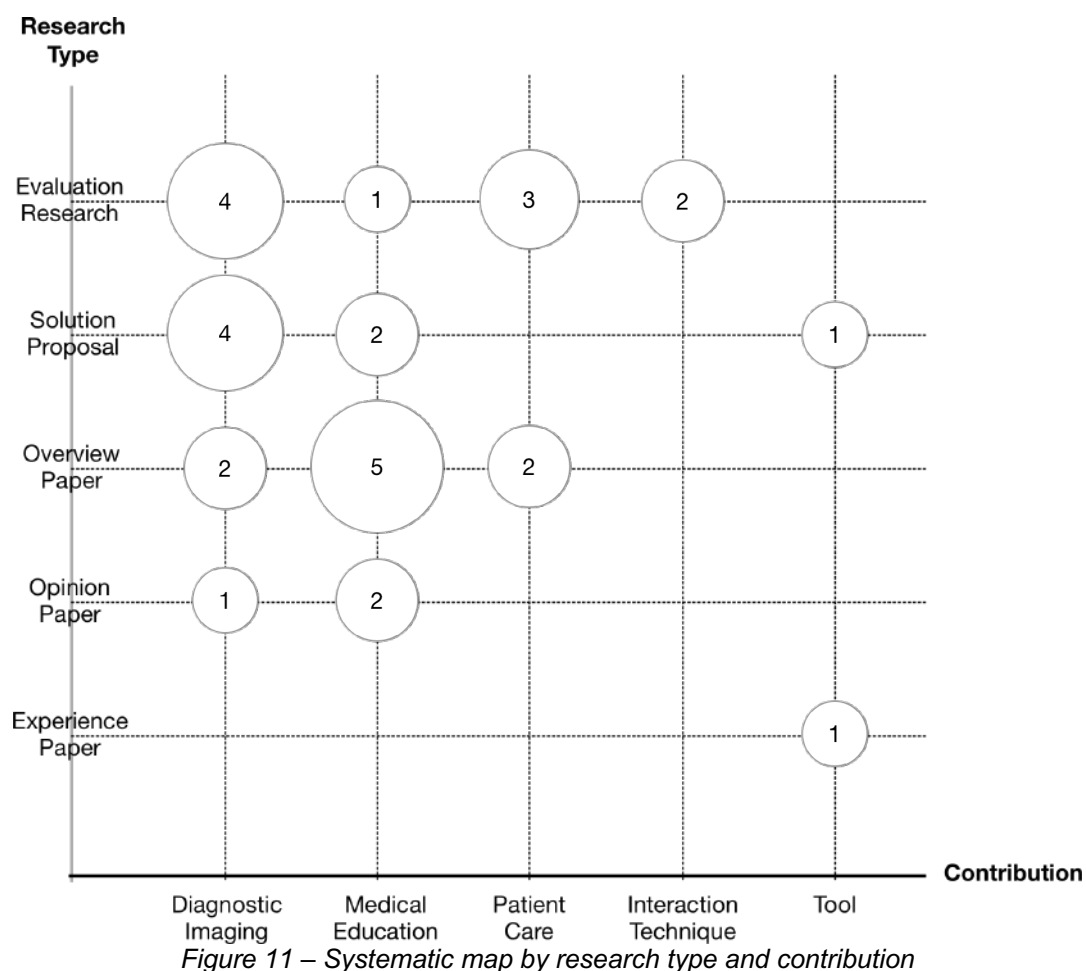


Figure 10 – Systematic map by publication year, research type and contribution

Source: The authors

On the research type, evaluation research, solution proposal and overview paper are the categories with the biggest number of publications in the past years, with evaluation research being the most explored one. This could be an indication that evaluation research is the preferred way to research in this area. Moreover, the year of 2021 has only one study published, which can be a consequence of the COVID-19 pandemic as evaluation research involves developing and validating techniques with real users.

In our second bubble (Figure 11) we combined the research type with the contribution. Regarding DI, this area is mainly explored through evaluation research and solution proposal. In fact, most of the work in DI either implement and validate a technique or propose new solutions, which could possibly explain the absence of validation research papers in the past years. About research type, 50% of the studies published about medical education are overview papers, which might indicate how resourceful and important this area is.



Source: The authors

Lastly, from Table 5 we identified that the majority of the primary studies selected were published in journals (15), followed by conferences (9).

In the following section we provide details about the 24 studies evaluated.

### 3.3. Analysis

In this section we analyze the three research questions proposed for this study. The answers for them came from the information we got in Section 3.2 combined with the learnings and insights from each of the 24 primary studies selected.

#### 3.3.1 RQ1. How is virtual reality used in radiology?

The overview of this systematic mapping study detailed in Table 5 indicates that VR has been used in the radiological field among three main areas, those being: diagnostic imaging, medical education, and patient care.

In regard to diagnostic imaging, we have VR radiology reading room that allows imagiologists to focus on the medical image data, while avoiding the conditions that can interfere with radiodiagnostic (Sousa et al., 2017; Wirth et al., 2018). Moreover, we have the



CAVE, an immersive, navigable, and interactive environment for visualizing complex data sets (Locuson et al., 2015).

In addition to that, we also have a multimodal real-time decision support system where radiologists can visualize and interact with patient data in VR by using natural speech and hand gestures (Prange et al., 2018; Xu et al., 2020). In regard to hand gestures, four studies use Leap Motion Controller<sup>3</sup> as their input system for the developed solution (Izard et al., 2018; Sapkaroski et al., 2019; Sousa et al., 2017; Wirth et al., 2018). Besides, a project called NextMed allows radiologists to visualize any anatomical structure of the patient on the table, as well as manipulate and analyze them in 3D as if they were real (Izard et al., 2018). Moreover, congenital heart disease data when conjoined with VR has been used to diagnose atrial septal defects (Sun et al., 2020). Furthermore, VR has also been used for detection of lung nodules on CT (Nguyen et al., 2018).

About medical education, a wide range of uses can be underlined. First, VR technology has been adopted in surgery residency programs to train residents in laparoscopic surgery technique (Friedman & Pace, 1996). Furthermore, surgeons are also using VR for making preoperative decisions as the surgical procedure can be planned non-invasively on already existing cross-sectional images (Xu et al., 2020) and simulated on patient-specific virtual models prior to being performed on the real patient (Marescaux & Diana, 2015). Moreover, in a study conducted in Spain, computed tomography (CT) was utilized to make 3D models to confirm anatomical compatibility with recipients (Fernandez-Alvarez et al., 2014). Besides, we also have low-cost VR simulations that can help reduce errors and the number of actions in a surgical operation (Park et al., 2014). In addition, VR has been successfully used for resident procedural training, e.g., to simulate lumbar punctures or to better understand complex imaging anatomy, for example, the ultrasound appearance of spinal anatomy (Ramlogan et al., 2017).

Regarding patient care, VR has emerged as a candidate to treat MRI-related anxiety as for most patients, lying inside the MRI scanner for the average examination time of 20 minutes is an unpleasant, sometimes frightening experience (Liszio et al., 2020). Furthermore, it can also be used as a tool to teach patients about their health or treatment, or to deliver treatment (Han et al., 2019; Sutherland et al., 2018). Beyond that, in the

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<sup>3</sup> <https://www.ultraleap.com/product/leap-motion-controller/>

absence of a patient's presence entirely, VR and AR are an interesting clinician tool of intervention planning aid (Sutherland et al., 2018).

Lastly, we noticed that VR can also be used as a tool for collaboration as it creates a wide variety of collaborative opportunities. An example of such use would be clinicians and other health care experts inhabit the same virtual space and discuss the same medical data that is either a mutually interactable object in front of them, or the shared virtual environment itself (Sutherland et al., 2018).

### 3.3.2 RQ2. What are the benefits of using virtual reality in radiology?

From the 24 primary studies, we found out many benefits in using VR in radiology. Regarding diagnostic imaging, the use of VR reading rooms could cut equipment and maintenance costs, and by eliminating effects of ambient lighting conditions it could potentially improve diagnostic accuracy (Elsayed et al., 2020). In addition to that, compared to the 3D printed model of the patient specific-anatomy and pathology, VR is a more flexible and inexpensive alternative (Venson et al., 2017).

Besides, one key element of using VR in any application is that it renders a comprehensive and intuitive visual representation of the data even for the non-specialist, which opens the possibility to provide exam data to referring physicians that can be used for detailed surgery planning and communication with the patients during medical appointments (Venson et al., 2017). Furthermore, Venson et al. (2016) demonstrated that VR shows high effectiveness in identifying superficial fractures for two different volume exams.

VR has the potential to augment the possibilities of grasping the complex morphology of anatomical structures or the pathological changes e.g., in cancer or cardiovascular disease. Thereby, medical immersive imaging not only improve diagnostic imaging and surgical procedure planning, but also serve educative purposes for medical students and doctors (Knodel et al., 2018).

About medical education, some VR systems allow surgeons to take completely free perspectives on the anatomical structures from all directions, which provides a much more intuitive understanding of the present situs, and even more of the underlying pathology (Zawy et al., 2020). Moreover, VR-based visualization of the native MRI grants surgeons an enhanced understanding of tumor localization and breast volumes and it can increase the incidence of breast-conserving surgeries allowing successful oncoplastic procedures (Laas et al., 2021).

In addition, by using VR, trainees can be transported into a procedure room where they may observe and even participate in virtual procedures before performing them on patients. This allows educators to provide standardized and curated educational training material to all trainees (Elsayed et al., 2020; Sapkaroski et al., 2019).

Another benefit of using VR equipment for delivering of medical training content is that such content can be reviewed at a time convenient to the learner, thereby decreasing the effort, coordination, resources, and expense associated with hands-on simulation training (Chang & Weiner, 2016).

Finally, in regard to patient care, VR technology has many advantages over conventional systems for patient entertainment during MRI examinations as it is most capable of distracting patients from the unpleasant sensations of the scanning procedure (Liszio et al., 2020). Besides, the reported successes of using VR for distraction therapy, during invasive surgical procedures warrants adoption in interventional radiology as well (Elsayed et al., 2020). Patients prone to anxiety, claustrophobia, or high analgesic requirements during interventional radiology procedures may find this therapy especially beneficial (Elsayed et al., 2020).

### 3.3.3 RQ3. What are the challenges of using virtual reality in radiology?

Although the number of benefits in using VR in the radiological field is quite remarkable, there are many challenges associated with the use of such technology. First, VR has computational limitations as its systems heavily rely upon central processing units (CPU) and graphics processing units (GPU) (Belmustakov et al., 2018). The demanding computational requirements of rendering images for VR (i.e., the requirement of having two high-definition displays, one for each eye, and both of which display data in a synchronized manner at a high frame rate) may limit the number of triangles/vertices that one can use in a model (or group of models whenever multiple models must be displayed) before impacting smooth rendering performance and subsequently introducing the risk of nauseating the user (Sutherland et al., 2018).

This creates a challenge for model creators to include sufficient anatomical detail to maintain clinical accuracy while allowing for smooth, real-time interactive visualization (Sutherland et al., 2018) as minute structures may be too small to resolve on the 3D reconstruction and VR environment depends on the quality of the original imaging dataset which is susceptible to artifacts secondary to motion and beam hardening (Mohammed et al., 2018). In addition to that, the development of high-quality content requires a degree of

technical knowledge that is beyond what an average technology user possesses (McCarthy & Uppot, 2019) and creating VR models currently requires the use of multiple software applications at the same time, which can be difficult for the user to learn (Ammanuel et al., 2019).

Moreover, image contrast and resolution might be more of an issue with the current generation of VR hardware (Klonig & Herrlich, 2020), and the costs associated with initial VR technology purchase remain high, relative to the price of textbooks and online resources (McCarthy & Uppot, 2019).

Furthermore, VR also requires adequate training to get familiarized with visualizing and manipulating tissue and organs in an open 3D space (Mohammed et al., 2018), but there are ergonomic limitations associated with the use of HMDs, including neck pain with prolonged use and the potential for nausea and vertigo related to issues surrounding latency (McCarthy & Uppot, 2019). Among medical students learning skull anatomy, both AR and VR were perceived to have a role as educational tools; however, headaches, dizziness, and blurred vision were more commonly reported when these supplanted more traditional tablet-based educational applications (Moro et al., 2017).

Beyond that, regarding the use of VR to reduce MRI-related anxiety, many HMDs are not suitable for it due to their magnetic components which are strongly attracted by the MRI scanner's magnets, hence carrying a high risk of injury (Liszio et al., 2020). Another problem is the, sometimes considerable, heating of ferromagnetic materials, which can lead to severe burns (Liszio et al., 2020).

Lastly, innovation in healthcare requires strict regulation and high sense of responsibility. Patient safety and quality of life are major issues and, for this reason, innovation in healthcare needs to be patient-centered in order to be effective (Marescaux & Diana, 2015), thus creating a barrier to novel solutions in that area. Besides, as stated by Sousa et al. (2017), there is also the physician's resistance to novel systems and technologies. Klonig and Herrlich (2020) also mention that the immersion in the virtual environment might increase the emotional gap between physicians and patient, and potentially contributes to objectifying patients.

### **3.4. Commercial applications**

We decided to search for commercial virtual reality applications in the radiology field in order to bring a complementary discussion to the findings of this study. To do so, we

searched on Google<sup>4</sup> using the same search string described in Section 3.1.2 with the addition of words “application” or “software” to the end of it. Table 6 depicts the 12 products we obtained from that research.

*Table 6 – Industry applications result*

Application	3D Model Visualization	Windowing	Scrolling	Markers	Medical Collaboration	Cost	Computer Target
Intravision XR (DICOM Director, n.d.)	✓	✓	✓	✓	✓	US\$ 750/month	Desktop
Mimics Viewer (Materialise, n.d.)	✓	✓	✓	✓	✓	Contact	Desktop/HMD
Medicalholodeck (Medicalholodeck, n.d.)	✓	✓	✓	✓	✓	Contact	Desktop/HMD
SieVRt (Luxsonic Technologies, n.d.)	✓	✓	✓	✓	✓	Free	Desktop
DICOM VR (DICOM VR, n.d.)	✓	✓	✓	✓		Contact	Desktop
MedicalVR (MedicalVR, n.d.)	✓	✓	✓	✓		Contact	Desktop
PrecisionXR (Surgical Theater, n.d.)	✓	✓	✓	✓		Contact	Desktop
ImmersiveView VR (ImmersiveTouch, n.d.)	✓	✓	✓	✓		Contact	Desktop
The Body VR (The Body VR, n.d.)	✓	✓	✓	✓		Free	Desktop/HMD
ChimeraX Virtual Reality (University of California, n.d.)	✓	✓	✓	✓		Free	Desktop
3D Slicer (3D Slicer, n.d.)	✓	✓	✓	✓		Free	Desktop
MedicalImagingVR (Hublab, n.d.)	✓	✓	✓			Free	Desktop

All 12 software found on this exploration grant users the ability to perform the two major tasks performed by radiologists, these being windowing and scrolling (see Subsection 2.2). In addition to that, they also allow doctors to visualize 3D models in a VE. Among the identified products, all but one permit physicians to add markers to individual regions on the 3D model. Such markers are useful when doctors want to label a region for further analysis or to call the attention of other clinicians in a shared VE.

Moreover, all applications use traditional desktop computers as their main source of computational power to provide real time rendering for the connected HMD. In addition, all solutions but one requires users to work with the controllers provided by the HMD as their primary input system. Only Intravision XR (DICOM Director, n.d.) does not allow such behavior as it uses conventional mouse and keyboard to execute the tasks. Furthermore, three software support the deployment in standalone HMD such as Oculus Rift (Meta, n.d.) as such HMD have their own built-in computer to run programs. This finding supports the results we found in Section 3.2, that most solutions are deployed in desktops.

About the cost, five are free to use. Six applications require customers to get in contact with the company to obtain more information about its pricing and deployment procedure. It is possible that these companies prefer an individual pricing approach so they can customize their solutions for the needs of their clients. It is also possible that the prices might be elevated for a technology that has been more explored in recent years and its consequences

<sup>4</sup> <https://www.google.com.br>

are yet to be unveiled. Only one company reveals its subscription price (DICOM Director, n.d.).

Regarding users collaboration, four products offer the medical collaboration feature to share the analysis and considerations of a 3D volume (DICOM Director, n.d.; Luxsonic Technologies, n.d.; Materialise, n.d.) among physicians or to invite other clinicians to a common VE where they can diagnose together (Medicalholodeck, n.d.).

### **3.5. Final remarks**

In this review we conducted a systematic mapping study in order to identify the main uses of VR in the context of radiology and characterize the benefits and challenges of it. The goal was not only to determine and characterize the state-of-the-art on VR in radiology, but also to create a general understanding of the area and find gaps for future exploration.

After performing the research, we classified the studies according to three categories: contribution, research type and computer target. The contribution category revealed five possible classifications in which the studies fit: diagnostic imaging, medical education, patient care, interaction technique and tools. In addition, computer target category showed presented four possibilities for papers, these being: desktop, smartphone, CAVE and HMD. Our study also indicates that there are many attempts to insert the VR in radiology. Most of the studies in the area are recent and the majority of them were published in journals.

Regarding the first research question proposed — How is VR used in radiology? — we could identify that it has been used in three major areas: diagnostic imaging, medical education, and patient care. In the diagnostic imaging area, VR has been used to protect physicians from external factors such as room illuminations. Some examples of that are virtual radiology reading rooms (Klonig & Herrlich, 2020; Nguyen et al., 2018; Prange et al., 2018; Sousa et al., 2017; Venson et al., 2016, 2017; Wirth et al., 2018) and physical immersive ones (Knodel et al., 2018; Locuson et al., 2015). About medical education, VR is being used to allow doctors to review medical data and take preoperative decisions before going to a real surgery (Marescaux & Diana, 2015; Xu et al., 2020). Besides, it also provides physicians a safe environment to learn medical content and practice techniques (Ramlogan et al., 2017). In regard to patient care, VR has emerged as a candidate to treat MRI-anxiety (Liszio et al., 2020) and educate patients about their health and treatment (Han et al., 2019; Sutherland et al., 2018). In general, VR could also be used as a tool to create a shared VE where clinicians and other health care experts inhabit the same virtual space and discuss

the same medical data that is either a mutually interactable object in front of them, or the shared virtual environment itself (Sutherland et al., 2018).

The second research question — What are the benefits of using VR in radiology? — brought some advantages in the area to highlight. First, the use of VR in radiology cuts the equipment and maintenance costs of a real radiology reading room and it could potentially improve accuracy in radiological diagnosis (Elsayed et al., 2020). Besides, it is also more flexible and unexpensive when compared to 3D printing (Venson et al., 2017). Moreover, VR can render easy to understand and intuitive visual depiction of the data even for non-experts, which fosters the possibility to provide medical data to referring clinicians that can be used for detailed surgery planning and conversation with the patients during medical consultations (Venson et al., 2017). In addition, VR enables physicians to have standardized and curated educational training material (Elsayed et al., 2020; Sapkaroski et al., 2019) that can be reviewed at a time convenient to the learner (Chang & Weiner, 2016). Furthermore, VR also distracts patients in unpleasant radiological procedures (Liszio et al., 2020).

From the third research question — What are the challenges of using VR in radiology? — we can see that despite the presented benefits of using VR in radiology, there are still some barriers along the way to its effective use. One example of it is that VR heavily relies upon powerful computers (Belmustakov et al., 2018) for real-time rendering, which makes its adoption expensive and less likely to happen, for now. Beyond the high price of computers, there are also high costs associated with the initial purchase of VR technology (McCarthy & Uppot, 2019), and even though they are expensive, not all of them are suitable for the radiology field as some VR hardware includes magnetic components that might prevent them from being used in radiological procedures (Liszio et al., 2020). Furthermore, an average technology user does not present the required degree of technical knowledge to create high-quality content for VR (McCarthy & Uppot, 2019). Moreover, doctors also present a resistance to novel systems and technologies (Sousa et al., 2017), and VR presents side effects on its use, such as neck pain, nausea, dizziness (Moro et al., 2017).

We also searched for commercial solutions in the area in order to bring more content to the state-of-the-art discussion carried out by this study, which brought us 12 products worth debating. All found applications allow users to perform both windowing and scrolling, two common tasks executed by radiologists. In addition, they also provide clinicians a way to visualize 3D medical data in a VE, which is said to be a relevant feature in the area according to 18 primary studies identified.

Moreover, none of the solutions work with Leap Motion Controller as their input system, even though such controller has been already analyzed in the academic field and proven to bring benefits to the area (Izard et al., 2018; Sapkaroski et al., 2019; Sousa et al., 2017; Wirth et al., 2018).

Besides, none of the applications do not offer an approach to visualize content in a CAVE system although some papers have already explored it (Knodel et al., 2018; Locuson et al., 2015). We believe CAVE systems are less adopted because they require more hardware and physical space to be deployed in comparison to traditional desktops and HMD, which increases the costs associated with this solution.

From the selected software, only 3D Slicer (3D Slicer, n.d.) is used as part of the solution explored in the academic research (Ammanuel et al., 2019; Xu et al., 2020; Zawy et al., 2020). This might be due to 3D Slicer being free and open source (3D Slicer, n.d.).

It is also important to highlight that some of the primary studies present similar solutions to the ones we found in commercial applications as the first also allow users to visualize 3D medical data and perform windowing and scrolling through HMD attached to desktops (Klonig & Herrlich, 2020; Laas et al., 2021; Nguyen et al., 2018; Prange et al., 2018; Sapkaroski et al., 2019; Venson et al., 2016, 2017; Zawy et al., 2020).

Although we have identified five papers that analyze the patient care field, only PrecisionVR (Surgical Theater, n.d.) explores it by allowing patients to see their own medical data in a VE. The remaining solutions are aimed for doctors to either perform diagnostic imaging or learn new medical content or train for procedures.

In conclusion, this systematic mapping was a first attempt to better understand the context of VR in the radiology field. We understand that several opportunities were created and can be explored from the findings we carried out.



## 4. PROPOSED APPROACH

After performing the systematic literature review, we found out that clinicians face some problems when diagnosing medical images in radiology reading rooms as such places might present external factors that can interfere with the diagnostic process, such as inadequate lighting environment condition (Samei et al., 2005). In addition to that, physicians also must analyze 3D images in 2D displays, which is known to be a hard skill to grasp as it requires doctors to create a mental visualization of the 3D model to diagnose (Drew et al., 2013; van der Gijp et al., 2014). Besides, we also concluded that most virtual reality work in radiology use traditional desktop computers as their main visualization device and the same happens with commercial applications.

**Therefore, we proposed to evaluate an immersive and stereoscopic visualization approach of medical images able to perform the two most common techniques used by professionals of the radiology area: windowing and scrolling.** The stereoscopic aspect of our tool was a necessary feature because we wanted to provide the sense of immersion and the approach was developed to be deployed on mobile devices as similar immersive and stereoscopic applications using smartphones are a gap in the literature. The developed approach is planned to be attached to a Google Cardboard (Google, n.d.b) like HMD (see Figure 12).



*Figure 12 – HMD similar to Google Cardboard*

Source: <https://www.pointmixacessorios.com.br/none-95730671>

The main challenge of this proposed approach was to develop the application for smartphones. After all, mobile devices have less computational power and memory when compared to traditional desktops. In addition to that, adapting the controls of a gamepad to

perform all desired features in a natural way was also challenging. Figure 13 depicts the selected gamepad for this study.



*Figure 13 – Generic gamepad controller*

Source: adapted from Sony, (n.d.a)

As part of the testing process, we used two different professional profiles from the field of radiology to evaluate our tool: radiologists (RA) and medical physicists (MP). The reason why we decided to add the medical physicists as a complementary candidate option for our study is because, even though they are not doctors, they deal with medical images on a daily basis. 16 professionals were selected for this study (11 RA and 5 MP).

We applied two different types of questionnaires to the testers at the end of each trial: one that we designed ourselves (ad-hoc) and one that we adapted from literature. With the ad-hoc questionnaire we evaluated the implemented features, background experience, real usage perception of users and future work. As for the second type, we assessed the usability level with the System Usability Scale and the overall effort necessary to use it with NASA-TLX.

It is relevant to state that the applied questionnaires were online, and testers were allowed to either answer them at the testing place (immediately after experimenting our application) or at their homes. The two possible testing places for the trials were the computer laboratory of the university this study was created or the hospital the professionals are currently working. In addition to that, the researchers were aware that requesting testers to answer a questionnaire right after a trial might provide more insightful data, but such option often discouraged our candidates to try our application out. Therefore, allowing testers to fill up the survey from home was a necessary addition.

Our goal with this questionnaire was not only to evaluate our approach, but also to address the lack of studies in the area that uses smartphones as their primary computational

deployment target. After applying the questionnaire and collecting the data, we were able to present a careful data analysis and to provide insights for future work.

## 5. DEVELOPMENT PROCESS

The following subsections depicts the features we decided to implement in our approach, based on the findings we obtained from the literature review. In addition to that, the hardware, software, and dataset we used to make our application possible are also presented. Finally, a thorough description of each developed version of the approach is explored, showing the feedback we obtained from a real user for every release.

### 5.1. Features

Based on systematic review presented in Chapter 0, we decided to implement the following features in our application:

- **3D rendering:** renders in the VE the 3D model created from the DICOM files. Users no longer need to scroll through an array of images to create a mental 3D visualization of the data;
- **Windowing:** changes the windowing level (WL) and width (WW) of the 3D model. In other words, users can adjust the brightness and contrast of the medical data and see the result in real time;
- **Scrolling:** scrolls through the slices of the 3D data in any custom anatomical cutting planes, including the three traditional ones (axial, coronal and sagittal);
- **Moving:** moves the 3D model in any direction in the VE. It is also possible to move the 3D volume forward and toward the camera. That way, users are free to decide the best position and distance for the model to perform the radiological diagnosis;
- **Rotating:** rotates the 3D model around its center of mass in the VE. That way, users can explore different viewing angles for the model and create a general understanding of the given data;
- **Scaling:** proportionally scales up and down the 3D model so that users can choose an adequate size to execute the diagnosis.

In order to create a safe space to make mistakes, regardless the functionality being used, the user always has a way to reset the parameters data to its default WW, WL, position, rotation, and scale initial values. Therefore, they can freely explore the tool and easily go back to the initial values.

## 5.2. Hardware, Software and Dataset

In order to create our application, we used Unity Engine (Unity Technologies, n.d.), a cross-platform game engine that is extensively used in the field of VR and AR due to the flexibility and ease of use. Unity is responsible for handling the physics simulation, rendering, the operations performed by the user, obtaining the inputs and generating outputs. In addition to that, we used Google Cardboard Software Development Kit (SDK) (Google, n.d.a) for Unity to deploy the developed approach on smartphones.

Regarding smartphones, the one we used to deploy our application and test out our approach was an iPhone XR, from Apple (Apple, n.d.) (see Figure 14). We decided to use a high-end cell phone device because we wanted to avoid performance issues. We also used a PlayStation 4 Controller, also known as DualShock 4 (Sony, n.d.a), connected via Bluetooth with the device to interact with the VE. It is important to state that, although we chose specific devices to run our solution, the software is compatible with common mobile devices and universal gamepad controllers.



*Figure 14 – iPhone XR*

Source: Adapted from Apple, (n.d.)

In order to keep compatibility with the standards adopted in the field of radiology, the application supports data in the Digital Imaging and Communications in Medicine (DICOM) format.

The main images used for our tests were obtained from Pancreas-CT dataset (Roth et al., 2016). The selected DICOM set of data is composed of 226 slices with a 512x512 resolution, and it is rendered on screen using the raymarching technique (Pauly et al., 2000).

Throughout the development process, we faced one main issue to make the application run on mobile devices, that being the amount of memory available on the cell phone to store the required data to display the 3D model. That problem was expected to appear as smartphones have less computational power compared to traditional desktops, which might explain why there are not so many applications designed for mobile phones. Because of that, it was necessary to scale down the resolution of the chosen DICOM from 512x512 to 128x128 (a quarter of the original width and height), and we achieved that result by using DICOM ToolKit (OFFIS Institute, n.d.), a set of software libraries and applications to work with DICOM files. The difference between the original DICOM and the reduced one is depicted in Figure 15.

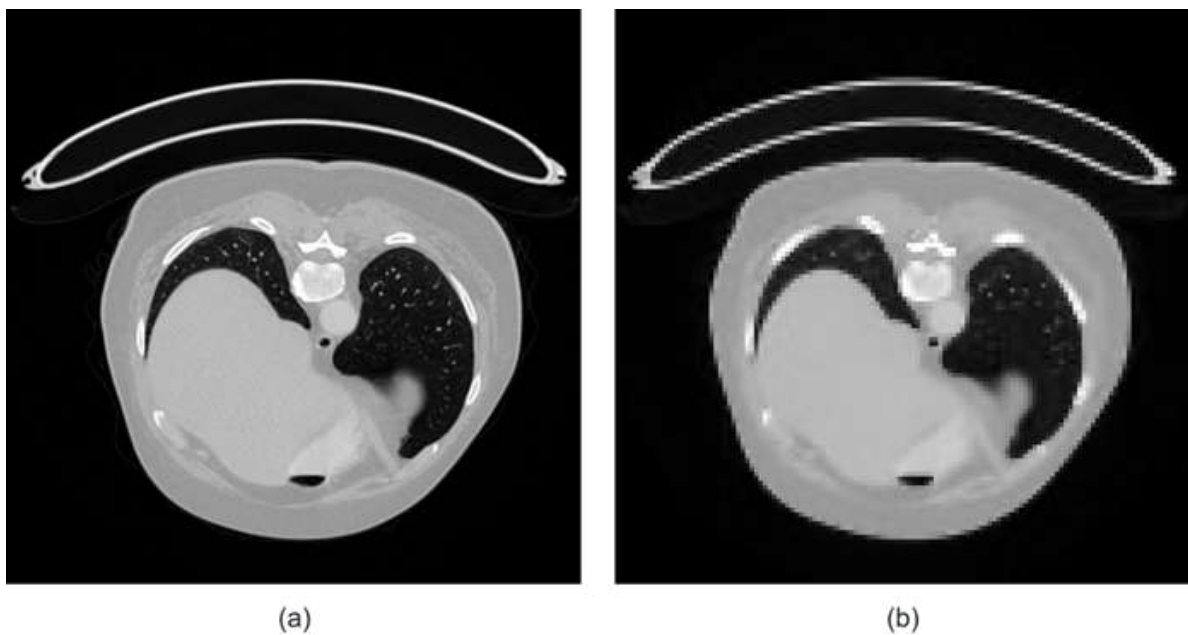


Figure 15 – (a) the original DICOM 512x512 resolution and (b) the reduced DICOM 128x128 resolution

Source: The authors

### 5.3. Developed versions

With the objective to develop a useful application to the problems discovered by this study, we constantly tested our application with professionals from the medical physics area. This validation process with specialists was keenly important for us because their feedback guided us to develop meaningful and useful interactions in our software.

The following subsections depicts the evolution of our approach throughout the developed versions. Screenshots and videos are also available for a better visualization of the application.

### 5.3.1 Version 1

The first version of our approach was already able to perform the 3D rendering, windowing, scrolling, moving, rotating, and scaling features. The main goal with this version was to evaluate the possibility to deploy the application in smartphones and to test out the developed functionalities. The interface of this version is depicted and detailed in Figure 16.

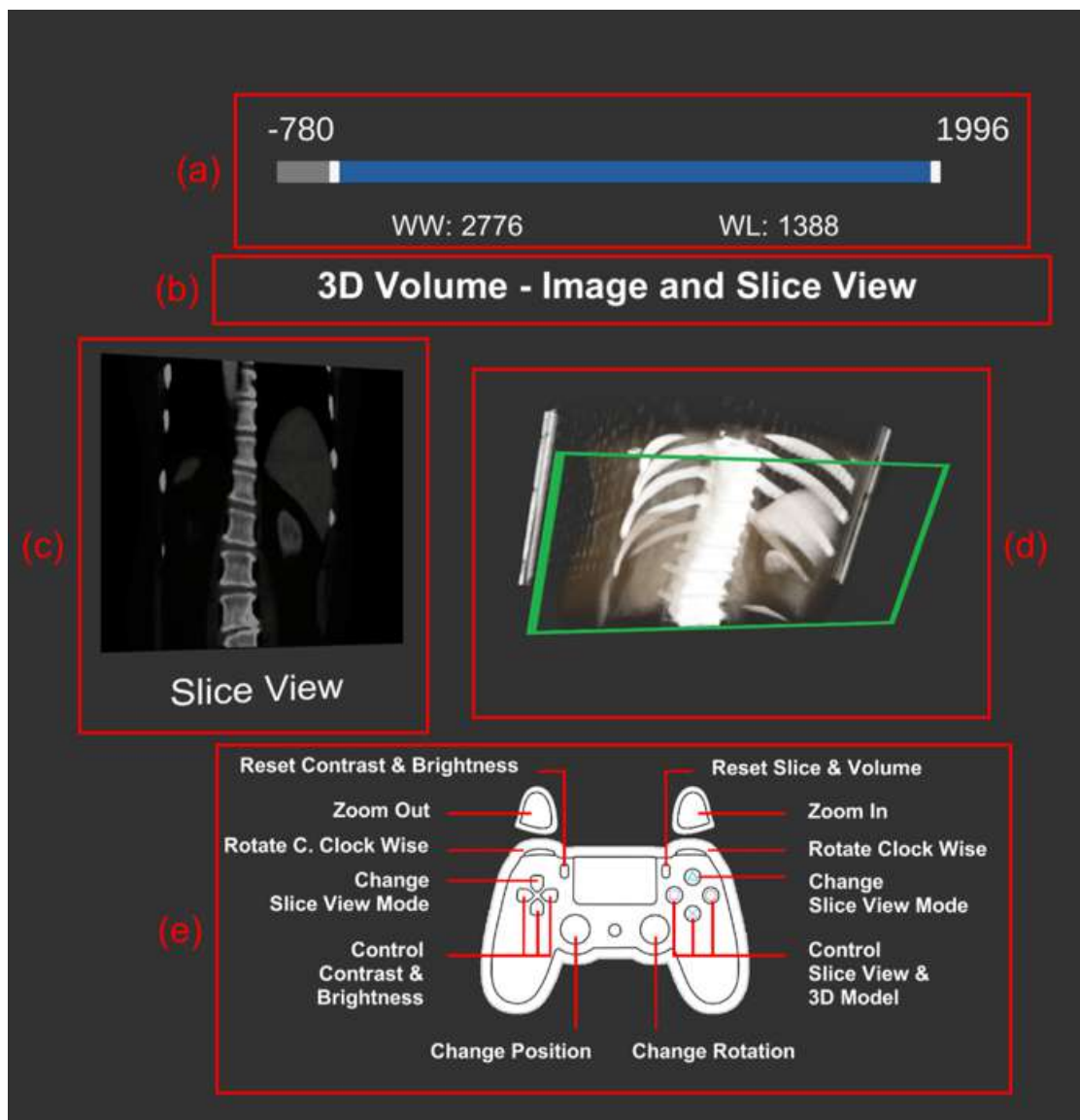


Figure 16 – Version 1 interface. (a) Windowing Bar, (b) Status Bar, (c) Slice View or 2D image, (d) 3D Model with 3D Slicer in green and (e) Controller layout

Source: The authors

The **windowing bar** (Figure 16 – (a)) shows meaningful information to the users regarding the brightness and contrast of the presented 3D model. Such information can be

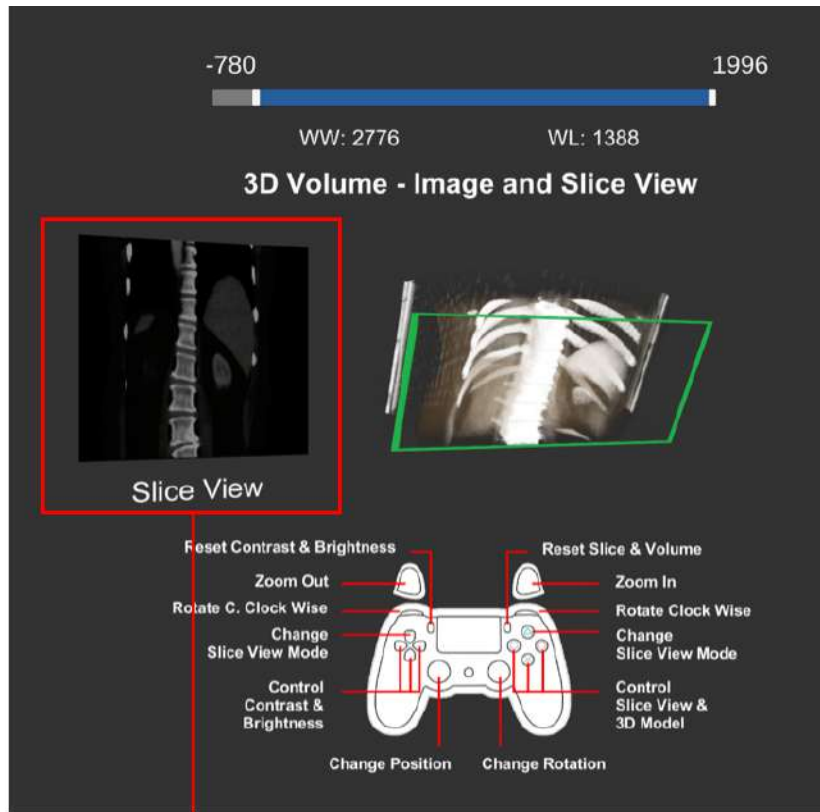
adjusted by moving the internal slider and verified by observing the values on the WW and WL labels. In addition, the **status bar** (Figure 16 – (b)) depicts the current application state, which means users can see what is being controlled at that moment (3D Volume) and what is being shown to them (Image and Slice View).

Moreover, the 3D model section (Figure 16 – (d)) supports two different features, those being (1) present the 3D volume and (2) slice it up with a 3D green slicer that prints the sliced frame in a view (Figure 16 – (c)).

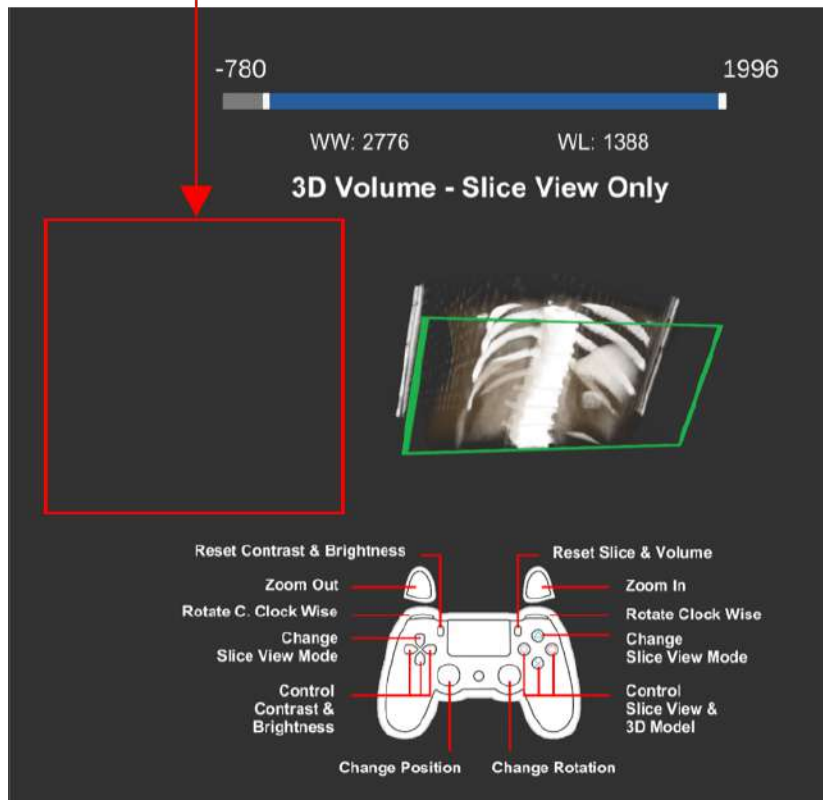
As users are immersed in a VE, they are not able to see their own hands or the controller they are using. Therefore, it was necessary to create a virtual representation for the gamepad so that users can identify the buttons they are currently pressing, increasing the usability of our approach. This representation interface is depicted in Figure 16 – (e).

Regarding the feature of slicing the 3D volume up, we also allow users to toggle on and off the view showing the slicing results (see Figure 17). It is also possible to toggle on and off the 3D slicer as seen in Figure 18.





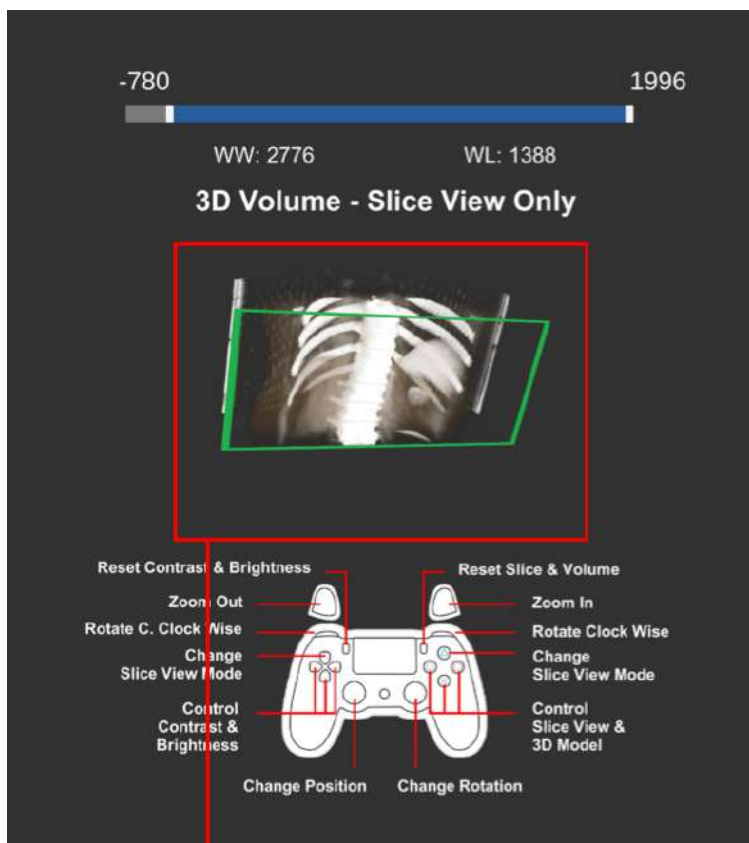
(a)



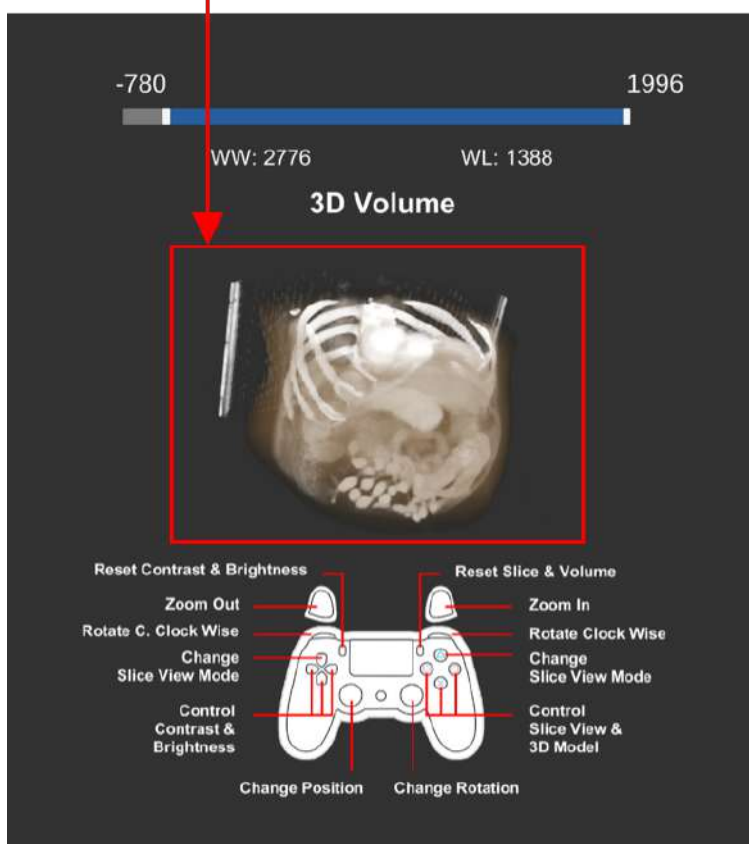
(b)

Figure 17 – (a) Slice view on and (b) slice view off

Source: The authors



(a)



(b)

Figure 18 – (a) 3D Slicer in green on and (b) 3D slicer in green off

Source: The authors

In order to evaluate the developed features, we invited an expert from the medical physics field to assess the created application in person. Before his/her arrival, we set up the environment for the study session by taking the following steps:

- Check if the application was installed correctly and it was running correctly;
- Check if the computer was ready to record the session;
- Check if the HMD and the gamepad controller were properly sanitized.

Upon the arrival of the tester, we:

- Attached the smartphone on the HMD in front of him/her;
- Asked him/her to sit down;
- Explained our application;
- Asked him/her to perform eight tasks on our application (see Table 7).

*Table 7 – Tasks to be performed on Version 1*

ID	Tasks
T1	Move the 3D model around the VE
T2	Rotate the 3D model
T3	Scale up and down the 3D model
T4	Toggle on and off the 3D slicer
T5	Move the 3D slicer
T6	Rotate the 3D slicer
T7	Toggle on and off the Slice View
T8	Change the brightness and the contrast of the 3D model

While the software was being tested, the researchers did not explain to the invited professional how to use the solution. In fact, the only information provided to the tester was a list of the available features. Besides, we also requested the professional an authorization to record the testing session, so that we could go back to the video<sup>5</sup> to gather some more insights.

After using our application for 30 minutes, the specialist stated that our solution presented many positive aspects and opportunities to be enhanced. Table 8 summarizes the feedback we acquired from this pilot study.

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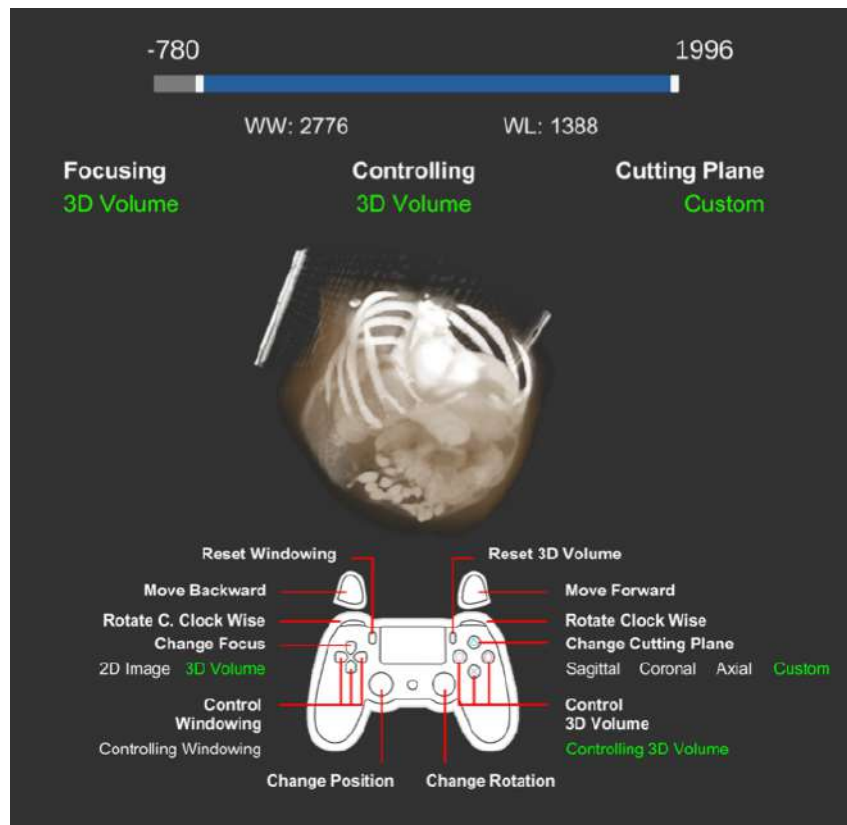
<sup>5</sup> <https://youtu.be/ZUBaSH5SOZk>

Table 8 – Feedback from Version 1

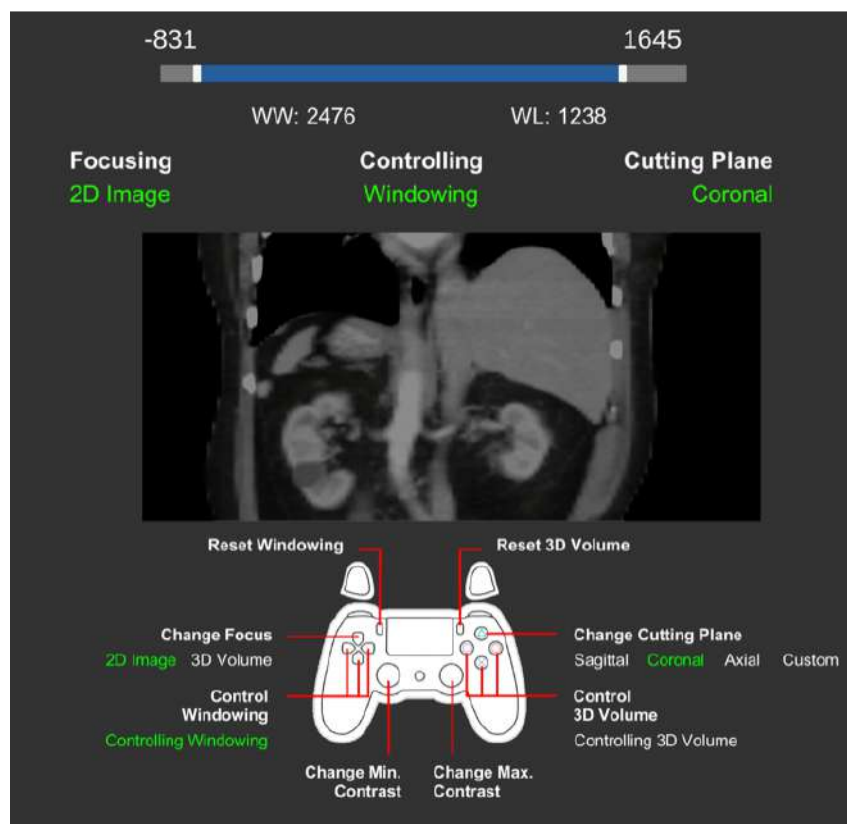
ID	Positive aspects
P1	Natural and intuitive use of the controller
P2	Good 3D model rendering quality and colors
P3	Intuitive information across the interface
P4	Interesting way of slicing the 3D model in any anatomical cutting plane (scrolling) using a 3D slicer
P5	Stable frames-per-second (FPS) rate
ID	Enhancement opportunities
E1	Provide a clearer way to identify what is being controller on the screen (3D model, windowing or 3D slicer)
E2	Create a connection between the buttons of the controller and the status bar
E3	Allow users to center the slice view at the middle of the screen
E4	Automatically update the slice view according to the current WW and WL
E5	Attach the 3D slicer feature onto the camera instead of being a separate mode to control
E6	Merge the two modes responsible for adjusting the WW and the WL into one
E7	Provide a way to change the cutting plane (sagittal, coronal and axial) of the 3D model

### 5.3.2 Version 2

With the feedback obtained from the previous version, we worked on a new version. The general interface of the resulting application is shown in Figure 19. In this new version, we made sure to keep the positive aspects highlighted by the tester and to seek to improve pointed issues.



(a)



(b)

Figure 19 – The new interface of the application version 2. (a) shows the user controlling the 3D volume and (b) depicts the user adjusting the WW and WL of the 3D model while slicing the volume

Source: The authors

Therefore, we redesigned the status bar on this new version to provide a better understanding of what is being currently controlled in the VE (see Figure 20). This update speaks for recommendation E1 from Table 8.

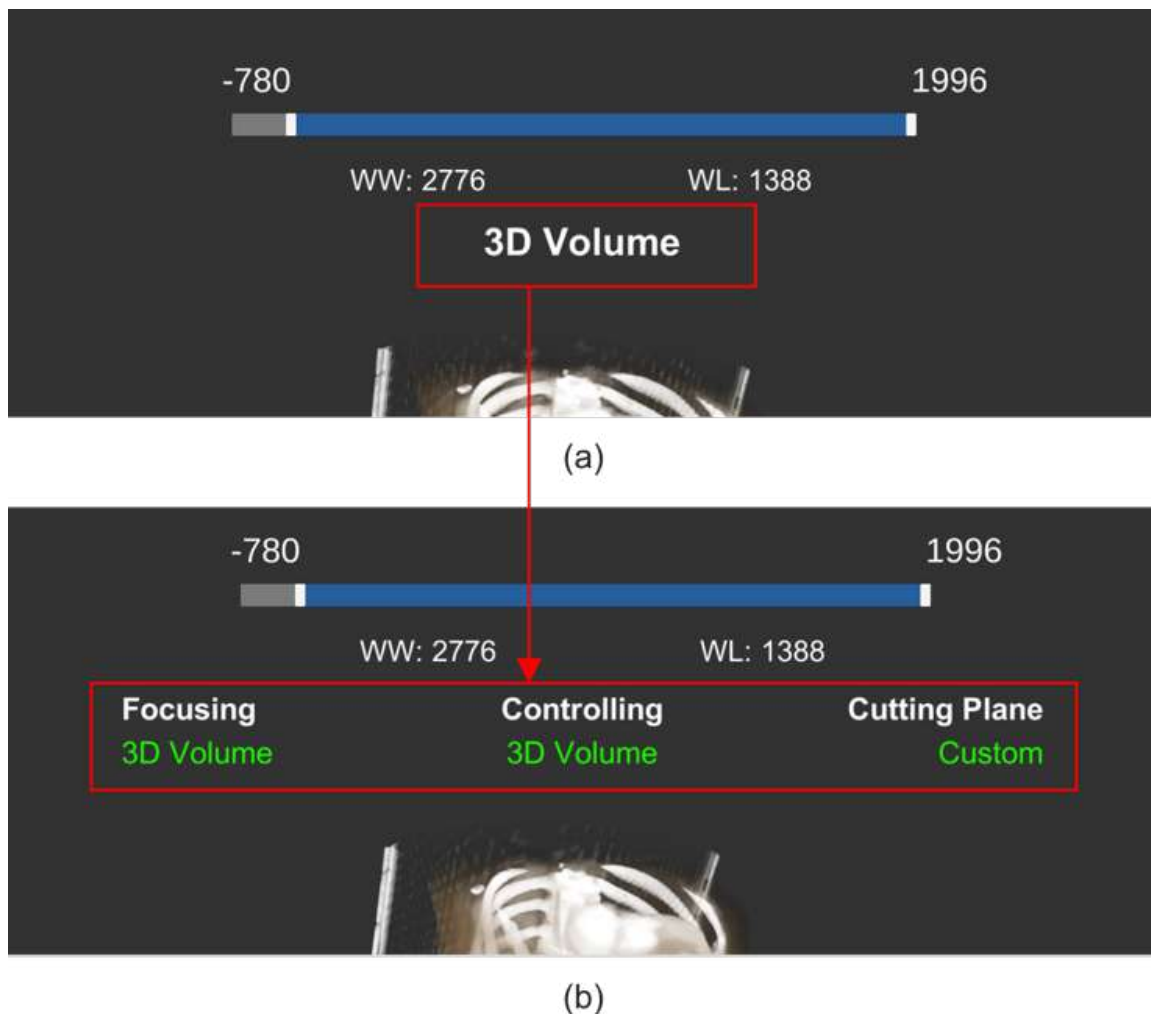


Figure 20 – (a) Version 1 status bar interface and (b) Version 2 new status bar interface with green labels for a better highlighting to users

Source: The authors

As for suggestion E2, the words we used on the new status bar are also shown in green on the controller layout, so then users can match the functionalities presented by the gamepad with the current application status. Figure 21 depicts this modification.

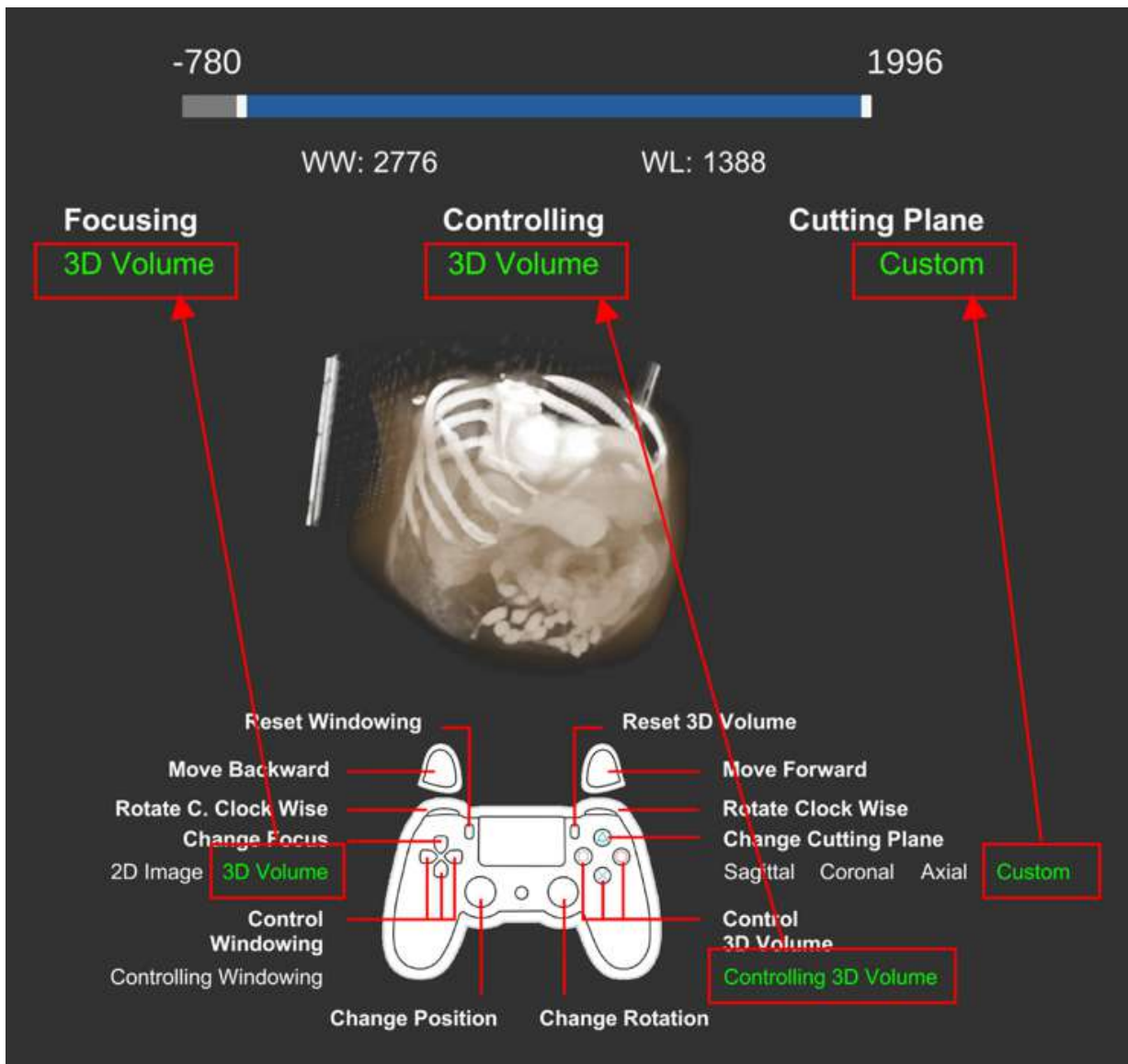
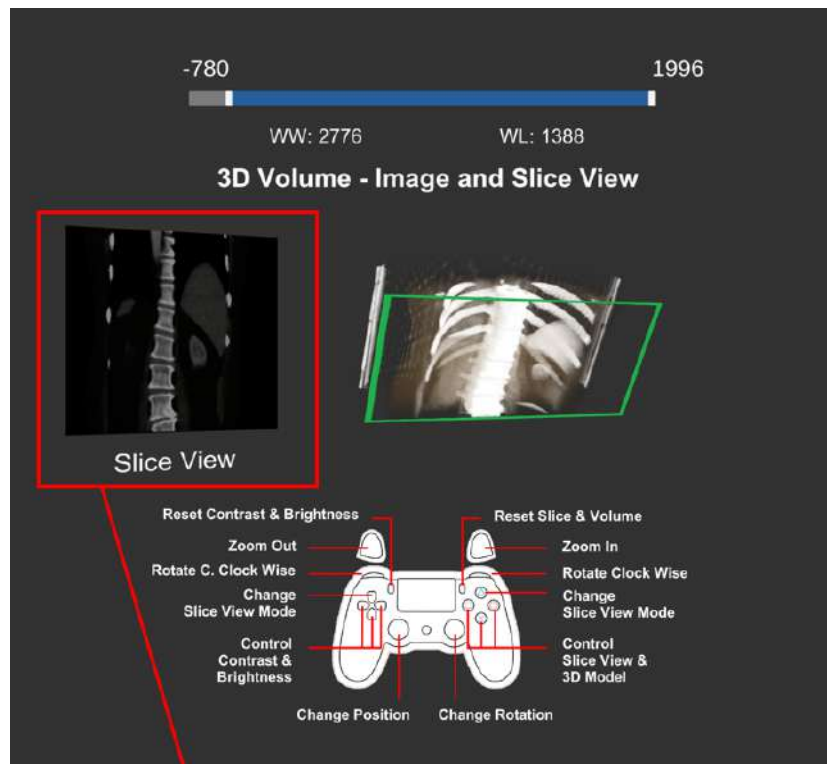


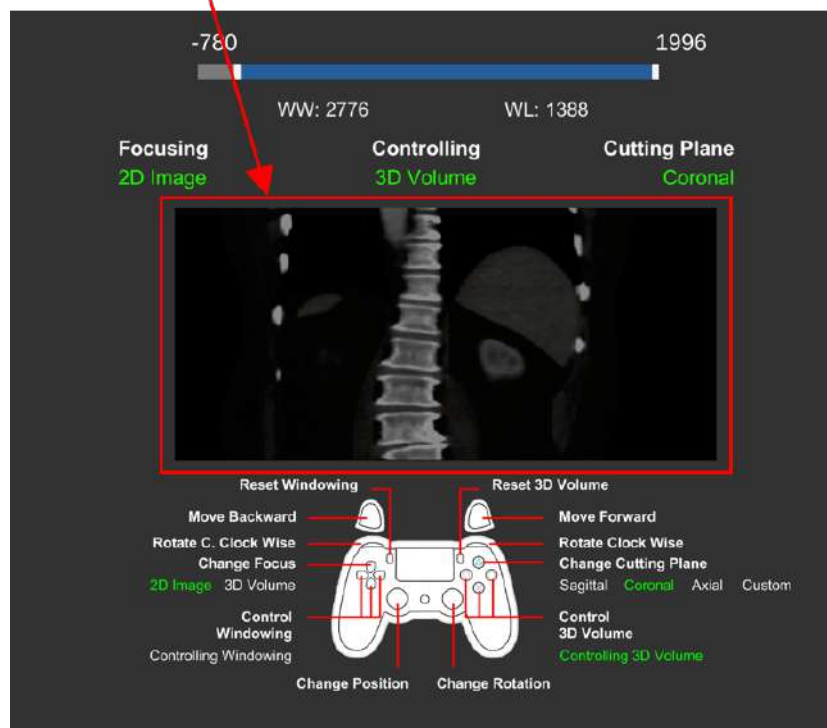
Figure 21 – Version 2 new interface with a stronger visual connection between status bar and controller layout

Source: The authors

Furthermore, regarding recommendation E3, while they are using the sagittal, coronal or axial cutting plane, it is now possible for users to exclusively focus on the slice view, as seen in Figure 22.



(a)



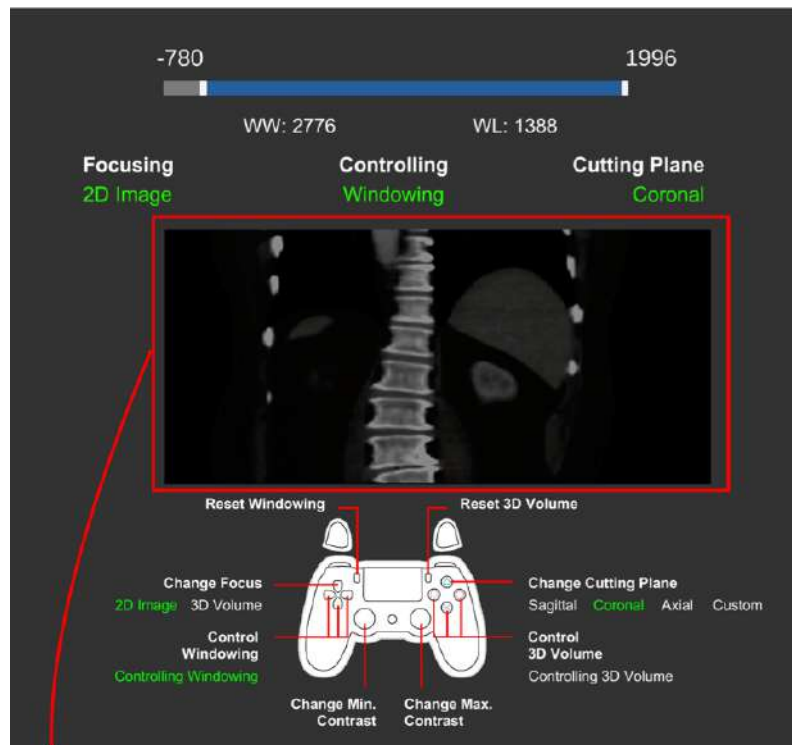
(b)

Figure 22 – (a) Version 1 interface presenting the slice view and (b) Version 2 new interface centering the slice view

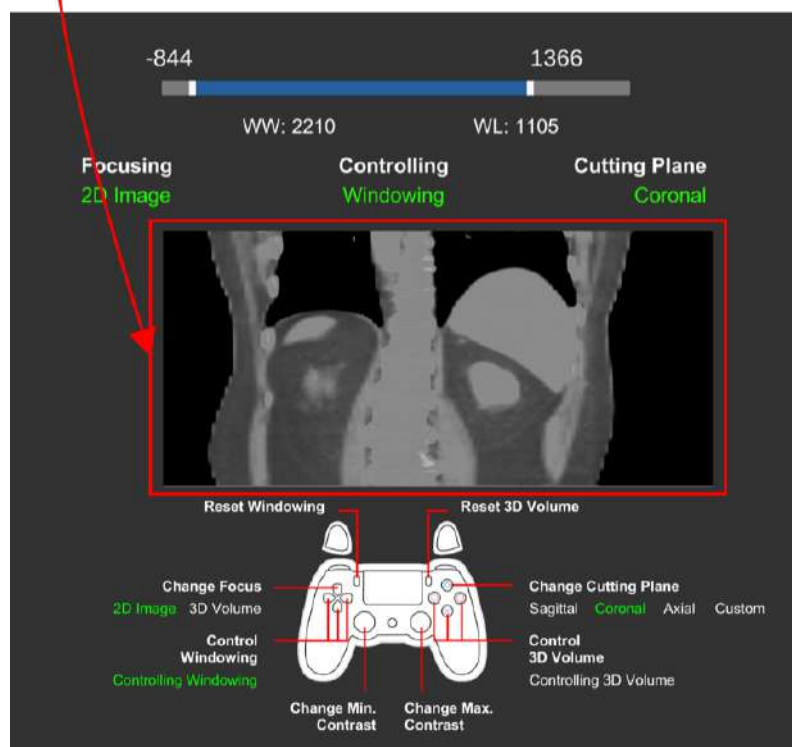
Source: The authors

We also worked on suggestion E4 and now the slice view reacts to the changes made on the WW and WL as shown in Figure 23.





(a)



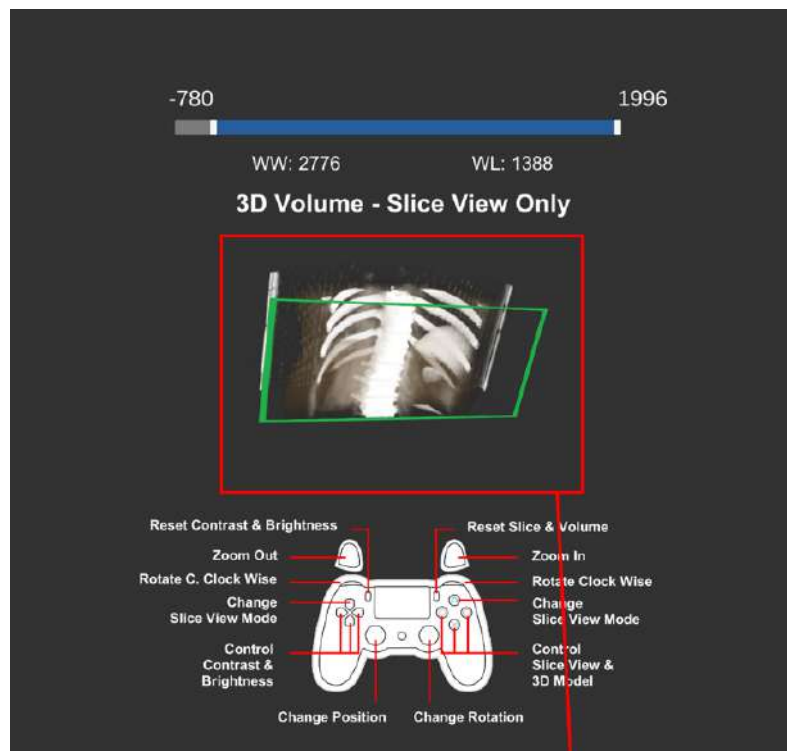
(b)

Figure 23 – Version 2 slice view reacting to changes being made on the WW and WL. (a) and (b) represent the before and after of a WW and WL adjustment

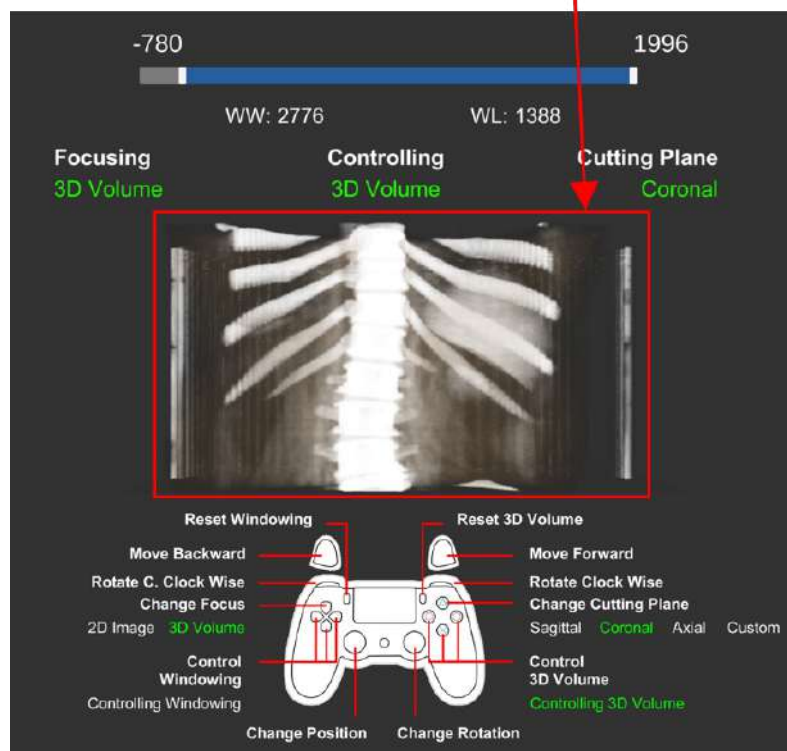
Source: The authors

According to recommendation E5, we removed the slicing plane from the 3D model and attached it onto the camera. That way, users do not have to control two separate entities (3D slicer and 3D volume) to perform the scrolling feature anymore (see Figure 24). We also

combined the two modes responsible for adjusting the WW and WL into one, as described in recommendation E6. This last change was especially beneficial because the less entities users need to control, the easier to use our application becomes.



(a)



(b)

Figure 24 – (a) Version 1 using the 3D slicer to cut the 3D model and (b) Version 2 using the camera as a 3D slicer itself

Source: The authors

Lastly, for suggestion E7, we added a button on the controller layout to allow users to change the cutting plane of the 3D model. Figure 25 shows that change.

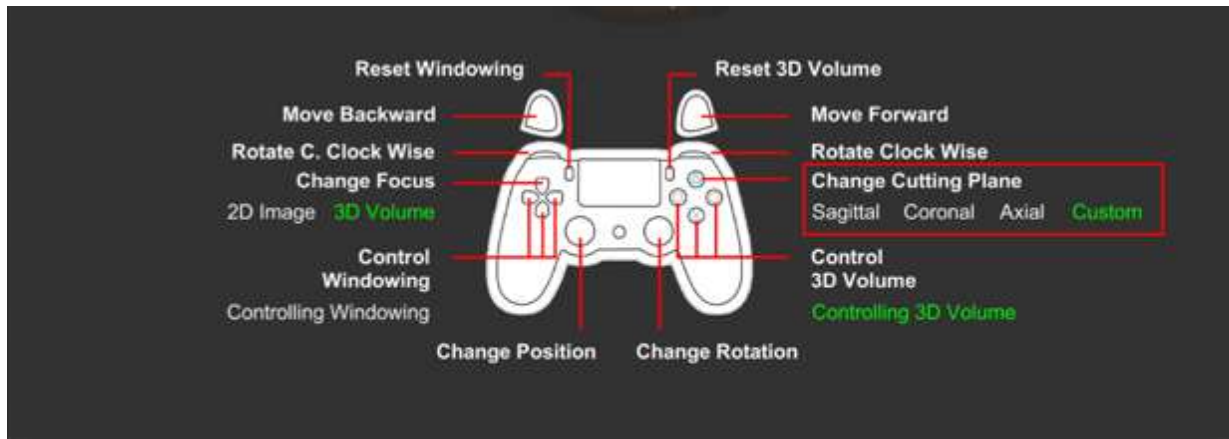


Figure 25 – Version 2 new button on the controller layout to change the 3D model cutting plane between sagittal, coronal, axial and custom

Source: The authors

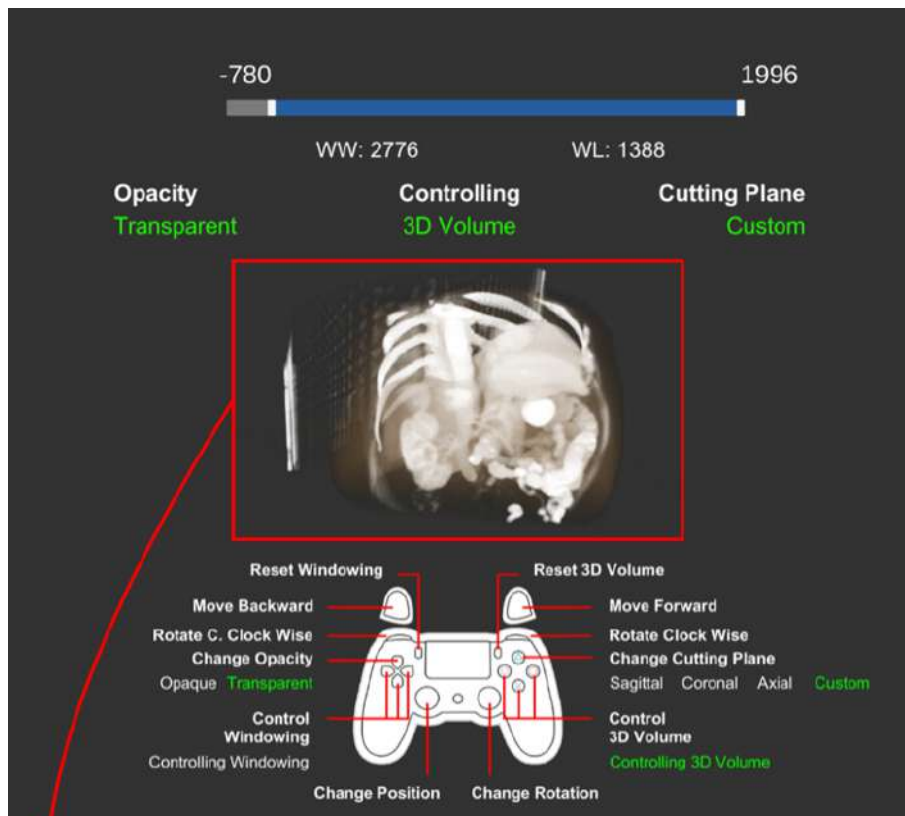
Finally, a feedback table regarding the version 2 of our application is presented in Table 9.

Table 9 – Feedback from Version 2

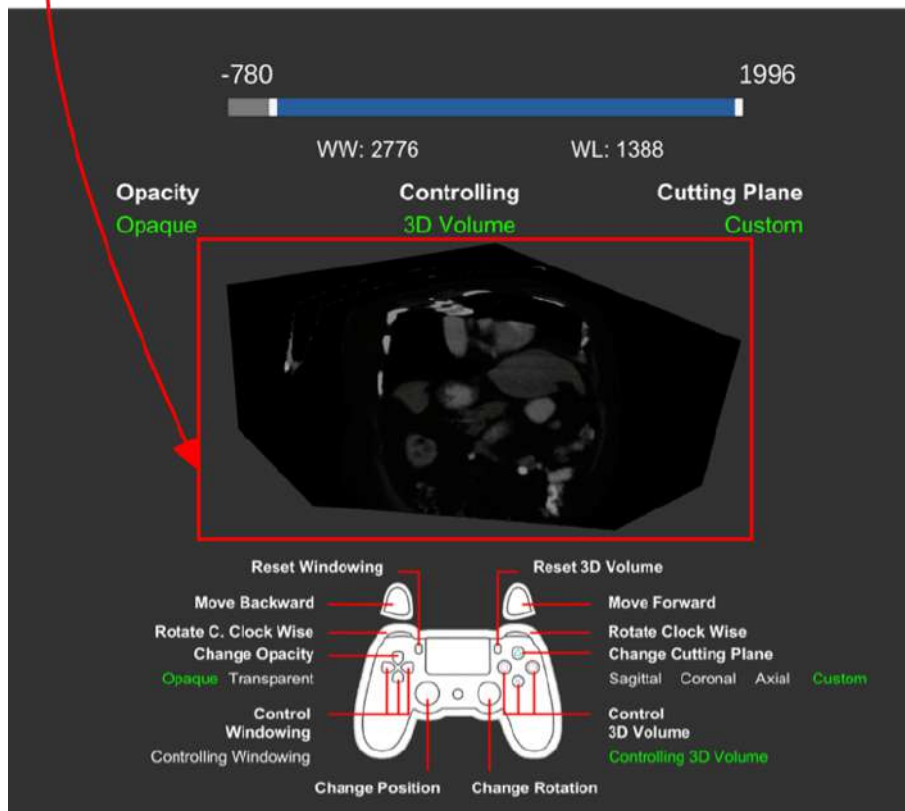
ID	Positive aspects
P1	The new status bar now clearly presents the state of the application
P2	The use of colors to visually connect the functionalities on the controller layout with the status bar made the interface more understandable
P3	The focus on the slice view works as expected
ID	Enhancement opportunities
E1	It should be possible to explore the 3D volume by viewing the slice view in any cutting plane, not only sagittal, coronal and axial

### 5.3.3 Version 3

Considering the feedback we gathered from the version 2, we developed the third version of the application. We implemented the recommendation E1 from Table 9 by allowing users to change the opacity of the 3D model from opaque to transparent, and this change is depicted in Figure 26.



(a)



(b)

Figure 26 – Version 3 changing the opacity of the 3D model between transparent (a) and opaque (b)

Source: The authors

This feature replaces the previous feature of being able to either focus on the slice view or the 3D model. Because of that, it was necessary to perform small changes on the status bar (see Figure 27) and on the controller layout (see Figure 28).



Figure 27 – (a) Version 2 status bar and (b) Version 3 new status bar with the new opacity label

Source: The authors

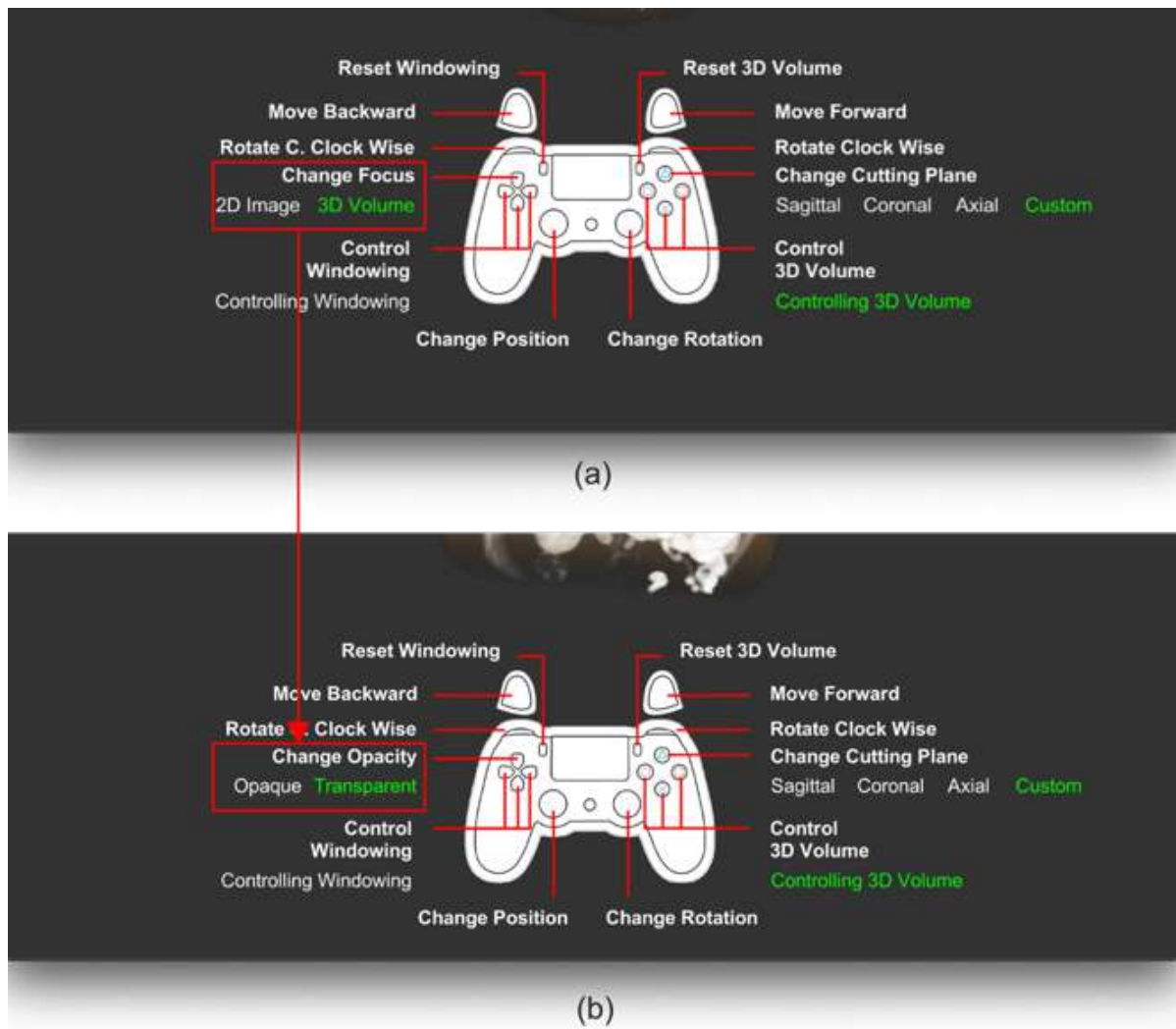


Figure 28 – (a) Version 2 controller layout and (b) Version 3 new controller layout with the new opacity feature

Source: The authors

Once more, we tested the application out with the same expert from the version 1 using an identical set of tasks from Table 7. However, this test was performed over a video conference, and the tester did not have any HMD to experience our approach in VR. We believe that not being able to use our immersive feature is not an issue to test this version because the tester already stated that our VE is fine since version 1. The feedback brought by the professional is summarized in Table 10.

Table 10 – Feedback from Version 3

ID	Positive aspects
P1	The exploration of the 3D volume in any cutting plane works exactly as expected
ID	Enhancement opportunities
E1	The upper part of the interface (windowing bar and status bar) should have their sizes reduced to give the 3D model more free space
E2	The controller should remain the same when windowing and scrolling instead of changing its layout in both features

### 5.3.4 Version 4

With the feedback we collected after testing out the version 3, we created the final version of the application. We started the development of version 4 by implementing the recommendation E1 from Table 10, which ended up giving more space to the 3D model to be viewed and controlled. In fact, as we are working with small sized displays, such as smartphones, this suggestion was an important feature to be done. Figure 29 depicts this modification.

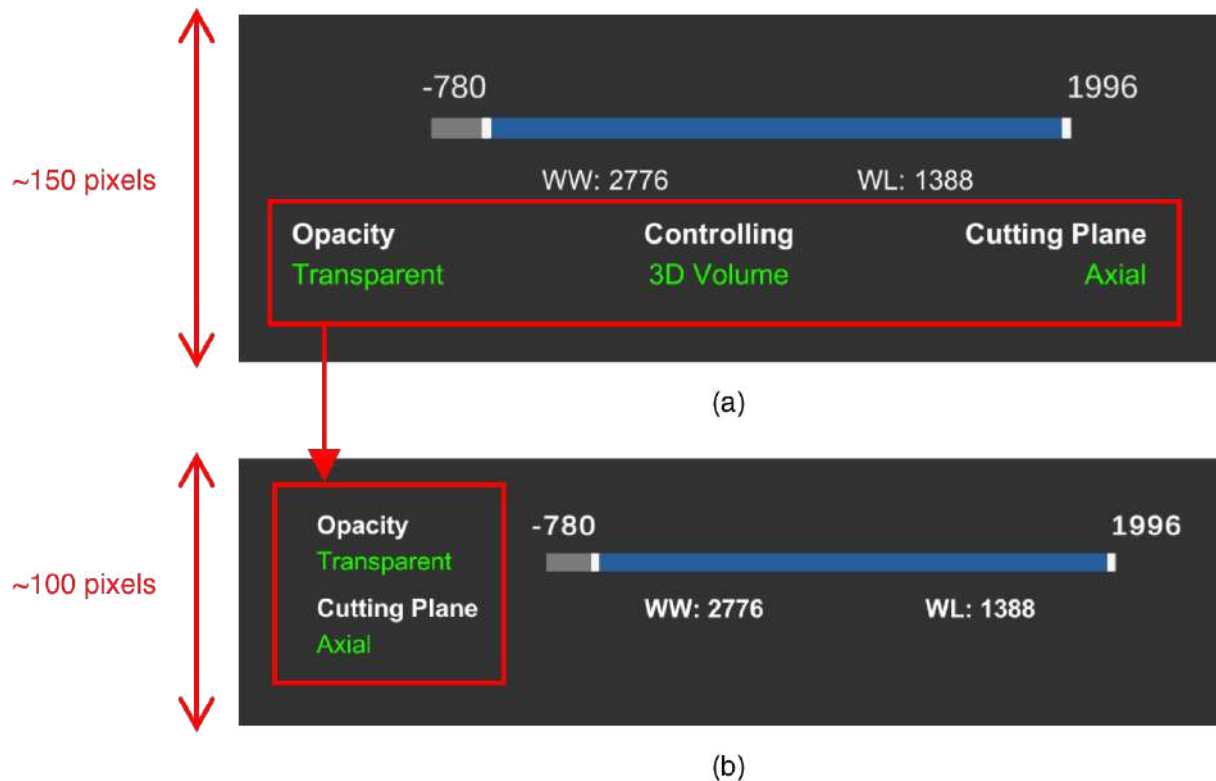
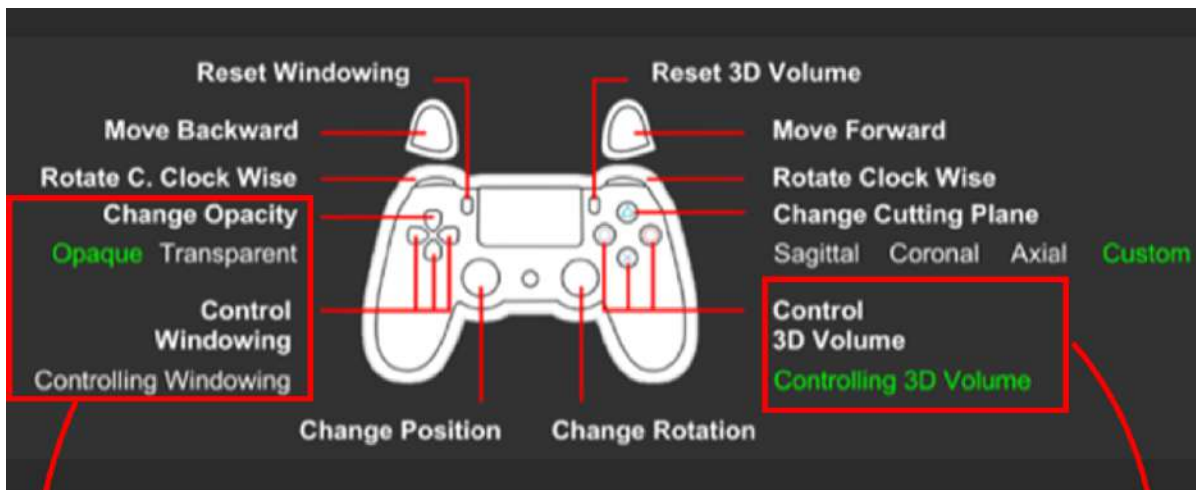


Figure 29 – (a) Version 3 windowing and status bar layout and (b) Version 4 new windowing and status bar layout

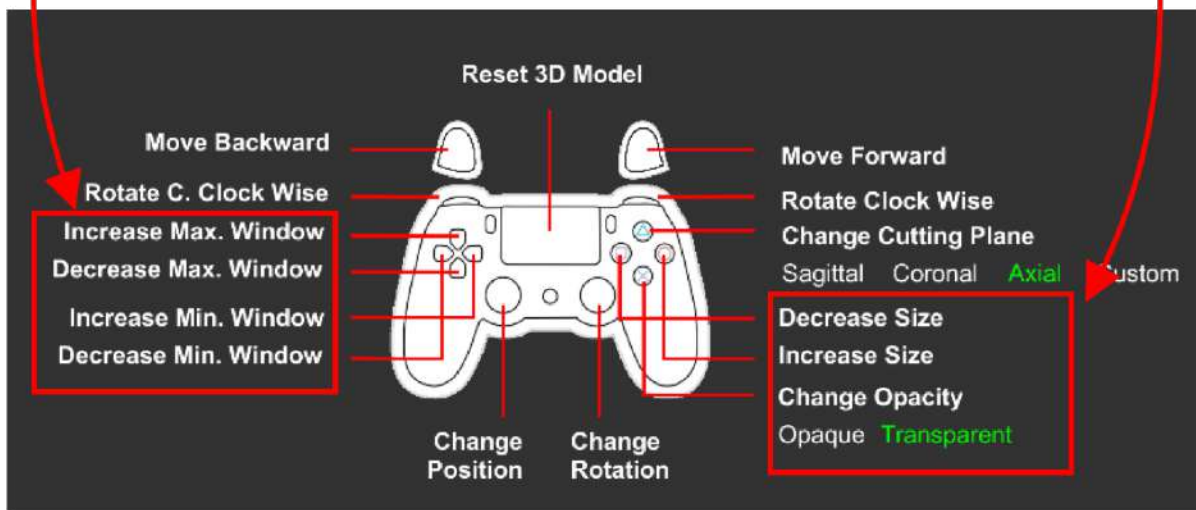
Source: The authors

In addition to that, we also changed the way the interface controller interacts with the application, as suggested by recommendation E2. The application used to have two different states for the controller: one state to control the windowing feature and another one to control the scrolling feature. This behavior would often get our expert confused, which is the reason why recommendation E2 was raised by him/her. Figure 30 frames the new interface compared to the old one.





(a)



(b)

Figure 30 – (a) Version 3 controller layout and (b) Version 4 new controller layout

Source: The authors

After finishing implementing all the recommendation for this version, we were ready to run real tests with real users in order to collect the data to validate our approach in a real case scenario. Figure 31 depicts how the final version of our application looks like.



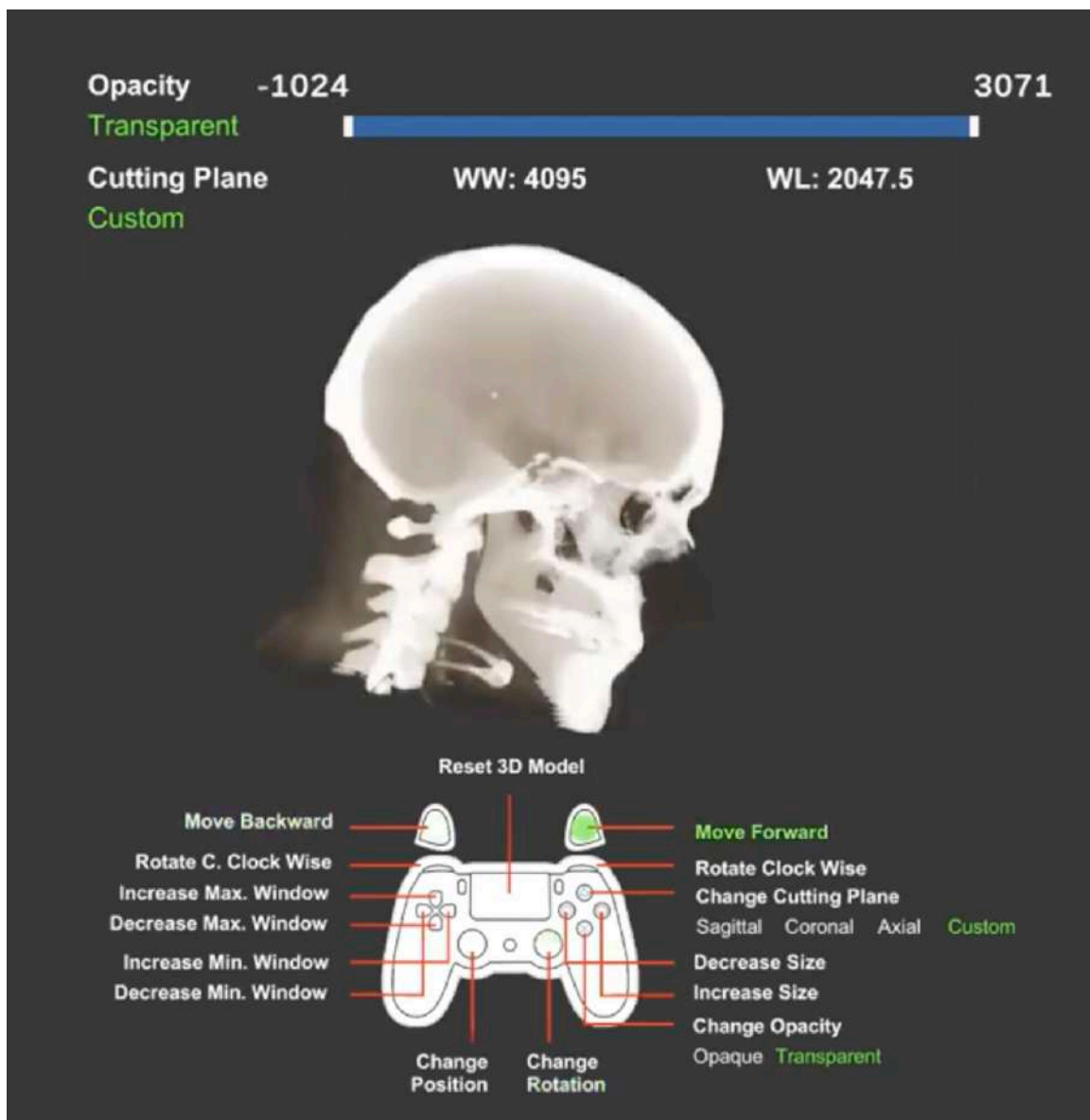


Figure 31 – The final version of our application

Source: The authors

## 6. USER STUDY

In order to evaluate the developed solution regarding its interface and techniques, we conducted a user study with a total of 16 users, from which 11 were radiologists and 5 were medical physicists. Both qualitative and quantitative data were collected at each trial of the test, the first through questionnaires with open fields and the second via System Usability Scale (SUS) (Brooke, 1996) (Subsection 6.3.1), Likert Scale (Hair et al., 2019; Joshi et al., 2015; Likert, 1932) (Subsection 6.3.2) and NASA Task Load Index (NASA-TLX) (Hart, 2006; Hart & Staveland, 1988) (Subsection 6.3.3). We also gathered information regarding their past experiences with videogames and other visual tools, and their perception about our application in real usage scenarios.

By using the SUS questionnaire, we planned to analyze the usability of our application through a set of 10 questions using the SUS scale to score them (Brooke, 1996). In addition to that, we decided to use the Likert Scale to assess the perception of the users regarding the features of our application (see Subsection 5.1). Finally, about NASA-TLX, we had the objective of analyzing learnability, effectiveness, ease of use, user performance, user satisfaction, and the level of confidence of the user.

In order to collect data from the users, it was necessary that they test our application using an HMD, and because the HMD will be shared across all users and tests, it was keenly important to sanitize all devices involved in this study. Besides COVID-19, many other diseases are possible to spread out due to the proximity of the equipment with the eyes, nose, and hands of the users.

To effectively clean up the devices, we started off by wiping down all the surfaces using antibacterial wipes, with particular focus on the areas where users are most likely to touch (Parlock, n.d.). In addition, we also cleaned the gamepad controller, and the smartphone with the same wipes used on the HMD (Parlock, n.d.). The whole sanitization procedure was performed before each new trial.

About the number of testers, we were aware one could argue that 16 people might not be enough to validate the proposed application, which is indeed a threat to validity in our study. However, this work was developed during the COVID-19 pandemic, and our highest priority is to keep all people involved safe. For that reason, we restricted the number of trials we applied in this study.

Finally, it is important to state that we only searched for candidates to test out our application after our study being approved by the ethical committee of our university. An online questionnaire was applied at the end of each session through an online questionnaire<sup>6</sup> built with Qualtrics (Qualtrics, n.d.) and users were allowed to answer the survey from home as they did not have enough time to do it right after the study session.

## 6.1. Participants

Regarding the profile of the participants of our user study, we looked for both medical physicists and radiologists. Although our application aims to solve an issue faced by the doctors from the radiology area, thus making radiologists the most appropriate candidate to evaluate our approach, we decided to add the medical physicists as a suitable option because we believed the mixture of both medical physicists and doctors could lead us to insightful conclusions regarding the proposed interface and techniques of the application.

About the conditions of the subjects, we expected them to have a normal vision (corrected or uncorrected) and a regular range of movement with their hands. These characteristics were necessary because the testers would wear an HMD to visualize the VR and make use of a gamepad controller to interact with the VE.

As a result, we ended up having a total of 16 subjects to test our application, 11 being radiologists and 5 being medical physicist.

## 6.2. Procedure

Upon arrival, the participant was asked to read and sign the Informed Consent form (see Appendix A). We also asked the subject if he/she wanted a digital copy of the document so he/she would be able to read on his/her electronic devices. The reading of the form took around 5 minutes.

After agreeing with the consent form, we explained to the tester what the project was about, the reasons why we created the application, and what it is capable of doing. The explanation took about 5 minutes.

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<sup>6</sup> [https://pucrs.qualtrics.com/jfe/form/SV\\_0GvxDQ6zOCWApRs](https://pucrs.qualtrics.com/jfe/form/SV_0GvxDQ6zOCWApRs)

Next, the subject was introduced to the equipment that he/she would use during the session. This included an HMD with a smartphone attached to it, and a hand-held control device. The HMD we used was a generic one that requires a mobile device to work as its display screen, the mobile phone was an iPhone XR (Apple, n.d.), and the joystick was a Sony PlayStation 4 Controller (Sony, n.d.a). This introduction took around 5 minutes.

Afterwards, the participant was asked to put on the HMD and go through a training session to get familiar with the interactions. He/she was asked to use the features of the application, such as moving, rotating, scrolling, and adjusting contrast and brightness of the 3D model. By completing this training session, the candidate was able to understand how to perform a radiological diagnosis within our application, and this step took around 5 minutes.

After that, the subject was then introduced to the experiment tasks (see Appendix C), which are similar to what they did in the training session. Such sessions occurred between the beginning of the morning and the end of the afternoon, and they took an average of 10 minutes.

Finally, after all tasks were completed, the participant was asked to answer 6 experiment surveys, 3 being of them created specifically for this study and the other 3 based on the literature (see Subsection 6.3).

The first ad-hoc questionnaire aims to collect his/her background experience data regarding videogaming and radiology (Appendix B). The second gathers his/her qualitative assessment of our application (Appendix F). Finally, the third ad-hoc one aims to gather his/her thoughts for future work (Appendix G). The other three surveys were based on the literature and aim to collect his/her general perception of our application (Appendix D, Appendix E and Attachment B). More details about these three literature-based questionnaires in the following subsection.

As most of our testers were busy professional doctors and medical physicists, we also made possible for them to answer the survey when they are home. An email with a link to the questionnaire was individually sent for them. Both qualitative and quantitative data were gathered, and the amount of time necessary to fully answer the survey was 20 minutes.

All the steps detailed are presented in Table 11.

*Table 11 – Steps of the procedure*

Step #	Description	Duration
1	Read and sign Informed Consent Form (see Appendix A)	5 minutes

2	Explain the application to the user	5 minutes
3	Show the equipment to the user	5 minutes
4	Wear the equipment on the user	1 minute
5	Let the user explore the tool	5 minutes
6	Execute the real experiment tasks	10 minutes
7	User answers the questionnaire	20 minutes
8	Researchers clean the equipment	5 minutes

### 6.3. Evaluation instruments

As mentioned previously, we used three traditional evaluation instruments for this study, these being: System Usability Scale (SUS), Functionality Evaluation (Likert Scale), and NASA Task Load Index (NASA-TLX). In the following subsections, we present their definition and explore their details.

#### 6.3.1 System Usability Scale (SUS)

The System Usability Scale (SUS) (Brooke, 1996) is a scale created in 1996 with the objective to quickly and easily assess the usability of a given product or service through a survey. The survey is composed of 10 statements (see Attachment B) that are scored on a 5-point scale of strength of agreement (see Attachment C). Final scores for the SUS can range from 0 to 100, where higher scores indicate better usability (Bangor et al., 2008) (see Figure 32). Those statements are evaluated after the respondent has had an opportunity to use the system being assessed, but before any debriefing or discussion takes place (Brooke, 1996).

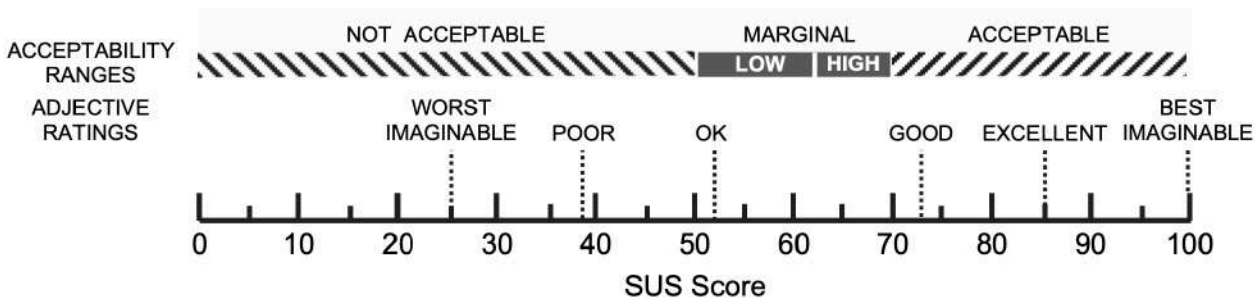


Figure 32 – System Usability Scale (SUS) scores by adjective ratings, and the acceptability of the overall SUS score

Source: Adapted from Bangor et al. (2008)

There are many attributes that make the SUS a good choice for general usability assessment. The first is that the survey is technology agnostic, making it flexible enough to assess a wide range of interface technologies, from interactive voice response systems (IVRs) to more traditional computer interfaces. Second, the survey is relatively quick and

easy to use by both study participants and administrators. Third, the survey provides a single score on a scale that is easily understood by the wide range of people (from project managers to computer programmers) who are typically involved in the development of products and services and who may have little or no experience in human factors and usability. Finally, the survey is nonproprietary, making it a cost-effective tool as well (Bangor et al., 2008).

We collected the SUS data through an online survey, and we exported the final data to a spreadsheet in order to automatically calculate the SUS score.

### 6.3.2 Likert Scale

The Likert Scale is a set of statements (items) offered for a real or hypothetical situation under study in which participants are asked to show their level of agreement (from strongly disagree to strongly agree) with the given statement (items) on a metric scale (see Attachment D) (Joshi et al., 2015). Since its proposition in 1932 (Likert, 1932), the Likert Scale has been used in numerous fields, especially in psychology, sociology, education, business administration, anthropology, among many other fields in the social sciences and humanities (Hair et al., 2019).

We used that scale to assess the main features of our application because it can be easily implemented in surveys as it has been used in many different areas for almost 100 years, and users can quickly answer its questions because the metric scale (strongly disagree to strongly agree) is deeply easy to comprehend (see Attachment D). Moreover, the outcomes from the Likert Scale are very straightforward to interpret in addition to being insightful.

We gathered the Likert Scale data through the same online questionnaire we used to collect the SUS data, and we also put the data in a spreadsheet to better visualize the results.

### 6.3.3 NASA Task Load Index (NASA-TLX)

NASA-TLX is a multi-dimensional scale designed to obtain workload estimates from one or more operators while they are performing a task or immediately afterwards (Hart, 2006). It has been used in a wide variety of fields such as studies regarding visual and audio displays, voice input devices and AR (Hart, 2006).

NASA-TLX consists of six subscales that represent somewhat independent clusters of variables: mental, physical, temporal demands, frustration, effort, and performance (see

Attachment E). The assumption is that some combinations of these dimensions are likely to represent the “workload” experienced by most people performing most tasks. These dimensions correspond to various theories that equate workload with the magnitude of the demands imposed on the operator, physical, mental, and emotional responses to those demands or the ability of the operator to meet those demands (Hart, 2006).

Normally, to obtain the NASA-TLX score, also known as the Weighted Workload Level (WWL) (Hart, 2006), one must apply an extra questionnaire requiring testers to weight the importance of each subscale compared other subscales for the performed activity. That way, tasks that require more physical effort (e.g.: pushing a box) would have the physical subscale weighting more than the mental one.

We decided, however, to use a common modification of the NASA-TLX score (referred as RTLX or Raw TLX) which is obtained when the subscales are averaged without completing the paired comparison survey (Hart, 2006). Some studies (Cox-Fuenzalida, 2007; Nygren, 1991) have shown there is a high correlation between the WWL and the RTLX. Table 12 shows how to interpret the WWL/RTLX. As we are assessing the demanded effort, the lower the values are, the less demanding the task was. Therefore: the lower, the better.

*Table 12 – The Interpretation Score of NASA TLX (Hart & Staveland, 1988)*

<b>Workload (WWL/RTLX)</b>	<b>Value</b>
Low	0-9
Medium	10-29
Somewhat high	30-49
High	50-79
Very high	80-100

#### **6.4. Results and discussion**

As discussed previously, we collected both quantitative and qualitative data from our users at every trial of our approach. We also asked them about their previous experiences with videogames and other imaging tools, and their perception regarding the usage of our application in real scenarios.

In total, 16 users tested out our application and filled up the survey, 11 being radiologists and 5 being medical physicists. When presenting the data from the survey, subjects will be identified with two possible abbreviations: RA for “radiologist” and MP for “medical physicist”. These abbreviations might come with a suffix number in some figures with the objective of

identifying the candidate. The result of the applied survey is presented in the following subsections.

#### 6.4.1 Background questionnaire

The first thing we asked on the background experience questionnaire was how long they had been using VR. Figure 33 depicts the results.

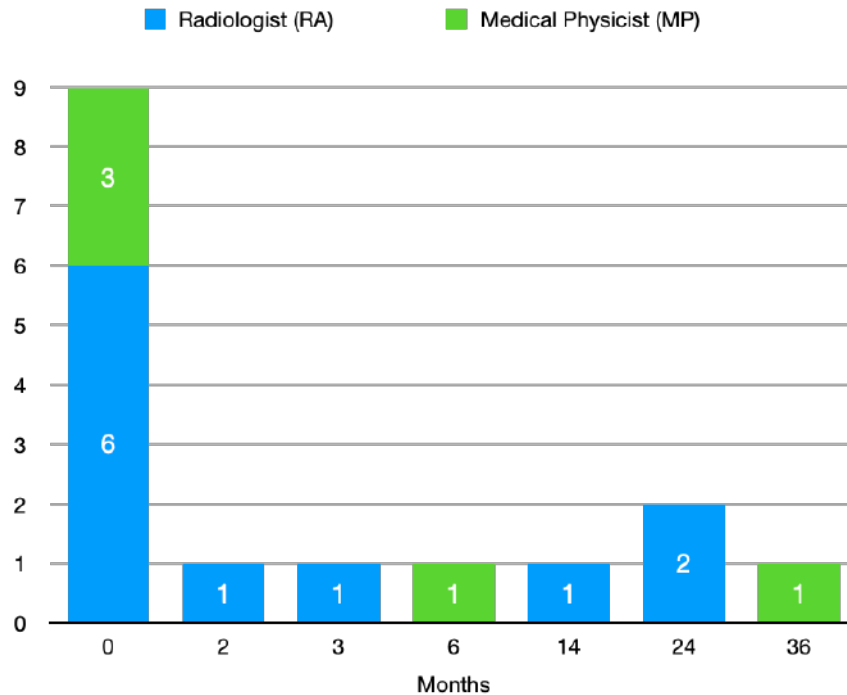


Figure 33 – The number of users by months of experience with VR

Source: The authors

It is possible to see that more than half of the participants (9 out of 16) has no experience with VR. Seven testers reported they have some experience with VR, and among them 3 have less than a year of experience, 1 has a bit more than a year, 2 have two years and 1 has three years. Moreover, the overall distribution of RA and MP over the years of experience is very balanced, with 8 RA and 4 MP having less than one year of experience, and 3 RA and 1 MP having more than one.

Next, we asked them about their experience with videogames. Figure 34 and Figure 35 depicts the answers from each RA and MP, respectively.



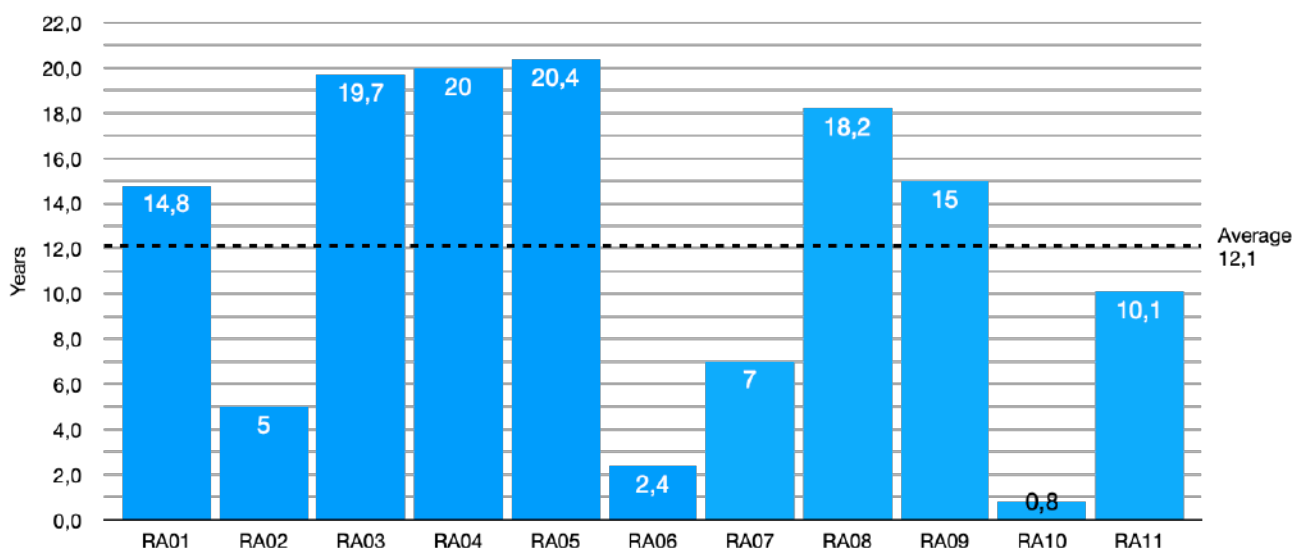


Figure 34 – Radiologists previous experience with videogaming (years)

Source: The authors

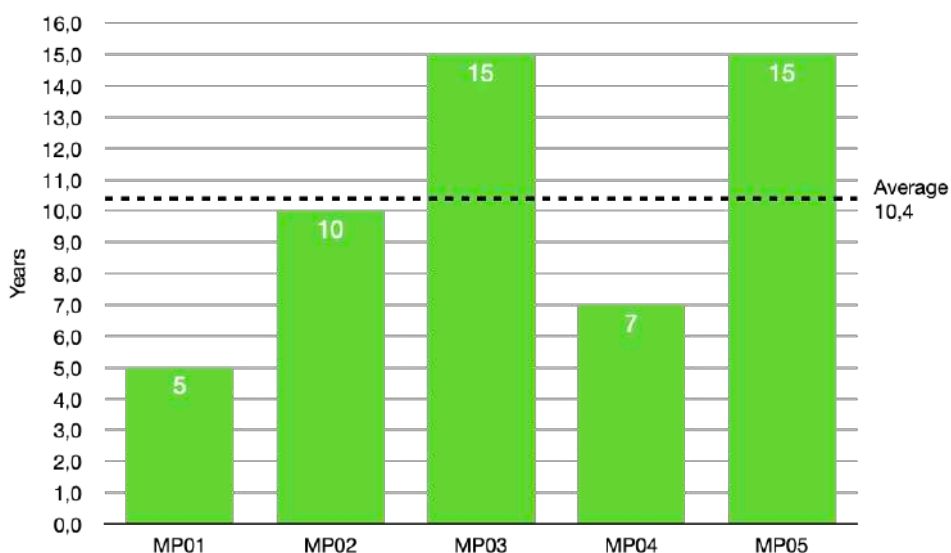


Figure 35 – Medical physicists previous experience with videogaming (years)

Source: The authors

From Figure 34, we can state that 7 doctors out of 11 (63%) have more than 10 years of experience with videogaming, 3 having around 20 years of experience, the biggest one being RA05 with a bit more than 20 years. The physician with the lowest practice with videogaming is RA10, with less than a year of practice. The average number of years is around 12.

Similarly, from Figure 35, 3 MP out of 5 (60%) having around 10 years of practice with videogaming, 2 having 15 years of experience, those 2 being the ones with the largest experience. On the other hand, the MP with the smallest expertise with videogaming is MP01, with five years of practice (4 years more when compared to RA10). The average number of years is around 10, which is similar to the RA average.

We also asked them which other imaging tools they have previously used. Figure 36 depicts the results of that question.

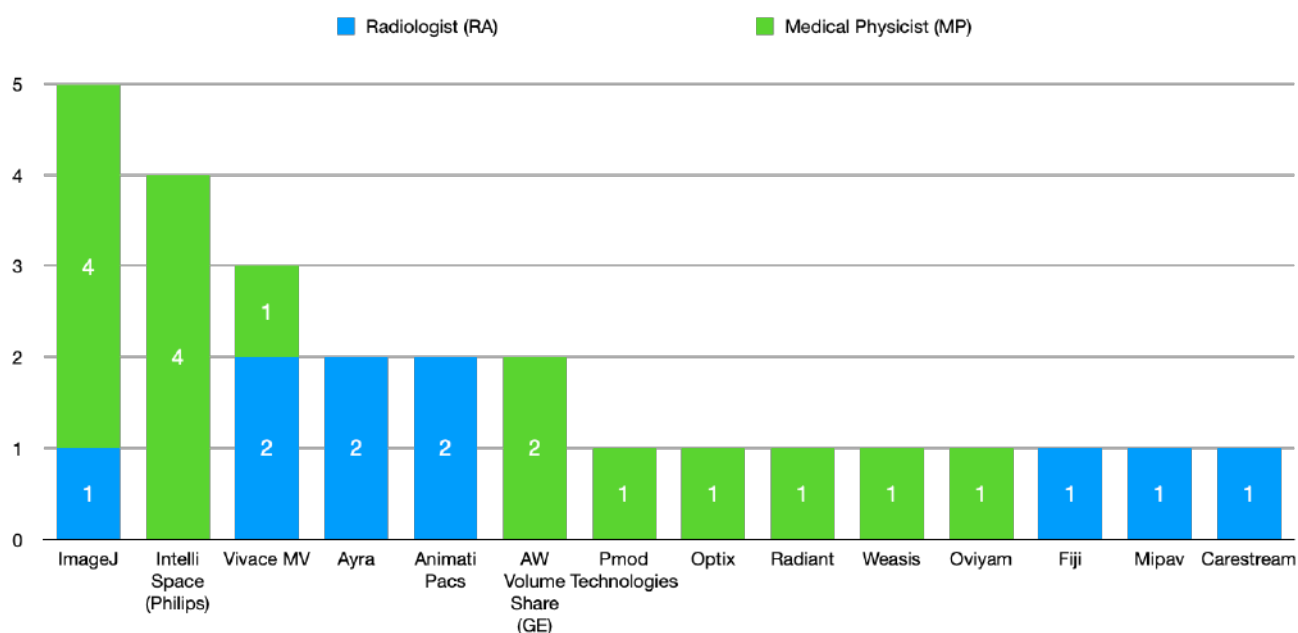


Figure 36 – Tools used by radiologists and medical physicists

Source: The authors

As can be seen, the most adopted tools by RA are Animati Pacs<sup>7</sup>, Vivace MV<sup>8</sup> and Ayra<sup>9</sup>, while the most used ones by MP are IntelliJ<sup>10</sup>, IntelliSpace (Philips)<sup>11</sup> and, again, Vivace MV<sup>8</sup>. Furthermore, it is also possible to observe that that MP explore more imaging software than MR, as 9 different programs are used by MP while 7 are adopted by MR.

Finally, we asked subjects about their experience using other software with similar purposes. Figure 37 and Figure 38 frame the results for both audiences.

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<sup>7</sup> <https://www.animati.com.br/animatipacs/>

<sup>8</sup> <https://mv.com.br/solucao/vivace-mv>

<sup>9</sup> <https://www.aryahospital.com/radiology.php>

<sup>10</sup> <https://www.jetbrains.com/pt-br/idea/>

<sup>11</sup> <https://www.philips.com.br/healthcare/product/HCNOCN180>

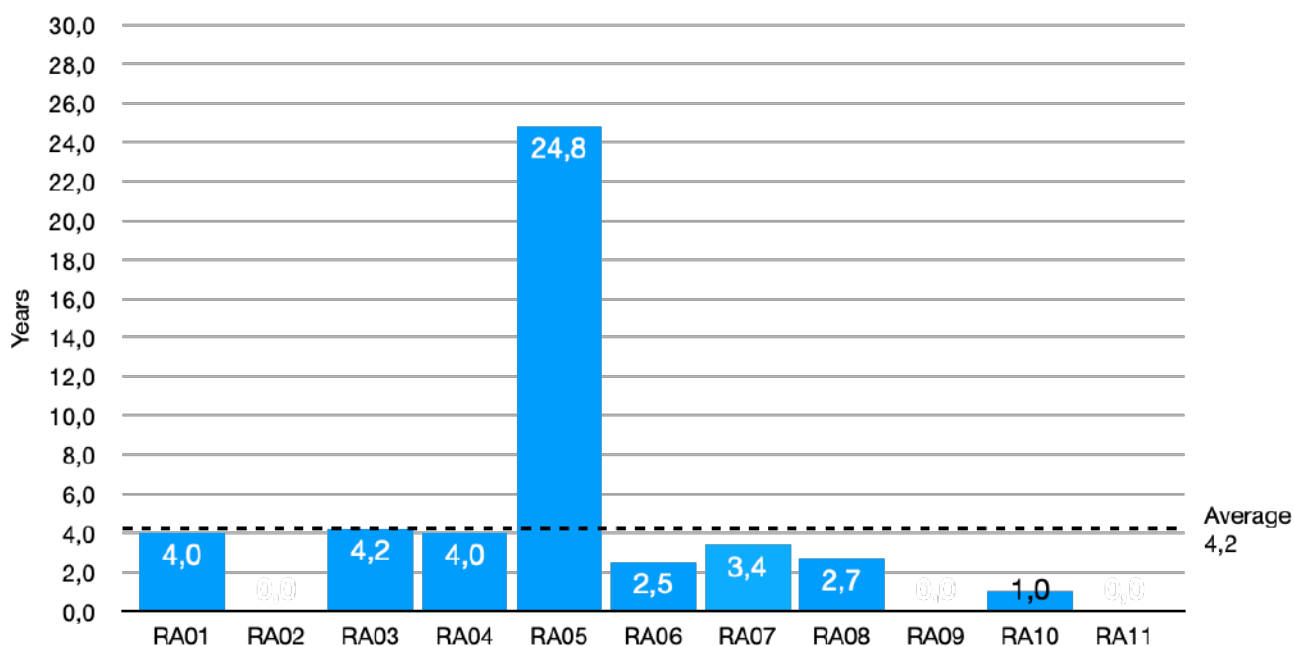


Figure 37 – Radiologists previous experience with other software (years)

Source: The authors

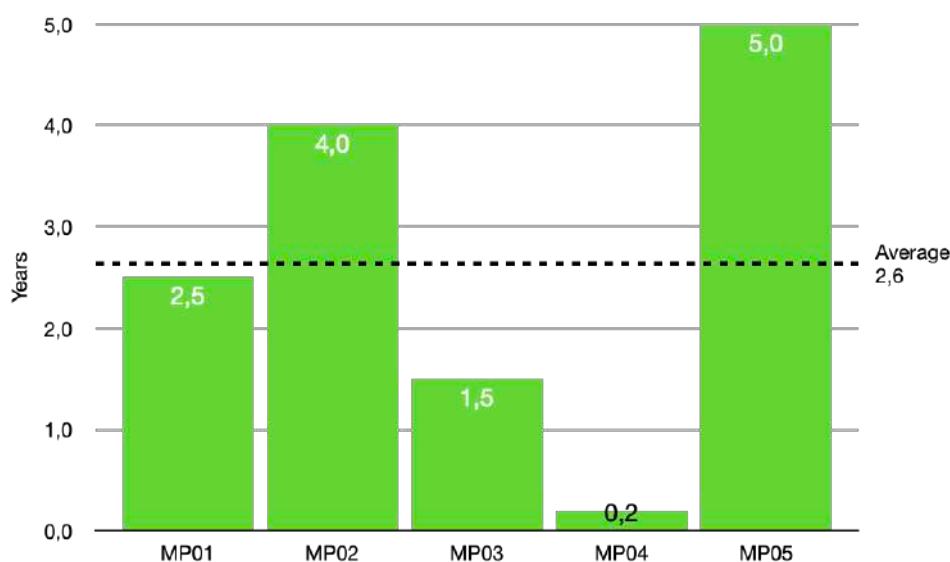


Figure 38 – Medical physicists previous experience with other software (years)

Source: The authors

From Figure 37 we can see 3 radiologists are brand new to the area, with other 7 having less than 4 years of experience. Only one radiologist has a very large experience with almost 25 years of practice.

Withing the MP audience, only one subject is new to the area (with less than 6 months of experience). All other candidates have at least one year of experience, and the maximum experience time is 5 years (MP05).

### 6.4.2 System Usability Scale (SUS)

As detailed in Subsection 6.3.1, we used SUS because it is a quick and easy way to assess the usability of a given product or service through a survey. It possesses 10 questions to be answered using a scale that ranges from 1 (completely disagree) to 5 (completely agree). The results of the SUS survey for RA and MP are presented at Figure 39 and Figure 40.

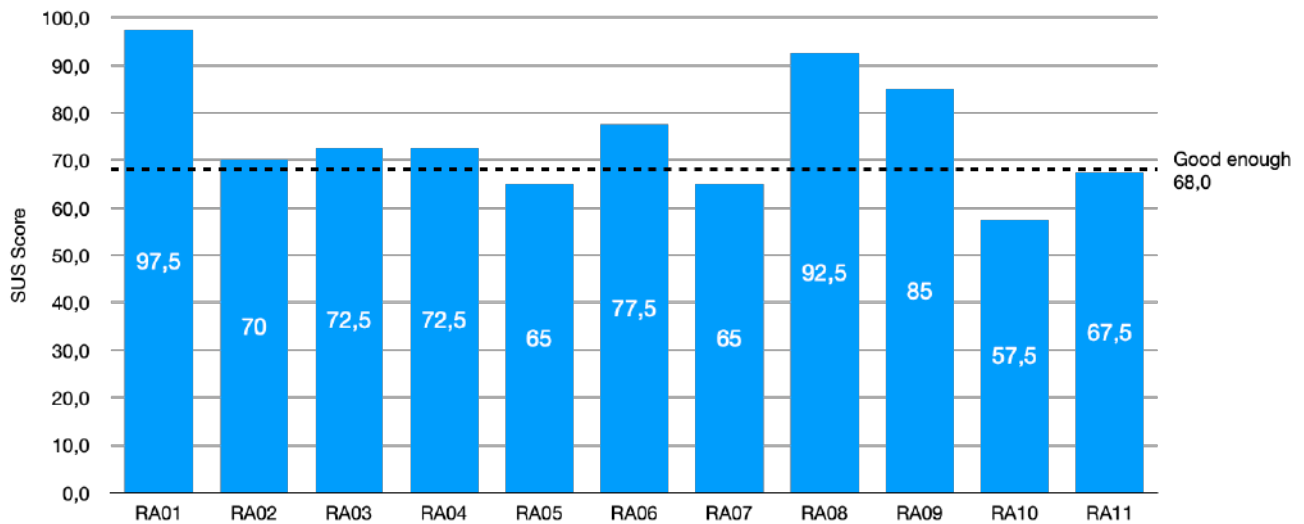


Figure 39 – SUS score by radiologists

Source: The authors

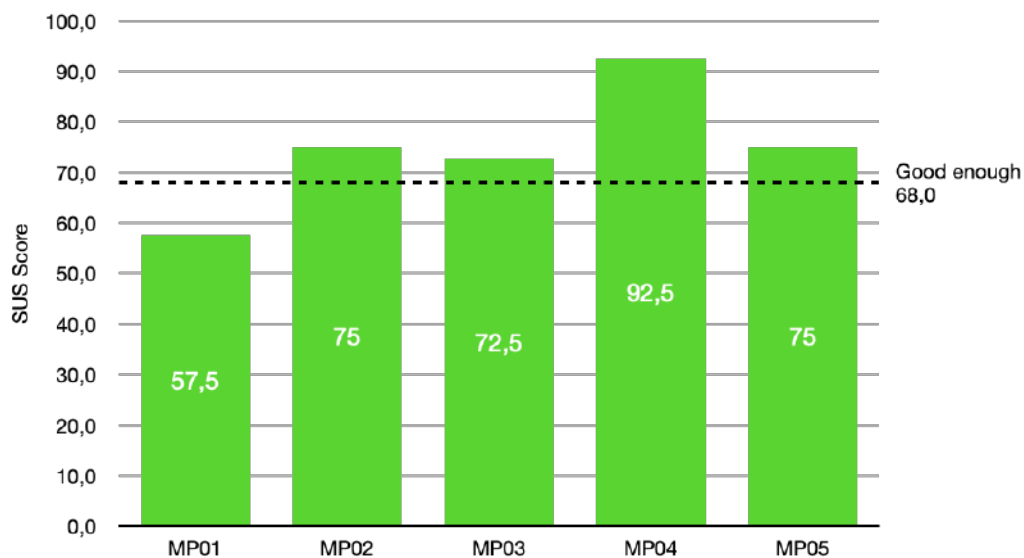


Figure 40 – SUS score by medical physicists

Source: The authors

As depicted in Figure 32, scores below 68 indicate issues with the design that need to be researched and resolved, while scores higher than 68 hint the need for minor improvements to the design and are considered acceptable.

Within the RA group, 7 subjects scored our application with points above 68, which means that 63% of our RA audience considered our application acceptable. Moreover, from

this group of seven radiologists, 3 scored our approach with more than 85, rating our application with an “excellent” grade. If we consider grades around 68 as “good enough”, then we would have 10 subjects (90%) assessing it as good enough. Lastly, the average SUS score inside the RA group is 74.8.

Among subjects of MP group, 4 (80%) assessed our approach with scores superior to 68, a grade that means our application is considered acceptable, as detailed previously. Only one MP gave us a score bigger than 85, and the average SUS score among the MP group is 74.5, which is very similar to the average of the RA team.

#### 6.4.3 Virtual reality and input/output system

On this part of the questionnaire, our goal was to assess the quality of virtual reality reconstruction of the 3D model and the way users interact with it using the gamepad controller, both using Likert Scale and NASA-TLX.

From Figure 41, we can see that only two radiologists rated our virtual environment with scores lower than 4, and only three did the same for the quality of our 3D model. The interaction with the environment through the gamepad controller was classified as “good” for the majority of radiologists, and only one assessed it as “bad”.

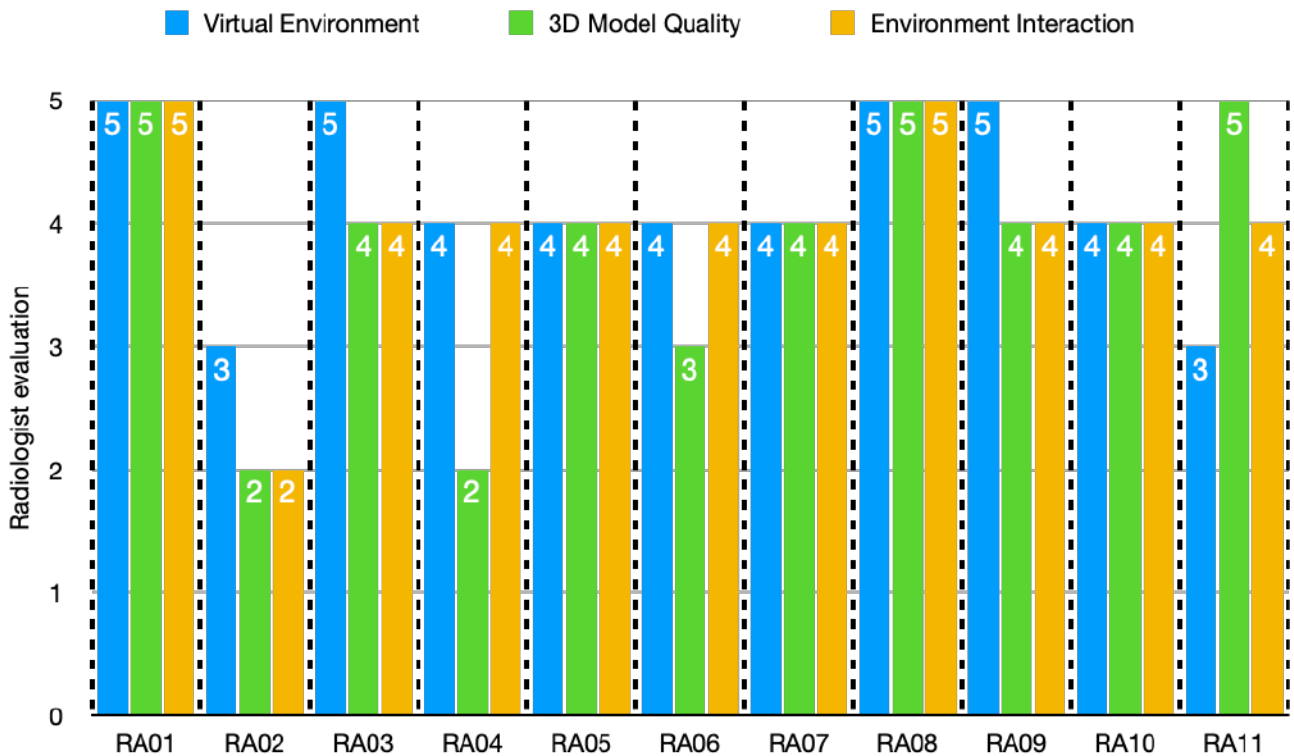


Figure 41 – Radiologists evaluation regarding the features of the virtual reality and its input/output system

Source: The authors

A similar result can be found in Figure 42 with the MP population as 3 of them assessed our 3D model with scores lower than 4 and only one evaluated our gamepad interaction as “bad”. In addition, only one found our virtual environment “bad”.

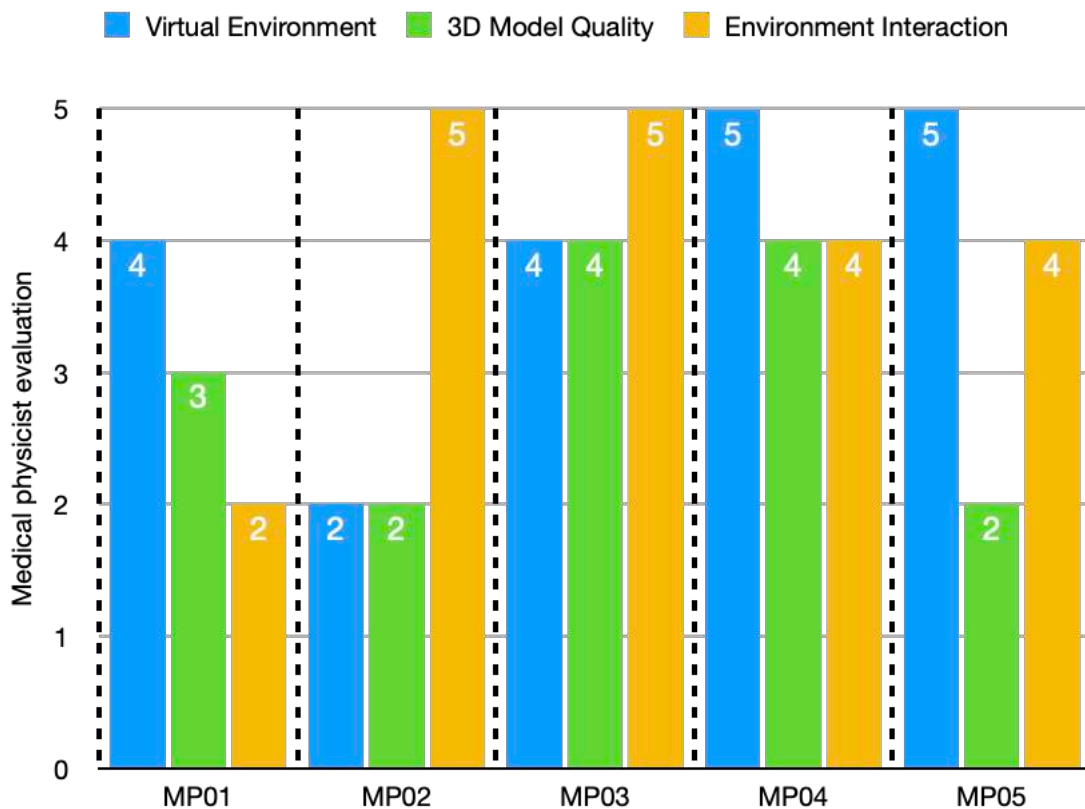


Figure 42 – Medical physicists evaluation regarding the features of the virtual reality and its input/output system

Source: The authors

Figure 43 depicts the NASA-TLX score obtained for both audience (RA and MP). We can see that the mental demand is the one with the highest score for them, being classified as “High”. That result is reasonable as the use of the gamepad controller, though rated as “Good” for the majority of users, represented a barrier during the test process with the subjects.

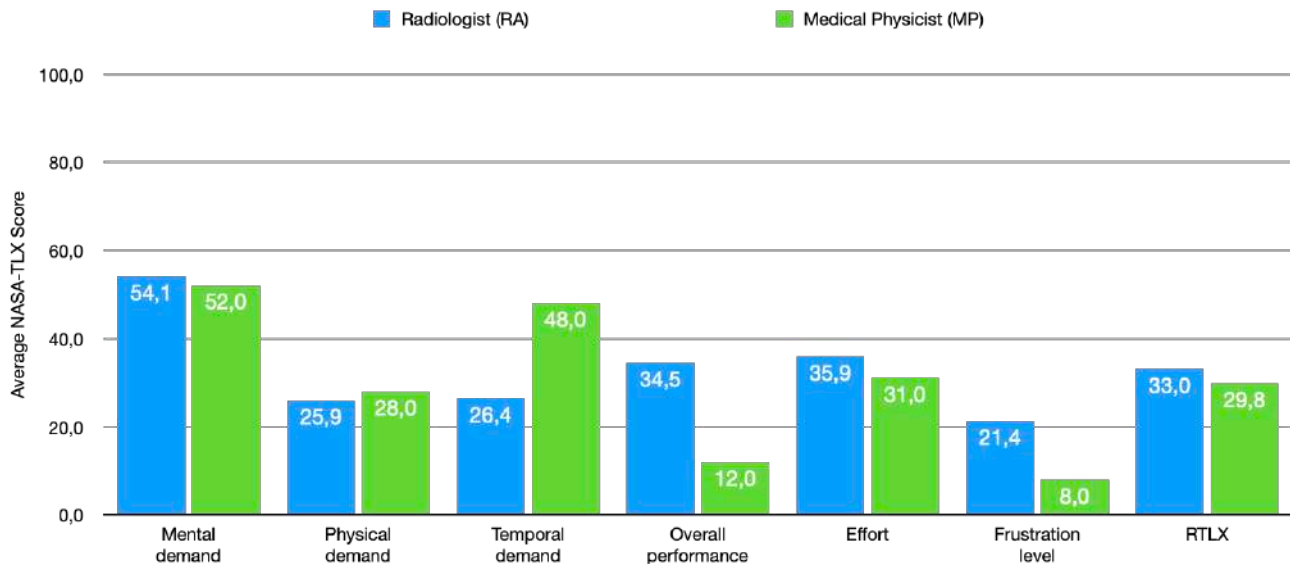


Figure 43 – Average NASA-TLX score by the radiologists and the medical physicists regarding the virtual reality and its input/output system

Source: The authors

Moreover, a difference can be seen within the performance and frustration subscale among the groups. For RA the experience was graded as “Somewhat high” and “Medium” while for MP it was “Medium” and “Low” respectively.

Even with such differences, the RTLX of both groups was very similar: 33 for RA and 29,8 for MP, which yields “Somewhat high” and “Medium” respectively.

#### 6.4.4 Geometric transformations on the 3D model

Another important aspect for us to be assessed was the control of geometric transformations on the 3D model, such as move, reset, rotate and change size. As the 3D model resides inside the VE, being able to interact with the space is fundamental.

Figure 44 depicts the evaluation given by each individual radiologist for every geometric feature we have. From that, we can see that the move, reset and rotate features were all scored as at least “Good”. The change size aspect was also positively assessed by doctors as they all evaluated it as “good” and only one rated it as “Neutral”. In the end, 3 out of 11 RA rated all four features with the maximum grade.

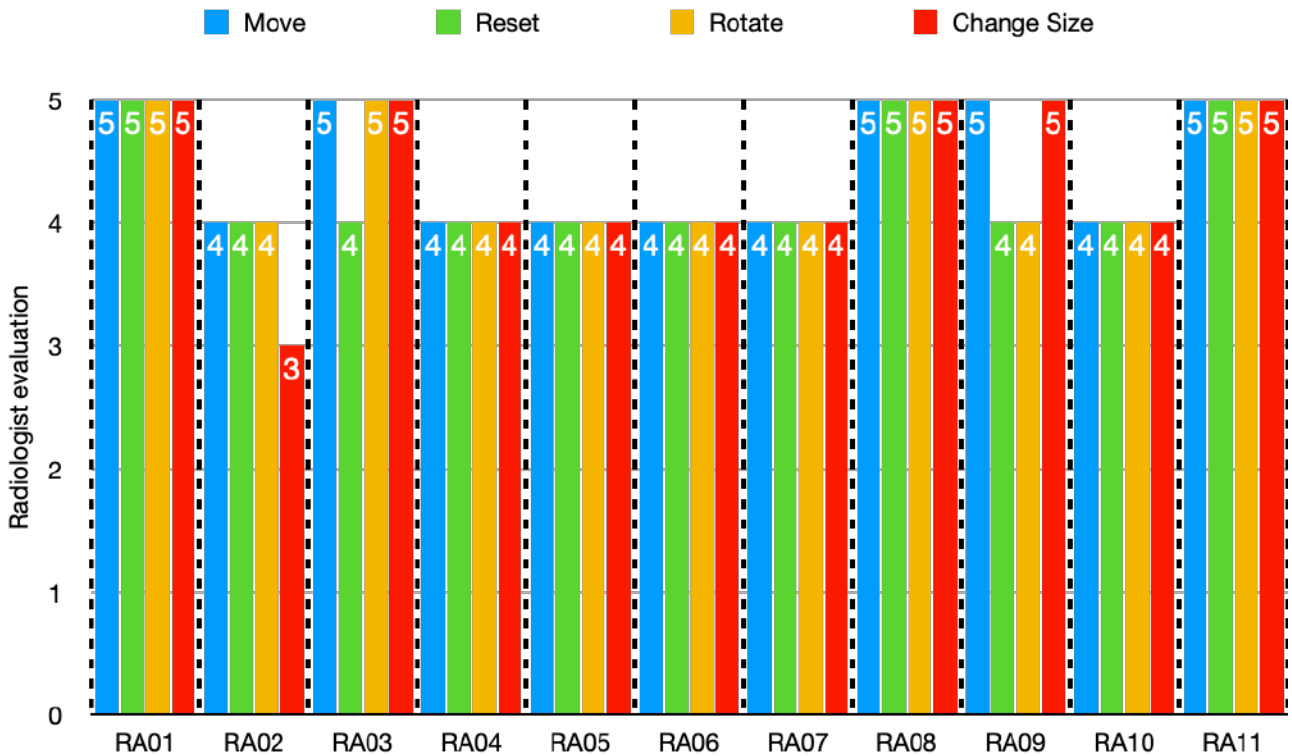


Figure 44 – Radiologists evaluation regarding the geometric transformation features on the 3D model

Source: The authors

Figure 45 frames the same evaluation within the medical physicist audience, but differently from the RA subjects, all MP assessed the four geometric features as at least “Good”. In fact, 2 out of 5 MP maxed out the scores for all evaluated aspects.



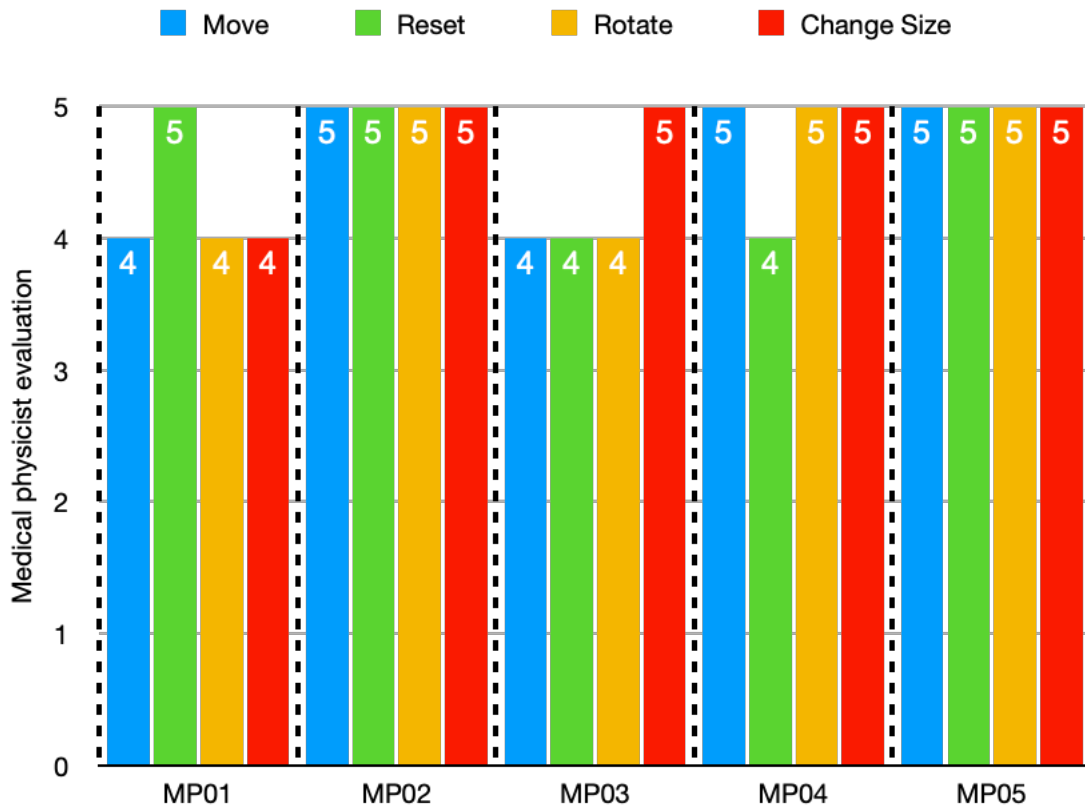


Figure 45 – Medical physicists evaluation regarding the geometric transformation features on the 3D model

Source: The authors

Figure 46 brings the results regarding the NASA-TLX evaluation for the geometric transformations. From that, we can observe that the subscale with the highest scores among the two groups is mental demand, classified as “High” for RA and “Somewhat high” for MP. Furthermore, the subscale with the lowest score is the frustration level, assessed as “Medium” for RA and “Low” for MP.

Finally, the RTLX of both groups presented a significant difference, as for the RA audience it is 35,9 and for the MP it is 22,5, which yields “Somewhat high” and “Medium” respectively.

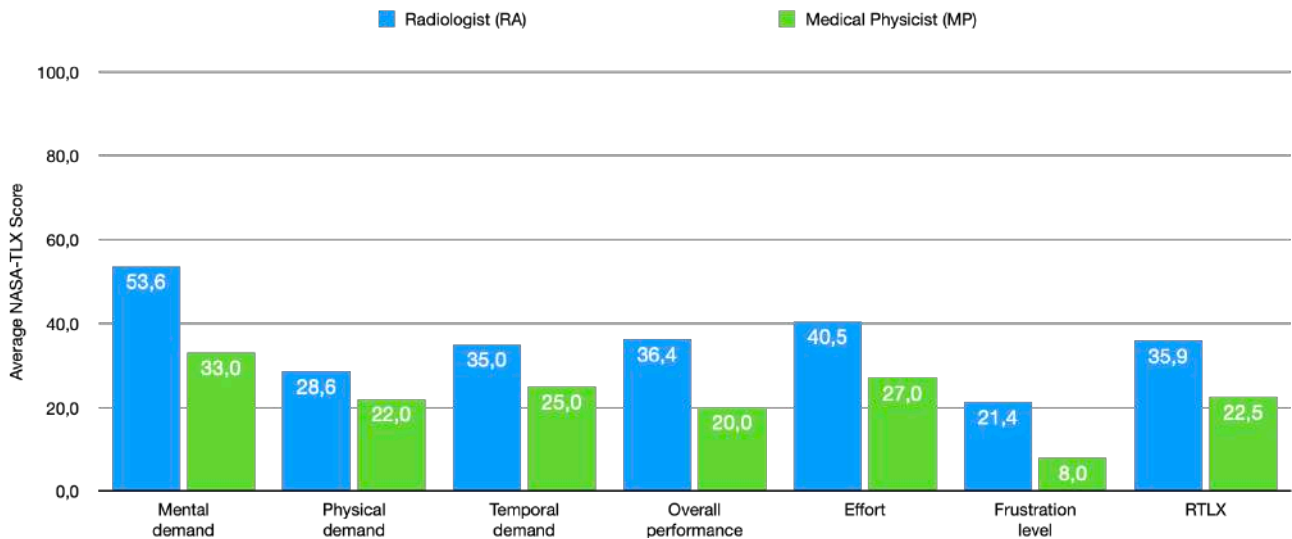


Figure 46 – Average NASA-TLX score by radiologists and medical physicists regarding the geometric transformation features on the 3D model

Source: The authors

#### 6.4.5 Windowing feature

The windowing feature refers to the possibility for testers to change the brightness and contrast of the 3D model in order to find abnormalities. In this subsection, we assessed the windowing adjusting, resetting and opacity change.

As depicted in Figure 47, 6 RA evaluated the windowing adjustment with the highest score (“Very good”), 3 with “Good”, and 2 with scores below “Good”. In addition, regarding the reset windowing, 5 RA gave us the maximum score and 6 rated it as “Good”. Lastly, about changing the opacity of the 3D model, 5 scored it as “Very good”, 5 as “Good” and 1 as “Neutral”.

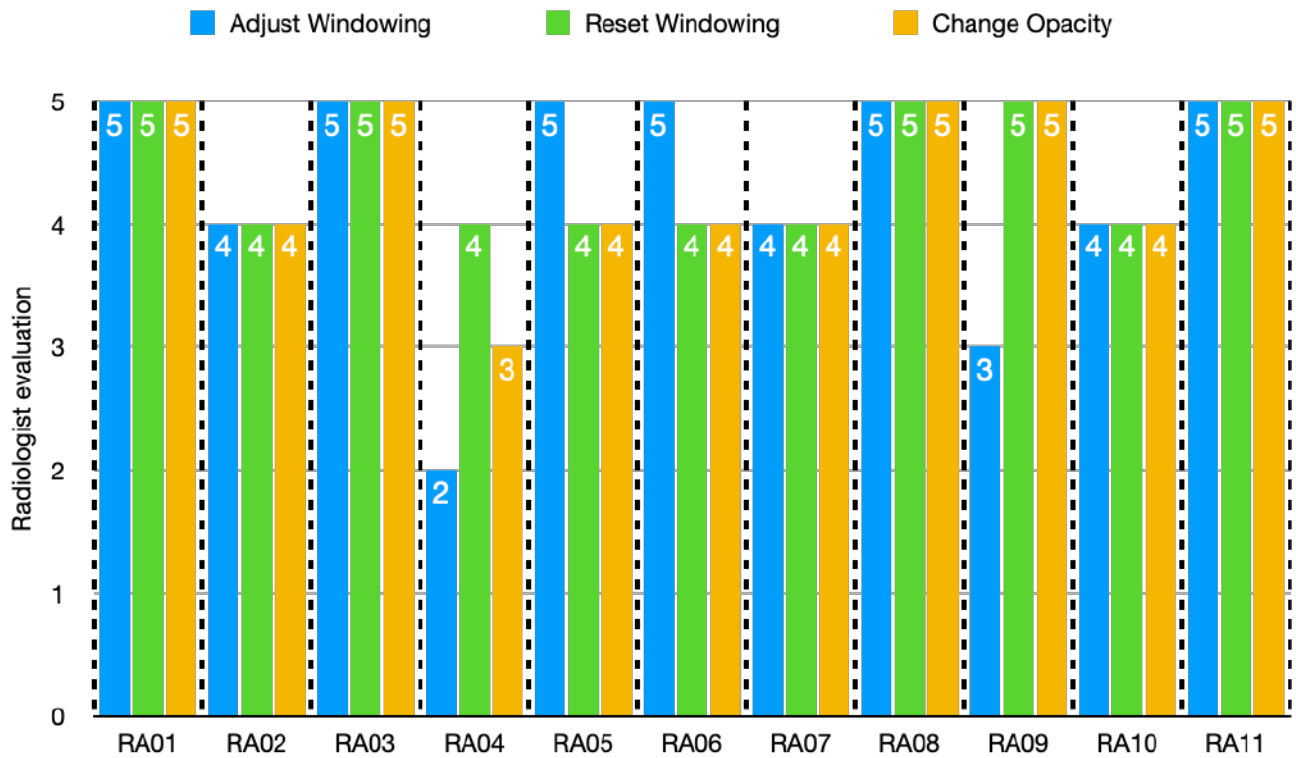


Figure 47 – Radiologists evaluation regarding the windowing features

Source: The authors

With the MP audience, shown in Figure 48, 4 out of 5 scored the adjust windowing as at least “Good”. Only one assessed that feature as “Neutral”. Moreover, all 5 MP graded with a minimum of “Good” the windowing reset feature. Finally, regarding the opacity change, 3 classified a minimum of “Good”, while 2 scored it as “Neutral”.

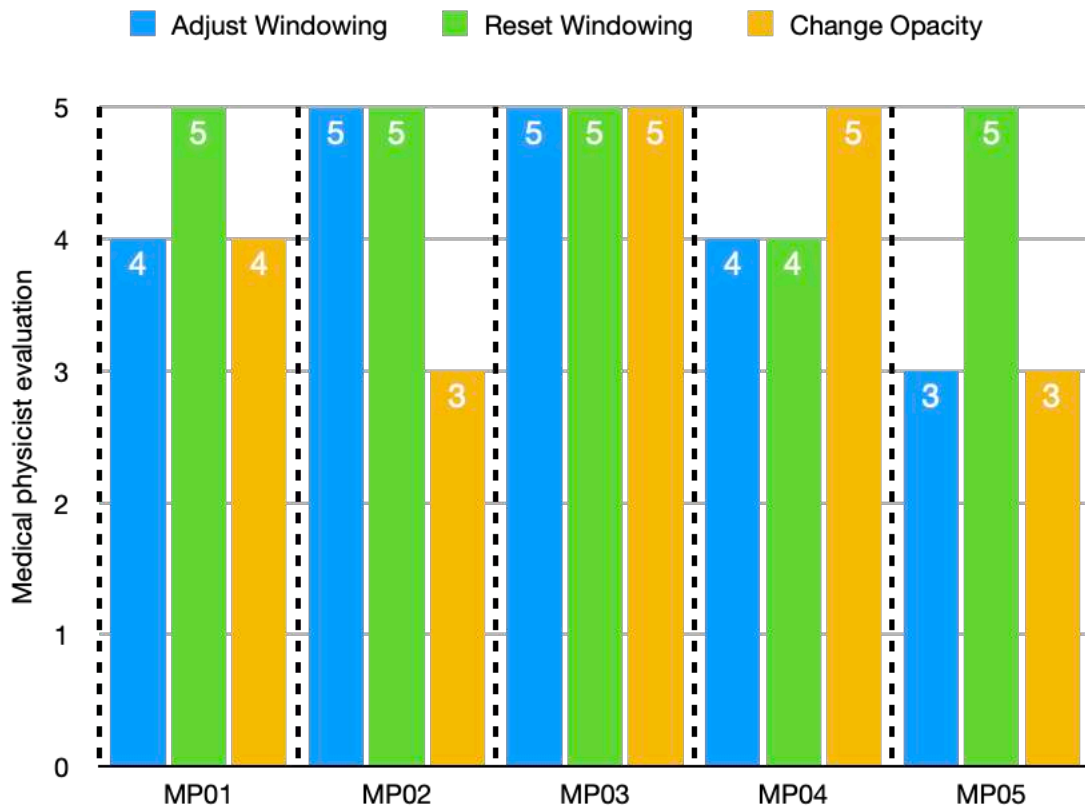


Figure 48 – Medical physicists evaluation regarding the windowing feature

Source: The authors

Figure 49 shows the NASA-TLX scored obtained for both audience groups regarding the windowing feature. The subscale “Overall performance” was the one with the highest values: 42,7 for RA and 45 for MP, both being graded as “Somewhat high”. This result might be due to the testers needed some time to figure out how this feature works, which made them feel they were not making any progress. Surprisingly, even though they were having overall performance issues, the “Effort” and “Frustration level” subscale presented “Medium” and “Low” scores for the MP.

Lastly, the final score for RA and MP was 33,6 and 21,2, which yields “Somewhat high” and “Medium” respectively.

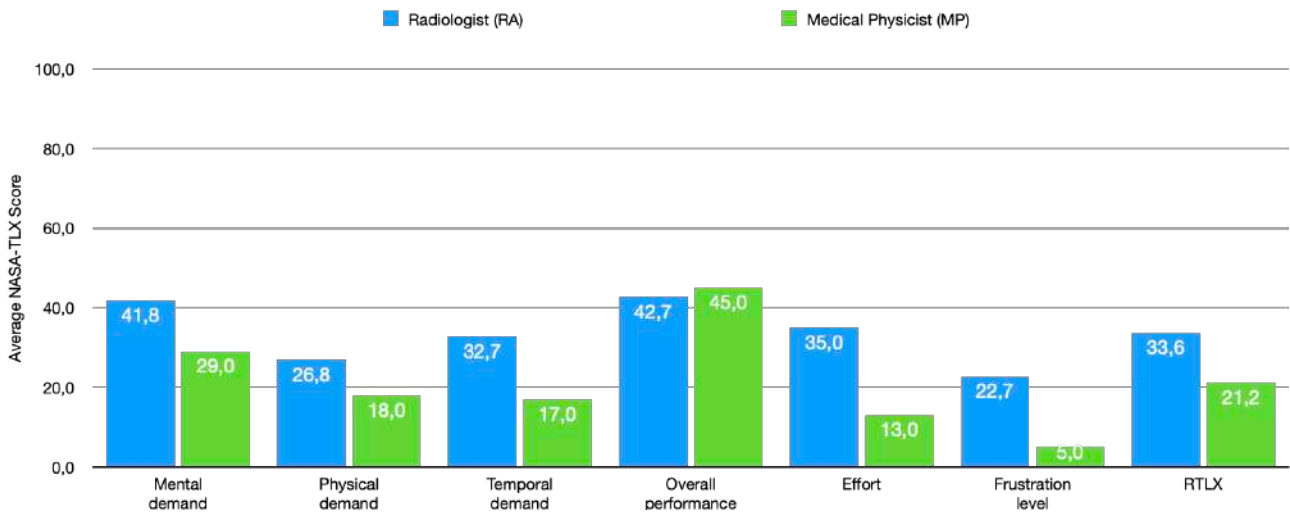


Figure 49 – Average NASA-TLX score by radiologists and medical physicists regarding the windowing features

Source: The authors

### 6.4.6 Scrolling feature

The last aspect to be assessed in our survey was the scrolling feature. Within that feature, users were able to see any slice of the 3D model as well as change the cutting plane of it (axial, coronal, and sagittal).

Regarding the opinion of RA, Figure 50 shows that, except for one RA, all others graded both features as at least “Good”. Indeed, 4 out of 11 maxed out the scores for these features.

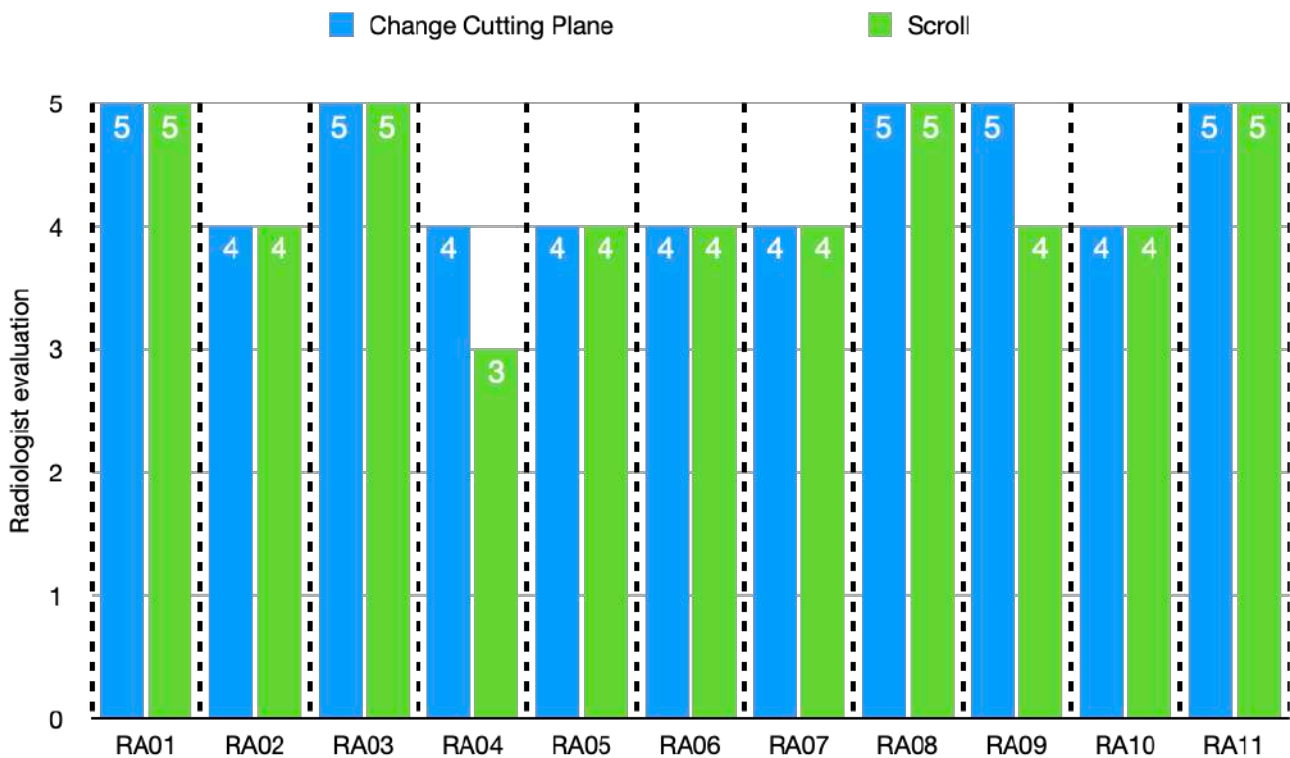


Figure 50 – Radiologists evaluation regarding the scrolling features

Source: The authors

Something similar happened to the MP group as well. From Figure 51, we can see that all testers assessed the two aspects of the scrolling feature as “Good”. In fact, 3 out of 5 MP gave us the maximum grade for both characteristics.

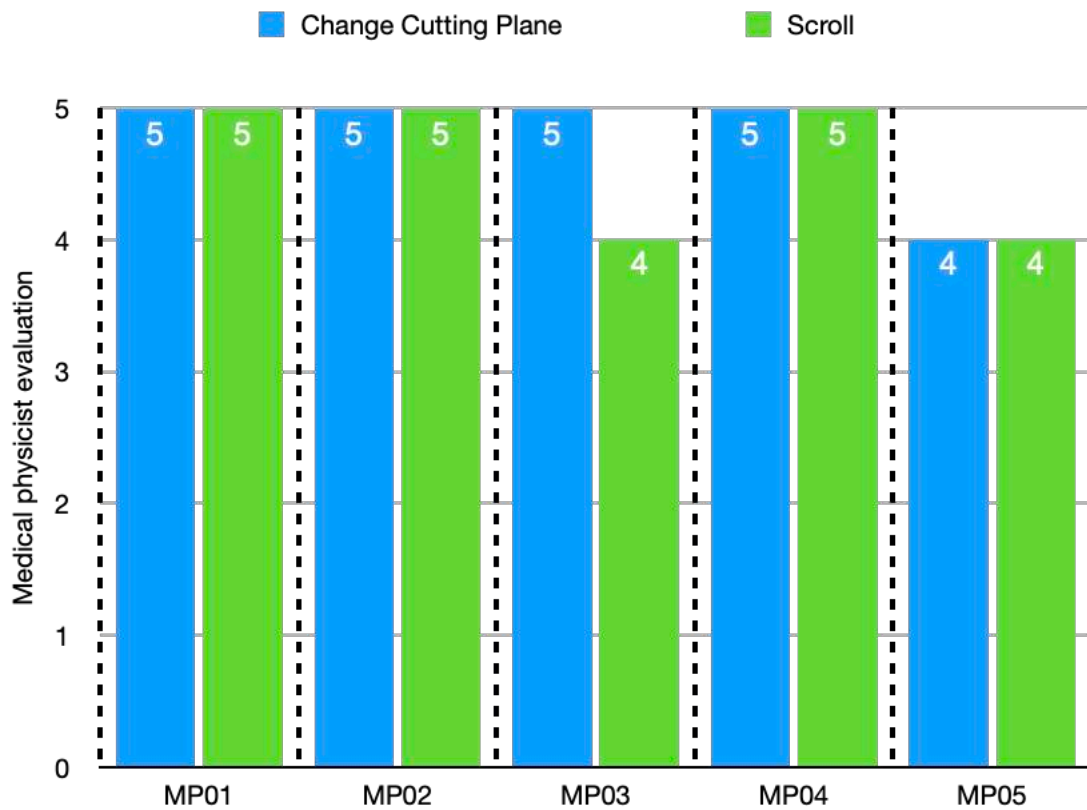


Figure 51 – Medical physicists evaluation regarding the scrolling features

Source: The authors

Regarding the NASA-TLX for this feature (see Figure 52), the “Mental demand” subscale was the one with the highest scores for RA and MP, them being 41,4 (Somewhat high) and 27 (Medium). In addition to that, we have a difference in the “Effort” and “Frustration level” subscale as they both present a gap of more than 15 scores between them.

Finally, the final score for RA and MP was 31,2 and 17,3, which yields “Somewhat high” and “Medium” respectively.

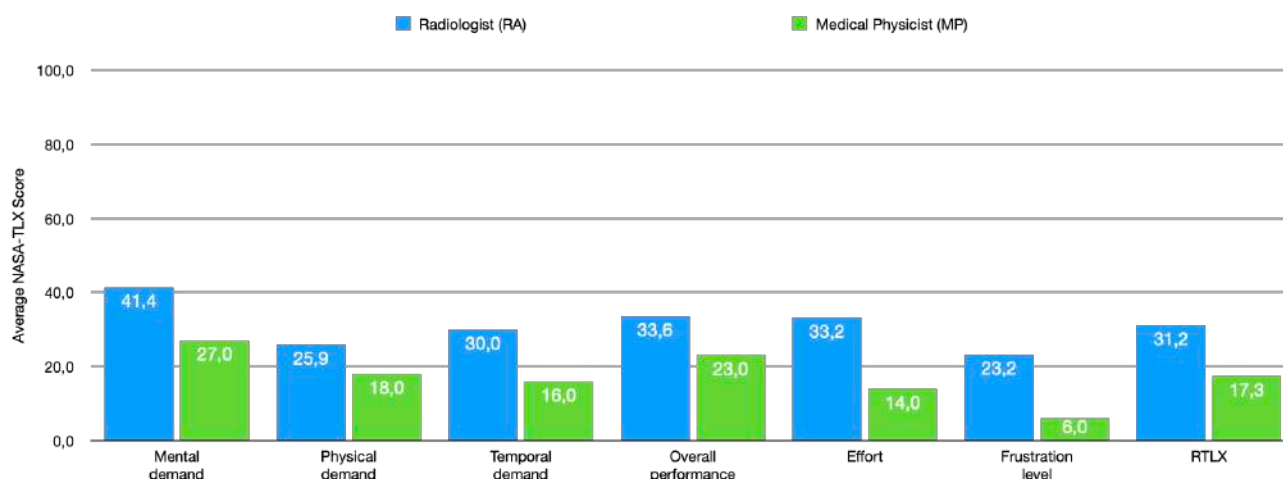


Figure 52 – Average NASA-TLX score by radiologists and medical physicists regarding the scrolling features

Source: The authors

#### 6.4.7 Real usage perception

For the last part of our survey, we decided to gather a general opinion of users regarding our application through open-ended questions. For the sake of organization, we will present the results in separate tables, one table for each posed question, identifying every row with the type of user and their identification (e.g.: RA01, MP02, etc.).

The first question of the real usage perception questionnaire was about the main contribution of the tool for the diagnostic process (see Table 13). From that question, 8 answers showed up, these being: i) freedom to see structures the way users want; ii) see the structure as a 3D model; iii) analyze the structure in a more fun way; iv) one more place (software) to analyze the data; v) bigger immersion; vi) enhance professional performance; vii) learning and viii) focusing.

Table 13 – Answers for the question what is the main contribution of this application to the diagnostic process

Tester	What is the main contribution of this application to the diagnostic process?
MP01	Nothing to declare.
MP02	I believe that the positioning freedom of the individual is the greatest contribution.
MP03	I believe that seeing the structures as a whole (in 3D) and the ease of viewing the exam.
MP04	I believe the tool helps streamline the diagnostic process, making it more fun as well.
MP05	Nothing to declare.
RA01	Nothing to declare.
RA02	It makes it possible to assess images in different environments.
RA03	Possibility of greater immersion.
RA04	I think it's more for illustrative purposes. Unfortunately, there is not enough image resolution and detail for adequate and complete patient assessment.
RA05	To improve the performance of the professional.
RA06	Learning.
RA07	Concentration.
RA08	Nothing to declare.

<b>RA09</b>	I believe that the development of this type of technology that facilitates the evaluation of images more easily is very necessary.
<b>RA10</b>	Nothing to declare.
<b>RA11</b>	Nothing to declare.

In addition to that, one user seemed to disagree about the assumption the application has a contribution to the field. Therefore, one argued that the tool does not present resolution and detail enough to allow a complete analysis of the data, which makes sense as we had to reduce the resolution of the volume data in order to make it possible to be rendered by the smartphone (see Subsection 5.2).

Moreover, we got an improvement suggestion from that question. One said that we should find a way to simplify the number of interactions with the gamepad controller, making easier for users to memorize the instructions. Furthermore, we should also move the windowing bar to the bottom of the screen as it might reduce the effort necessary to read the values.

Afterwards, the second question of our survey asked testers what is the main aspect of our application that facilitates the diagnostic process for users. Table 14 summarizes the answers, and from that we can say that the benefits are: i) the execution of many operations at the same time; ii) zooming in infinitely to see more details; iii) easiness when changing the cutting plane of the 3D model; iv) the use of simple commands to control the application, which ends up making an easy visualization of the data; v) the focus on the image and the environment illumination provided by the VR and vi) the blocking of distractions inside VR.

We also got one improvement suggestion. MP01 suggests that we should find a way to use the volume data in its original resolution, when and if possible. RA01 says that the creation of 3D models from other datasets might also be an enhancement.

*Table 14 – Answers for the question what in the tool facilitates the diagnostic process*

<b>Tester</b>	<b>What in the tool facilitates the diagnostic process?</b>
<b>MP01</b>	Nothing to declare.
<b>MP02</b>	I believe that the possibility of performing several operations (rotate, move, etc.) at the "same" time is a benefit in relation to software on computers, for example. Also, being able to zoom in very closely with the glasses is very good for viewing details.
<b>MP03</b>	The ease of exploring the cuts, the movement of the 3D object.
<b>MP04</b>	I think the controls are simpler and the visualization ends up being easier.
<b>MP05</b>	Mainly the focus on the image, the lighting condition provided by VR.
<b>RA01</b>	Nothing to declare.
<b>RA02</b>	You see the control keys on the screen.
<b>RA03</b>	Ease of commands.
<b>RA04</b>	Not applicable.
<b>RA05</b>	It makes it easy.
<b>RA06</b>	Yes.
<b>RA07</b>	No distractions.
<b>RA08</b>	Nothing to declare.



<b>RA09</b>	This tool facilitates the visualization of images.
<b>RA10</b>	Nothing to declare.
<b>RA11</b>	Nothing to declare.

As for the third question (“What, in the tool, gets in the way of the diagnostic process?”), presented in Table 15, we obtained that the field of view and the reduced quality of the selected dataset (skull and brain) were barriers. In addition to that, it was hard for testers to see the details located on the edges of the screen. The low resolution of the screen also affected negatively the user experience, and one tester reported that the selected gamepad had small buttons.

Moreover, the lack of audio recording or keyboard to write down the diagnosis was also reported as a struggle, in addition to the absence of other necessary tools to diagnose inside the application such as ruler, volume area, density measurement, etc. Finally, the weight of the HMD was also mentioned as a problem.

*Table 15 – Answers for the question what in the application gets in the way of the diagnostic process*

<b>Tester</b>	<b>What, in the tool, gets in the way of the diagnostic process?</b>
<b>MP01</b>	Nothing to declare.
<b>MP02</b>	I believe the field of view of the eyeglasses affected my experience. Also, the images the used anatomical region did not have high quality of detail, so it was not possible to visualize minor aspects. I think that the use contrast exam images would be more interesting for the evaluation (as they are naturally low resolution). In the case of brain imaging, it was not possible to differentiate several boundaries such as white/grey matter and other cortical regions.
<b>MP03</b>	The edges were not clearly visible inside the HMD and I believe this can get in the way.
<b>MP04</b>	The resolution. I'm not sure if wearing the HMD for hours wouldn't end up making this process a little tiring.
<b>MP05</b>	At this moment, only the quality of the image and the text that is on the screen.
<b>RA01</b>	Nothing to declare.
<b>RA02</b>	The used gamepad controller sometimes confuses by the small size of the keys and proximity of the keys.
<b>RA03</b>	It lacks a keyboard to type the report out. It is a different software (doctors would have to change their routines).
<b>RA04</b>	There is no voice or keyboard function to write the report referring to the exam under study. There are not all the necessary tools for the diagnosis and detailing of findings (such as: ruler, area and volume measurements, simultaneous multiparametric reproduction, density measurement, among other functions).
<b>RA05</b>	No. It is a very easy to use tool.
<b>RA06</b>	Nothing to declare.
<b>RA07</b>	The weight of the HMD.
<b>RA08</b>	Nothing to declare.
<b>RA09</b>	Nothing to declare.
<b>RA10</b>	Nothing to declare.
<b>RA11</b>	Nothing to declare.

*Table 16 – Answers for the question if testers would use an application like this in the diagnostic process, why and in which way*

<b>Tester</b>	<b>Would you use a tool like this in the diagnostic process? Why? In which way?</b>
<b>MP01</b>	Nothing to declare.
<b>MP02</b>	Certainly. The ease of performing multiple operations at the same time greatly helps the visualization of multiple anatomical structures. In addition to that, the virtual environment brings a different (comfortable) “vibe” to a task.
<b>MP03</b>	I believe so, but as a support tool.

<b>MP04</b>	I think so. It makes the task more interesting and fun. Not sure if I would completely switch to this tool, but having this option sure sounds good!
<b>MP05</b>	Yup. It looks promising for the features and the focus on the image.
<b>RA01</b>	Nothing to declare.
<b>RA02</b>	I would use it, but directly on the cell phone
<b>RA03</b>	Yes, because I believe the control adds more speed when visualizing and performing changes on the image.
<b>RA04</b>	I wouldn't use it the way it is today, especially because of the image resolution.
<b>RA05</b>	I would use it. That way, I can make reports from either my phone or my lab computer.
<b>RA06</b>	Yes, for learning.
<b>RA07</b>	Yes, if the HMD was less heavy and more comfortable.
<b>RA08</b>	Nothing to declare.
<b>RA09</b>	It could be used in the routine of a radiologist to speed up reports, with better visualization. More accurate diagnoses would be achieved.
<b>RA10</b>	Nothing to declare.
<b>RA11</b>	Nothing to declare.

#### 6.4.8 Future work

The future work section of our survey was the smallest part of it, being composed of only two questions, these being: i) “What changes would you do in our application?” and ii) “Are there any other observation regarding this study you would like to add?”. Table 17 and Table 18 summarize the answers we obtained.

Regarding the first question of the “Future work” section, most users answered they did not have any change to suggest for the application. Nevertheless, we still gathered some recommendations. MP01 says that moving the windowing bar from the top to the bottom might reduce the current discomfort when trying to visualize the values of the windowing. Moreover, MP01, MP05 and RA09 recommended that we should find a way to use the original resolution of the dataset instead of the reduced one. That way, images would have more image quality.

Still about the suggested changes, one tester said we should adapt our program to support the adjustment of the windowing in two dimensions. We only allow one dimension at a time currently. MP04 suggested we should adapt our controller to be more similar to the ones inside traditional diagnostic software. Furthermore, RA04 said we should allow other users to add their own image dataset rather than always use the same one (the crane). The person who gave us that suggestion had in mind the tested software might not be complete yet.

For the second question regarding future work, again most testers stated they did not have any observation for this study. Even so, we obtained insightful considerations. MP02 believes that our tool contributes a lot to the diagnostic area, and that it should be continuously upgraded to facilitate the diagnose process more and more. MP03 said that

because he/she has astigmatism, he/she makes more effort to visualize the content, thus possibly causing headaches with prolonged use. Finally, MP05 believes the tool is a great initial tool to explore the VR in the medicine area.

*Table 17 – Answers for the question what changes testers would do in our application*

Tester	What changes would you do in our application?
MP01	Moving the windowing bar to the inferior area of the screen might reduce the effort to read the values. Finding a way to use the original images without reducing its resolution if the device supports it.
MP02	Nothing to declare.
MP03	Nothing to declare.
MP04	I think the input controllers, although easy, could be adjusted to look more similar to the current used software.
MP05	Enhance the quality of the presented image. Optimize the windowing feature to work with the two dimensions (suggestion: use the analogical button)
RA01	I cannot think of a change to suggest. The application works well both from a practical and an aesthetic point of view.
RA02	Nothing to declare.
RA03	Nothing to declare.
RA04	I understand that this study is a proof of concept, but I imagine that, in the future, a challenge to be considered is the issue of creating the 3D model from different images.
RA05	Nothing to declare.
RA06	Nothing to declare.
RA07	Nothing to declare.
RA08	Nothing to declare.
RA09	I think it could have better image quality.
RA10	Nothing to declare.
RA11	Nothing to declare.

*Table 18 – Answers for the question if testers would like to report any observation about the study*

Tester	Are there any other observation regarding this study you would like to add?
MP01	Nothing to declare.
MP02	I think the idea is sensational and contributes a lot to the advancement in the area of diagnostic imaging. I believe that the tool should be continually improved to facilitate the process.
MP03	I believe that because I have astigmatism, I had a greater effort to visualize things inside the VE. Perhaps with continued use with this condition it can lead to headaches for example.
MP04	Nothing to declare.
MP05	I believe it is an excellent tool for starting an exploration of virtual reality applied to diagnostic medicine.
RA01	Nothing to declare.
RA02	Nothing to declare.
RA03	Nothing to declare.
RA04	Not applicable.
RA05	No.
RA06	No.
RA07	No.
RA08	Nothing to declare.
RA09	I hope you can successfully develop this project.
RA10	Nothing to declare.
RA11	Nothing to declare.

## 6.5. Limitations

Although the steps to conduct this study, ranging from the design of the tool, validation with real users and testing with subjects, were taken careful and thoughtfully, there are still some threats to the validity.

The first threat is the limited number of subjects we had in our survey (16). There were a couple of reasons for that number. First, the users needed to be either a doctor or a medical physicist. The former is easy to find, but they are rarely available to be interrupted for an academic study. The latter is more uncommon to find, and they also have a very busy schedule as some of them work close to doctors.

Second, the study was conducted while the COVID-19 pandemic was still going on. Going to hospitals to find doctors was not only difficult (as they were all busy doing other tasks), but also dangerous for the researchers as we were being exposed to many diseases or to many people who often deal with contagious diseases.

Finally, we do not have unlimited time to perform this study, which limits the number of interactions we can do with doctors, collecting feedback and improving more and more our application.

## 7. CONCLUSION AND FINAL REMARKS

In this work **we evaluated an immersive and stereoscopic visualization approach of medical images** that is able to perform the two most common techniques applied in the radiology area: windowing and scrolling.

To do so, we first performed a literature review and found out that most studies about VR approaches and applications rely on traditional desktop computers as their source of computational power. Only a few research explore the use of smartphones as their processing unit. Therefore, we perceived that as a gap in the literature to explore.

In order to fill up this gap, we developed an immersive VR application that runs on smartphones and, following the development of the application, we test it out with two types of professionals from the field (radiologists and medical physicists) and applied a questionnaire with them.

From the data we collected in our questionnaire during the tests and considering the NASA-TLX results, we realized that radiologists struggled more than medical physicists in all features evaluated. This result was surprising because the RA audience has more years of experience with videogames and other visualization tools than the MP audience, so we expected RAs to better handle the application compared to MPs. Moreover, the average NASA-TLX scores for both audiences were 33,4 for RA and 22,7 for MP, which means the application demands a general “Somewhat high” and “Medium” effort respectively.

Still regarding NASA-TLX and its subscales, we noticed that the “mental demand” in all NASA-TLX charts was the one with the highest score in both audiences (RA and MP). Even though both groups have years of experience with other visualization software and videogames, the learning curve to work with our application was apparently high. However, even with this mental demand barrier, most testers scored our application as “good enough” to use.

In addition to that, the “physical demand” was the subscale with the lowest scores in all assessed features. This might be due to the fact the only effort professionals have to make when using our tool is to tap the buttons of a gamepad controller. As we planned our controllers to be similar to the commands we find in videogames and most of our testers had experience with videogaming, dealing with the input system (gamepad) did not seem a problem.

Furthermore, the “frustration level” from both audiences was always less than 25 points (and in the MP group it is always below 10 scores). This low score might explain the positive feedback we obtained in the “Real usage” and “Future work” section of our survey, as users showed to be excited about the development of this tool and wished that we keep improving it, as it can bring benefits to the field.

Finally, we believe that our research has the potential to help several professionals in the radiology field. The data and feedback we obtained from professionals during our study show that the tool has the potential to help other researchers to create new approaches focusing on low-cost three-dimensional visualization as well, and the application we developed might be the first step towards it. The current limitations we faced using smartphones (graphic memory, screen resolution, computational power, etc.) are likely to diminish throughout next years, and therefore the most mentioned problem about our software (the low-resolution of the dataset) might disappear.

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## APPENDIX A – INFORMED CONSENT FORMS

Nós, Renan Magalhães Trévia (aluno de Mestrado) e Márcio Sarroglia Pinho (professor orientador), responsáveis pela pesquisa **Investigação das Possibilidades de Uso de Dispositivo de Visualização Tridimensional de Baixo Custo para Apoiar o Diagnóstico Radiológico**, estamos fazendo um convite para você participar como voluntário nesse estudo.

Esta pesquisa pretende identificar como o método de visualização de exames radiológicos 3D em realidade virtual utilizando dispositivos de baixo custo pode contribuir para o processo de diagnóstico. Para isso precisamos testar o método criado, a partir de cenários reais, a fim de analisar seu uso. Acreditamos que ela seja importante porque poderemos identificar um método alternativo e de baixo custo para a visualização de exames volumétricos, facilitando, assim, a realização de diagnósticos radiológicos.

Para realização da pesquisa serão seguidas as seguintes etapas: realização de uma revisão sistemática da literatura dos artefatos disponíveis para visualização de exames volumétricos; desenvolvimento do método de visualização; teste do método proposto. Sua participação será na etapa de teste do método proposto e constará de navegar e realizar as tarefas propostas no protótipo construído, além de responder um questionário ao final do teste. A duração prevista é de 30-90 minutos, com possibilidade de intervalo e descanso a cada 30 minutos.

É possível que aconteçam os seguintes desconfortos ou riscos como dor de cabeça e cansaço ou aborrecimento durante a realização das tarefas ou durante as discussões. Além disso, desconforto, constrangimento ou alterações de comportamento durante as gravações de áudio e vídeo também podem acontecer. Você tem o direito de pedir uma indenização por qualquer dano que, comprovadamente, resulte da sua participação no estudo. Os benefícios que esperamos do estudo são: análise de um método de visualização de imagens tridimensionais; identificação de técnicas de interação que permita manipular dados radiológicos; criação de diretrizes de desenvolvimento de uma ferramenta que possa auxiliar o processo de diagnóstico radiológico. Durante todo o período da pesquisa você tem o direito de esclarecer qualquer dúvida ou pedir qualquer informação sobre o estudo, bastando para isso entrar em contato, com Márcio Pinho (pinho@puccrs.br) no telefone [REDACTED] a qualquer hora.

Em caso de algum problema relacionado com a pesquisa você terá direito à assistência gratuita que será prestada por/pelos pesquisadores a partir dos celulares citados anteriormente. Você tem garantido o seu direito de não aceitar participar ou de retirar sua permissão, a qualquer momento, sem nenhum tipo de prejuízo ou retaliação, pela sua decisão. Se por algum motivo você tiver despesas decorrentes da sua participação neste estudo com transporte e/ou alimentação, você será reembolsado adequadamente pelos pesquisadores.

As informações desta pesquisa serão confidenciais, e serão divulgadas apenas em eventos ou publicações científicas, não havendo identificação dos participantes, a não ser entre os responsáveis pelo estudo, sendo assegurado o sigilo sobre sua participação.

Caso você tenha qualquer dúvida quanto aos seus direitos como participante de pesquisa, entre em contato com Comitê de Ética em Pesquisa da Pontifícia Universidade Católica do Rio Grande do Sul (CEP-PUCRS) em (51) 33203345, Av. Ipiranga, 6681/prédio 50 sala 703, CEP: 90619-900, Bairro Partenon, Porto Alegre – RS, e-mail:

cep@pucrs.br, de segunda a sexta-feira das 8h às 12h e das 13h30 às 17h. O Comitê de Ética é um órgão independente constituído de profissionais das diferentes áreas do conhecimento e membros da comunidade. Sua responsabilidade é garantir a proteção dos direitos, a segurança e o bem-estar dos participantes por meio da revisão e da aprovação do estudo, entre outras ações.

Ao assinar este termo de consentimento, você não abre mão de nenhum direito legal que teria de outra forma.

Não assine este termo de consentimento a menos que tenha tido a oportunidade de fazer perguntas e tenha recebido respostas satisfatórias para todas as suas dúvidas.

Se você concordar em participar deste estudo, você rubricará todas as páginas e assinará e datará duas vias originais deste termo de consentimento. Ao assinar e rubricar todas as páginas deste documento, você de forma voluntária e esclarecida, nos autoriza a utilizar todas as informações de natureza pessoal que constam em nas respostas de sua entrevista, bem como as imagens da tela do computador durante o uso do protótipo, para finalidade de pesquisa e realização deste estudo. Você receberá uma das vias para seus registros e a outra será arquivada pelo responsável pelo estudo.

Eu, (**nome completo do participante**), após a leitura (ou a escuta da leitura) deste documento e de ter tido a oportunidade de conversar com o pesquisador responsável, para esclarecer todas as minhas dúvidas, acredito estar suficientemente informado, ficando claro para mim que minha participação é voluntária e que posso retirar este consentimento a qualquer momento sem penalidades ou perda de qualquer benefício. Estou ciente também dos objetivos da pesquisa, dos procedimentos aos quais serei submetido, dos possíveis danos ou riscos deles provenientes e da garantia de confidencialidade e esclarecimentos sempre que desejar.

Diante do exposto expresse minha concordância de espontânea vontade em participar deste estudo, autorizando o uso, compartilhamento e publicação dos meus dados e informações de natureza pessoal para essa finalidade específica.

Assinatura do participante da pesquisa ou de seu representante legal

Assinatura de uma testemunha

### **DECLARAÇÃO DO PROFISSIONAL QUE OBTEVE O CONSENTIMENTO**

Expliquei integralmente este estudo ao participante. Na minha opinião e na opinião do participante, houve acesso suficiente às informações, incluindo riscos e benefícios, para que uma decisão consciente seja tomada.

Data: \_\_\_\_\_

\_\_\_\_\_  
Assinatura do Investigador

\_\_\_\_\_  
Márcio Sarroglia Pinho

Rubrica do participante

Rubrica do pesquisador resp.

**APPENDIX B – BACKGROUND QUESTIONNAIRE**

<b>Past Experiences</b>		
<b>#</b>	<b>Description</b>	<b>Answer Type</b>
1	How much time of experience do you have with VR?	Open Field
2	How much time of experience do you have with video games and video game controllers?	Open Field
3	What other radiological software tools have you ever used?	Open Field
4	How much time of experience do you have with these other tools?	Open Field

## APPENDIX C – EXPERIMENT SEQUENCE OF TASKS

Sequence of Tasks	
#	Description
1	Observe the virtual environment and tell me what you think the elements you see are
2	Localize the 3D model and tell me what it is
3	Move the 3D model around the four corners of the screen
4	Reset the 3D model
5	Change the cutting plane of the 3D model to the <b>axial cutting plane</b>
6	Change the opacity of the 3D model to <b>opaque</b>
7	Adjust the brightness and contrast of the 3D model
8	Scroll through the 3D model in the <b>axial cutting plane</b>
9	Scale up and down the 3D model
10	Reset the 3D model
11	Reset the WW and WL of the 3D model
12	Change the opacity of the 3D model to <b>transparent</b>
13	Rotate the 3D model the best you can to face its <b>coronal cutting plane</b>
14	Change the opacity of the 3D model to <b>opaque</b>
15	Adjust the brightness and contrast of the 3D model
16	Scroll through the 3D model in the <b>custom cutting plane</b>
17	Scale up and down the 3D model

## APPENDIX D – FEATURE EVALUATION QUESTIONNAIRE (LIKERT SCALE)

<b>Feature Questionnaire</b>			
<b>#</b>	<b>Category</b>	<b>Description</b>	<b>Answer Type</b>
1	<b>Virtual Reality and Input/Output System</b>	What is your perception regarding the virtual environment?	Likert Scale
2		What is your perception regarding the 3D model?	Likert Scale
3		What is your perception regarding the interaction with the virtual environment (gamepad controller)?	Likert Scale
4	<b>Geometric Transformations on the 3D model</b>	What is your perception regarding the move feature?	Likert Scale
5		What is your perception regarding the reset 3D model feature?	Likert Scale
6		What is your perception regarding the rotation feature?	Likert Scale
7		What is your perception regarding the scale feature?	Likert Scale
8	<b>Windowing</b>	What is your perception regarding the windowing feature?	Likert Scale
9		What is your perception regarding the reset windowing feature?	Likert Scale
10		What is your perception regarding the opacity feature?	Likert Scale



11	<b>Scrolling</b>	What is your perception regarding the scrolling feature?	Likert Scale
12		What is your perception regarding the change cutting plane feature?	Likert Scale

## APPENDIX E – FEATURE EVALUATION QUESTIONNAIRE (NASA-TLX)

<b>Feature Questionnaire</b>			
<b>#</b>	<b>Category</b>	<b>Description</b>	<b>Answer Type</b>
1	<b>Virtual Reality and Input/Output System</b>	What is your perception regarding the virtual environment, the quality of the 3D model and the interaction with the virtual environment thought a gamepad controller?	NASA-TLX
2	<b>Geometric Transformations on the 3D model</b>	What is your perception regarding the geometric transformations on the 3D model, such as move, rotate, resize, and reset?	NASA-TLX
3	<b>Windowing</b>	What is your perception regarding the windowing (WW and WL) and the changing of opacity of the 3D model?	NASA-TLX
4	<b>Scrolling</b>	What is your perception regarding the scrolling and the change of cutting plane of the 3D model?	NASA-TLX

**APPENDIX F – QUALITATIVE ASSESSMENT OF THE APPROACH**

<b>Qualitative Assessment</b>		
<b>#</b>	<b>Description</b>	<b>Answer Type</b>
1	What is the main contribution of this tool to the diagnostic process?	Open Field
2	What in the tool facilitates the diagnostic process?	Open Field
3	What, in the tool, gets in the way of the diagnostic process?	Open Field
4	Would you use a tool like this in the diagnostic process? Why? In which way?	Open Field

**APPENDIX G – FUTURE WORK QUESTIONNAIRE**

<b>Future Work</b>		
<b>#</b>	<b>Description</b>	<b>Answer Type</b>
1	What changes would you do in our application?	Open Field
2	Are there any other observation regarding this study you would like to add?	Open Field

# APPENDIX H – SHORT PAPER PUBLISHED AT THE 21TH SYMPOSIUM ON VIRTUAL AND AUGMENTED REALITY

## Virtual Reality in Radiology: A Systematic Mapping Study

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### ABSTRACT

In radiology, virtual reality has emerged as a candidate to solve some issues of the area, such as the ambient lighting and ergonomic postures when diagnosing.

The goal of this study is to explore the literature of virtual reality in radiology in order to define and describe the state-of-the-art in addition to finding gaps and opportunities for future research.

To do so, we carried out a systematic mapping study covering the period from January 2014 to July 2021. We initially found 329 papers to be reviewed, but after applying our exclusion criteria we ended up with 24 primary studies.

Our results suggest that the use of virtual reality has grown recently in the field, however there are many gaps and opportunities to explore in the area.

### CCS CONCEPTS

• **General and reference** → **Surveys and overviews**; • **Applied computing** → **Imaging**; • **Software and its engineering** → **Virtual worlds software**; • **Human-centered computing** → **Virtual reality**.

### KEYWORDS

virtual reality, radiology, systematic literature review

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### 1 INTRODUCTION

A potential use for virtual reality (VR) technology in the medical area is to assist radiologists when performing a radiological diagnosis as they usually do it in workstations to analyze the medical data using three-dimensional visualization [15] in traditional 2D desktop displays [32]. Hence, inadequate ergonomic postures and, more importantly, improper room conditions can cause erroneous diagnostics when professionals examine such digital images using common displays [30].

Based on this scenario, the objective of this work is to determine and characterize the state-of-the-art on VR in radiology. To do so,

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we performed a systematic mapping study [3][5][27] aimed at: (1) discovering the uses, benefits and main barriers of VR in radiology and (2) identifying gaps for future studies.

From an initial set of 329 papers, we have identified 24 primary studies worth analyzing from 6 individual scientific databases.

This work is organized as follows: Section 2 introduces the main area explored in this study. In Section 3 we detail the research methodology, including the presentation of the research questions. We explore the results from the systematic mapping study in Section 4. In Section 5 we present the answers to the research questions. Lastly, Section 6 concludes the paper by describing our final remarks.

### 2 BACKGROUND

Radiology is a medical discipline in which images visualizing human bodies are examined for abnormalities [8] and radiological studies are undoubtedly one of the most important resources when diagnosing different clinical pathologies, used in different medical specialties [15].

It is remarkable that medical images which are inherently 3D in nature are mostly visualized in clinical practice by physicians and radiology technicians [20] in reading rooms [38], using multiple 2D displays among 1D or 2D input media [6].

When reading 3D images, radiologists need to view and scroll through a substantial number of image slices (a slice is a single 2D image of a cross section of the human body [8]) and manipulate that image in such a manner that abnormalities become visible [8].

Therefore, clinicians have to deal with the presence of external factors such as external lights and screen color saturation when diagnosing, which might interfere with the process [30][32]. Besides, the interpretation of these images is considered a highly complex task since medical images are not self-explanatory [9][35].

### 3 METHODOLOGY

As stated in Section 1, the goal of this study is to determine and characterize the state-of-the-art on VR in radiology. To do so, we conducted this systematic mapping following the recommendation from influential researchers in the software engineering area [3][5][27].

#### 3.1 Research questions

In order to determine and characterize the state-of-the-art on VR in radiology, the following research questions were defined:

- **RQ1:** How is virtual reality used in radiology?
- **RQ2:** What are the benefits of using virtual reality in radiology?
- **RQ3:** What are the challenges of using virtual reality in radiology?

The purpose of RQ1 is to discover the ways VR has been used in radiology and its main techniques and applications. From the following questions (RQ2 and RQ3) we intend to analyze the benefits and the challenges of using VR in radiology in order to find out the reasons it is applied to radiology and the difficulties it may have.

### 3.2 Data source and search strategy

After defining the research questions, we built up a general string based on Kitchenham et al. [3] guidelines to identify primary studies on electronic databases to answer the research questions. The general string used in this study was: "(virtual reality OR vr) AND (radiology)".

About the inclusion criteria, we decided to select papers from January 2014 to July 2021 in order to get the most recent works in the research area. We also only included papers that were accepted in journals, conferences, workshops, and symposia and were written in English. In addition to that, we excluded duplicated papers, literature only available in the form of abstracts or presentations and publication not related to the field of study.

To start the process of finding primary studies, we performed an initial research on the selected databases using the general string and the inclusion criteria, which yielded 329 studies. Table 1 summarizes the number of papers returned from each database.

Table 1: Returned papers

Database	# Papers
IEEEExplore ( <a href="https://ieeexplore.ieee.org/">https://ieeexplore.ieee.org/</a> )	24
ACM Digital Library ( <a href="https://dl.acm.org/">https://dl.acm.org/</a> )	3
Engineering Village ( <a href="https://www.engineeringvillage.com/">https://www.engineeringvillage.com/</a> )	50
ScienceDirect ( <a href="https://www.sciencedirect.com/">https://www.sciencedirect.com/</a> )	41
Scopus ( <a href="https://www.scopus.com/">https://www.scopus.com/</a> )	168
PubMed ( <a href="https://pubmed.ncbi.nlm.nih.gov">https://pubmed.ncbi.nlm.nih.gov</a> )	43
Total	329

### 3.3 Keywording, data extraction and mapping

In our study, three main categories were created to classify the studies, these being: contribution category, research type category and computer target category. The contribution category describes the main contribution of the work to the area, and it was created from the keywords found on the keywording process. The options for that category are: diagnostic imaging, medical education, patient care, interaction technique and tool. Furthermore, the research type category reflects the research approach used in the papers. We chose an existing classification of research approach presented by Wieringa et al. [37] and added a new research type called "Overview Paper" to fit the papers that were only reviewing the available content of VR in radiology. Besides, the computer target category details the source of computational power in which the developed solutions aim to be deployed, these being: desktop, smartphone, HMD and CAVE.

## 4 RESULTS

From an initial set of 329 papers identified through the search strategy (see Section 3.2), we have come across 24 primary studies

after applying the exclusion criteria. The systematic map result is presented in Table 2.

About the distribution of the studies according to their computer target category, it is clear that most papers aim traditional computers (desktop) as their main research deployment target, leaving smartphone, CAVE and standalone HMD as possible gaps in the area for further solution development.

In regards to the contribution, it is possible to see that the ones with the highest number of studies throughout the years are diagnostic imaging (DI), medical education (ME) and patient care (PC), with 2018 being the year with the greatest number of papers about DI. There seems to be a gap on interaction techniques and tools when it comes to the contribution.

In the following section we provide details about the 24 studies evaluated.

## 5 ANALYSIS

In this section we analyze the three research questions proposed for this study. The answers for them came from the information we got in Section 4 combined with the learnings and insights from each of the 24 primary studies selected.

### 5.1 RQ1. How is virtual reality used in radiology?

The overview of this systematic mapping study detailed in Table 2, indicates that VR has been used in the radiological field among three main areas, those being: diagnostic imaging, medical education, and patient care.

In regard to diagnostic imaging, we have VR radiology reading room that allows imagiologists to focus on the medical image data, while avoiding the conditions that can interfere with radiodiagnostic [32][38]. Moreover, we have the CAVE, an immersive, navigable, and interactive environment for visualizing complex data sets [20].

In addition to that, we also have a multimodal real-time decision support system where radiologists can visualize and interact with patient data in VR by using natural speech and hand gestures [28][39]. In regard to hand gestures, it is interesting to highlight that four studies use Leap Motion Controller<sup>1</sup> as their input system for the developed solution [15][31][32][38]. Besides, a project called NextMed allows radiologists to visualize any anatomical structure of the patient on the table, as well as manipulate and analyze them in 3D as if they were real [15]. Moreover, congenital heart disease data when conjoined with VR has been used to diagnose atrial septal defects [33]. Furthermore, VR has also been used for detection of lung nodules on CT [25].

About medical education, a wide range of uses can be underlined. First, VR technology has been adopted in surgery residency programs to train residents in laparoscopic surgery technique [13]. Furthermore, surgeons are also using VR for making preoperative decisions as the surgical procedure can be planned non-invasively on already existing cross-sectional images [39] and simulated on patient-specific virtual models prior to being performed on the real patient [21]. Moreover, in a study conducted in Spain, computed tomography (CT) was utilized to make 3D models to confirm anatomical compatibility with recipients [12]. Besides, we also have

<sup>1</sup><https://www.ultraleap.com/product/leap-motion-controller/>

**Table 2: Systematic map result**

Author	Year	Research Type	Forum Type	Contribution	Computer Target
Venson et al. [36]	2016	Evaluation Research	Conference	Diagnostic Imaging	Desktop/Smartphone
Sousa et al. [32]	2017	Evaluation Research	Conference	Interaction Technique	Desktop
Klonig et al. [16]	2020	Evaluation Research	Conference	Diagnostic Imaging / Medical Education	N/A
Wirth et al. [38]	2018	Evaluation Research	Symposium	Interaction Technique	Desktop
Liszio et al. [19]	2020	Evaluation Research	Symposium	Patient Care	N/A
Venson et al. [10]	2017	Evaluation Research	Journal	Diagnostic Imaging	Desktop/Smartphone
Nguyen et al. [25]	2018	Evaluation Research	Journal	Diagnostic Imaging	Desktop
Han et al. [14]	2019	Evaluation Research	Journal	Patient Care	HMD
Sapkaroski et al. [31]	2019	Evaluation Research	Journal	Medical Education	Desktop
Sun et al. [33]	2020	Evaluation Research	Journal	Patient Care	N/A
Locuson et al. [20]	2015	Solution Proposal	Conference	Diagnostic Imaging	CAVE
Izard et al. [15]	2018	Solution Proposal	Conference	Diagnostic Imaging	Desktop
Prange et al. [28]	2018	Solution Proposal	Conference	Diagnostic Imaging	Desktop
Xu et al. [39]	2020	Solution Proposal	Conference	Medical Education	Desktop
Knodel et al. [17]	2018	Solution Proposal	Journal	Tool	CAVE
Alsofy et al. [1]	2020	Solution Proposal	Journal	Diagnostic Imaging	N/A
Laas et al. [18]	2021	Solution Proposal	Journal	Medical Education	N/A
Marescaux et al. [21]	2015	Overview Paper	Journal	Medical Education	Desktop
Belmustakov et al. [4]	2018	Overview Paper	Journal	Medical Education	Desktop
Sutherland et al. [34]	2018	Overview Paper	Journal	Diagnostic Imaging / Medical Education / Patient Care	Desktop/Smartphone
McCarthy et al. [22]	2019	Overview Paper	Journal	Medical Education	Desktop/Smartphone
Elsayed et al. [11]	2020	Overview Paper	Journal	Diagnostic Imaging / Medical Education / Patient Care	N/A
Ammanuel et al. [2]	2019	Experience Paper	Journal	Tool	N/A
Abdelrazek et al. [23]	2018	Opinion Paper	Journal	Diagnostic Imaging / Medical Education	N/A

low-cost VR simulations that can help reduce errors and the number of actions in a surgical operation [26]. In addition, VR has been successfully used for resident procedural training, e.g., to simulate lumbar punctures or to better understand complex imaging anatomy, for example, the ultrasound appearance of spinal anatomy [29].

Regarding patient care, VR has emerged as a candidate to treat MRI-related anxiety as for most patients, lying inside the MRI scanner for the average examination time of 20 minutes is an unpleasant, sometimes frightening experience [19]. Furthermore, it can also be used as a tool to teach patients about their health or treatment, or to deliver treatment [14][34]. Beyond that, in the absence of a patient's presence entirely, VR and AR are an interesting clinician tool of intervention planning aid [34].

Lastly, we noticed that VR can also be used as a tool for collaboration as it creates a wide variety of collaborative opportunities. An example of such use would be clinicians and other health care experts inhabit the same virtual space and discuss the same medical data that is either a mutually interactable object in front of them, or the shared virtual environment (VE) itself [34].

## 5.2 RQ2. What are the benefits of using virtual reality in radiology?

Regarding diagnostic imaging, the use of VR reading rooms could cut equipment and maintenance costs, and by eliminating effects of ambient lighting conditions it could potentially improve diagnostic accuracy [11]. In addition to that, compared to the 3D printed model of the patient specific-anatomy and pathology, VR is a more flexible and inexpensive alternative [10].

Besides, one key element of using VR in any application is that it renders a comprehensive and intuitive visual representation of the data even for the non-specialist, which opens the possibility to provide exam data to referring physicians that can be used for detailed surgery planning and communication with the patients during medical appointments [10]. Furthermore, Venson et al. [36] demonstrated that VR shows high effectiveness in identifying superficial fractures for two different volume exams.

VR has the potential to augment the possibilities of grasping the complex morphology of anatomical structures or the pathological changes e.g., in cancer or cardiovascular disease. Thereby, medical immersive imaging not only improve diagnostic imaging and surgical procedure planning, but also serve educative purposes for medical students and doctors [17].

About medical education, some VR systems allow surgeons to take completely free perspectives on the anatomical structures from all directions, which provides a much more intuitive understanding of the present situs, and even more of the underlying pathology [1]. Moreover, VR-based visualization of the native MRI grants surgeons an enhanced understanding of tumor localization and breast volumes and it can increase the incidence of breast-conserving surgeries allowing successful oncoplastic procedures [18].

In addition, by using VR, trainees can be transported into a procedure room where they may observe and even participate in virtual procedures before performing them on patients. This allows educators to provide standardized and curated educational training material to all trainees [4][11][31].

Another benefit of using VR equipment for delivering of medical training content is that such content can be reviewed at a time

convenient to the learner, thereby decreasing the effort, coordination, resources, and expense associated with hands-on simulation training [7].

Finally, in regard to patient care, VR technology has many advantages over conventional systems for patient entertainment during MRI examinations as it is most capable of distracting patients from the unpleasant sensations of the scanning procedure [19]. Besides, the reported successes of using VR for distraction therapy, during invasive surgical procedures warrants adoption in interventional radiology as well [11]. Patients prone to anxiety, claustrophobia, or high analgesic requirements during interventional radiology procedures may find this therapy especially beneficial [11].

### 5.3 RQ3. What are the challenges of using virtual reality in radiology?

Although the number of benefits in using VR in the radiological field is quite remarkable, there are many challenges associated with the use of such technology. First, VR poses a challenge for model creators to include sufficient anatomical detail to maintain clinical accuracy while allowing for smooth, real-time interactive visualization [34] as minute structures may be too small to resolve on the 3D reconstruction and VR environment depends on the quality of the original imaging dataset which is susceptible to artifacts secondary to motion and beam hardening [23]. In addition to that, the development of high-quality content requires a degree of technical knowledge that is beyond what an average technology user possesses [22] and creating VR models currently requires the use of multiple software applications at the same time, which can be difficult for the user to learn [2].

Beyond that, regarding the use of VR to reduce MRI-related anxiety, many HMDs are not suitable for it due to their magnetic components which are strongly attracted by the MRI scanner's magnets, hence carrying a high risk of injury [19]. Another problem is the, sometimes considerable, heating of ferromagnetic materials, which can lead to severe burns [19].

Lastly, innovation in healthcare requires strict regulation and high sense of responsibility. Patient safety and quality of life are major issues and, for this reason, innovation in healthcare needs to be patient-centered in order to be effective [21], thus creating a barrier to novel solutions in that area. Besides, as stated by Sousa et al. [32], there is also the physician's resistance to novel systems and technologies. Klonig et al. [16] also mention that the immersion in the VE might increase the emotional gap between physicists and patient, and potentially contributes to objectifying patients.

## 6 FINAL REMARKS

In this paper we conducted a systematic mapping study in order to identify the main uses of VR in the context of radiology and characterize the benefits and challenges of it. The goal was not only to determine and characterize the state-of-the-art on VR in radiology, but also to create a general understanding of the area and find gaps for future exploration.

After performing the research, we classified the studies according to three categories: contribution, research type and computer target. The contribution category revealed five possible classifications in which the studies fit: diagnostic imaging, medical education, patient

care, interaction technique and tools. In addition, computer target category showed four possibilities for papers, these being: desktop, smartphone, CAVE and HMD. Most of the studies in the area are recent and the majority of them were published in journals. Our study also indicates that there are many attempts to insert the VR in radiology.

Regarding the first research question proposed — How is VR used in radiology? — we could identify that it has been used in three major areas: diagnostic imaging, medical education, and patient care. In the diagnostic imaging area, VR has been used to protect physicians from external factors such as room illuminations [10][16][17][20][25][28][32][36][38]. About medical education, VR is being used to allow doctors to review medical data and take preoperative decisions before going to a real surgery [21][39]. In regard to patient care, VR has emerged as a candidate to treat MRI-anxiety [19] and educate patients about their health and treatment [14][34].

The second research question — What are the benefits of using VR in radiology? — the use of VR in radiology cuts the equipment and maintenance costs of a real radiology reading room and it could potentially improve accuracy in radiological diagnosis [11]. Besides, VR also distracts patients in unpleasant radiological procedures [19] and it is also more flexible and unexpensive when compared to 3D printing [10].

From the third research question — What are the challenges of using VR in radiology? — not all VR hardware are suitable for the radiology field as some of them include magnetic components that might prevent them from being used in radiological procedures [19]. Moreover, doctors also present a resistance to novel systems and technologies [32], and VR presents side effects on its use, such as neck pain, nausea, dizziness [24].

In conclusion, this systematic mapping was a first attempt to better understand the context of VR in the radiology field. We understand that several opportunities were created and can be explored from the findings we carried out. We intend to examine the identified gaps in order to develop further research on the proposed topic.

## ACKNOWLEDGMENTS

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**ATTACHMENT A – PUCRS CEP APPROVAL LETTER**

PONTIFÍCIA UNIVERSIDADE  
CATÓLICA DO RIO GRANDE  
DO SUL - PUC/RS



## PARECER CONSUBSTANCIADO DO CEP

### DADOS DO PROJETO DE PESQUISA

**Título da Pesquisa:** Investigação das possibilidades de uso de dispositivo de visualização tridimensional de baixo custo para apoiar o diagnóstico radiológico

**Pesquisador:** Marcio Sarroglia Pinho

**Área Temática:** Equipamentos e dispositivos terapêuticos, novos ou não registrados no País;

**Versão:** 1

**CAAE:** 47621321.0.0000.5336

**Instituição Proponente:** UNIÃO BRASILEIRA DE EDUCAÇÃO E ASSISTENCIA

**Patrocinador Principal:** Financiamento Próprio

### DADOS DO PARECER

**Número do Parecer:** 4.769.091

#### Apresentação do Projeto:

As informações elencadas nos campos "Apresentação do Projeto", "Objetivo da Pesquisa" e "Avaliação dos Riscos e Benefícios" foram retiradas do arquivo Informações Básicas da Pesquisa (PB\_INFORMAÇÕES\_BÁSICAS\_DO\_PROJETO\_1689899.pdf, de 28/05/2021) e/ou do Projeto Detalhado (Documento\_Unificado\_do\_Projeto\_de\_Pesquisa.pdf, de 29/04/2021).

#### Introdução:

O processo de diagnóstico radiológico através de imagens médicas tridimensionais (3D) normalmente se faz utilizando monitores tradicionais (2D) em salas especialmente feitas para apoiar essa tarefa. No entanto, mesmo tendo sido projetadas para realizar análises de imagens médicas, essas salas são afetadas por fatores externos como a intensidade luz ambiente e os reflexos na tela, que por sua vez podem interferir no resultado do diagnóstico. Por conta das dificuldades decorrentes do processo de diagnóstico tradicional (uso de monitores 2D), alguns métodos de visualização 3D têm surgido nos últimos tempos, e dentre eles tem se destacado a realidade virtual (RV). Os últimos 6 (seis) anos mostraram um grande aumento na disponibilidade e no uso de equipamentos de RV e realidade aumentada (RA). Esses dispositivos normalmente assumem a forma de capacetes que podem ser usados para apresentar imagens 3D, bloqueando estímulos visuais externos (RV) ou sobrepor imagens 3D em um ambiente do mundo real (AR) (Colin e Raul, 2019). As principais características da RV são (a) a imersão do usuário em um

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Continuação do Parecer: 4.769.091

ambiente virtual (AV) e (b) a possibilidade de criar um número grande de experiências nele, seja para atingir uma meta planejada pelo desenvolvedor do AV ou para observar o comportamento do usuário utilizando este AV. Essas duas características fazem com que a RV seja uma boa candidata para reduzir as dificuldades presentes no método tradicional de visualização de imagens médicas para diagnósticos radiológicos. Apesar de ter se mostrado promissora para diminuir dificuldades comuns durante o diagnóstico radiológico, a RV ainda é uma tecnologia financeiramente dispendiosa pois os equipamentos necessários (capacete RV e computador com placa de vídeo de alto desempenho) possuem um custo elevado. Por conta disso, o objetivo geral deste trabalho é buscar formas de apoiar a execução de diagnósticos radiológicos através de ambientes virtuais em realidade virtual utilizando equipamentos de baixo custo, como capacetes de RV baseados em celulares.

**Hipótese:**

Nossa hipótese é que utilizando características da realidade virtual, como imersão em ambientes virtuais e interação com objetos virtuais, tudo isso executando em dispositivos de baixo custo, é uma forma atrativa de aprimorar a realização de diagnósticos radiológicos.

**Metodologia Proposta:**

A metodologia desta pesquisa se divide em três etapas, sendo elas: 1) Revisão Sistemática da Literatura: na primeira etapa, o objetivo foi identificar o estado da arte sobre o uso de RV no processo de diagnóstico radiológico. Para isso, uma RSL foi realizada. Segundo Kitchenham e Charters (Kitchenham e Charters, 2007), o uso de uma abordagem sistemática é um meio de avaliar, identificar e interpretar pesquisas científicas disponíveis. Essa revisão sistemática nos mostrou que havia poucos trabalhos sobre o uso de dispositivos de baixo custo como apoio para o diagnóstico radiológico. 2) Desenvolvimento do método de visualização para dispositivos de baixo custo: uma vez identificado o estado da arte, seguimos com a implementação de um método de visualização tridimensional tendo como plataforma alvo dispositivos tipo celular. 3) Teste do método proposto com os usuários: com o método desenvolvido e devidamente instalado em um dispositivo, iremos conduzir um teste com usuários, a fim de analisar o método proposto. Após os usuários efetuarem as tarefas, conduziremos uma discussão a fim de coletar as impressões de cada usuário em relação ao método.

**Critério de Inclusão:**

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Pessoas maiores de idade que trabalhem realizando diagnósticos radiológicos.

**Critério de Exclusão:**

Menores de idade.

**Metodologia de Análise de Dados:**

Como instrumento para coleta e análise dos dados foi escolhido o questionário semiestruturado a ser utilizado como base de discussão após cada participante ter finalizado uma série de tarefas de forma individual. Para termos percepções diferentes e evitarmos um único viés, os participantes receberão a mesma lista de tarefas, porém com ordens diferentes. As respostas serão armazenadas via software. Durante o teste e a discussão, poderá também ser realizada a gravação da interação em áudio ou vídeo. Para todos os casos, o participante inicia sua participação no estudo somente após ser informado e concordar com as condições da atividade conforme declarado no TCLE. O tempo de participação por sessão é planejado para o mínimo de 30 minutos e máximo de 1 hora e 30 minutos, com intervalos para descanso a cada 30 minutos.

**Desfecho Primário:**

Usabilidade do sistema de realidade virtual em dispositivos de baixo custo quando comparado a solução tradicional.

Tamanho da Amostra no Brasil: 15

**Objetivo da Pesquisa:**

O objetivo desta pesquisa é identificar como o método de visualização de exames médicos 3D em realidade virtual utilizando dispositivos de baixo custo pode contribuir para o processo de diagnóstico radiológico, analisando seu uso.

**Avaliação dos Riscos e Benefícios:**

**Riscos:**

De acordo com o formato da nossa dinâmica, é possível que aconteçam os seguintes desconfortos ou riscos como dor de cabeça e cansaço ou aborrecimento durante a realização das tarefas ou durante as discussões. Além disso, desconforto, constrangimento ou alterações de comportamento durante as gravações de áudio e vídeo também podem acontecer.

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**Benefícios:**

Análise de um método de visualização de imagens tridimensionais; identificação de técnicas de interação que permita manipular dados radiológicos; criação de diretrizes de desenvolvimento de uma ferramenta que possa auxiliar o processo de diagnóstico radiológico.

**Comentários e Considerações sobre a Pesquisa:**

Trata-se de pesquisa prospectiva acadêmica, realizada com médicos radiologistas, de percepção de usabilidade de um sistema de baixo custo utilizando celular, para visualização de exames médicos 3D em realizada virtual.

**Considerações sobre os Termos de apresentação obrigatória:**

Todos os termos foram apresentados.

**Recomendações:**

Recomenda-se que a data do Primeiro Recrutamento dos 15 participantes, citada nas Informações Básicas do Projeto, seja postergada para data posterior à aprovação do projeto no CEP-PUCRS, pois tal data deveria ser a mesma que consta do cronograma do projeto.

**Conclusões ou Pendências e Lista de Inadequações:**

Aprovação com recomendação. Não há pendências.

**Considerações Finais a critério do CEP:**

Diante do exposto, o CEP-PUCRS, de acordo com suas atribuições definidas na Resolução CNS n° 466 de 2012 e da Norma Operacional n° 001 de 2013 do CNS, manifesta-se pela aprovação do projeto de pesquisa Investigação das possibilidades de uso de dispositivo de visualização tridimensional de baixo custo para apoiar o diagnóstico radiológico proposto pelo pesquisador Marcio Sarroglia Pinho com número de CAAE 47621321.0.0000.5336.

**O presente projeto, seguiu nesta data para análise da CONEP e só tem o seu início autorizado após a aprovação pela mesma.**

**Este parecer foi elaborado baseado nos documentos abaixo relacionados:**

Tipo Documento	Arquivo	Postagem	Autor	Situação
Informações Básicas do Projeto	PB_INFORMAÇÕES_BÁSICAS_DO_PROJETO_1689899.pdf	28/05/2021 11:24:16		Aceito
Outros	Questionario.pdf	27/05/2021 18:22:29	RENAN MAGALHAES	Aceito
Outros	Carta_De_Anuencia.pdf	27/05/2021 18:16:22	RENAN MAGALHAES	Aceito
Declaração de concordância	Carta_De_Concordancia.pdf	27/05/2021 18:15:53	RENAN MAGALHAES	Aceito

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Orçamento	Orcamento.pdf	22/05/2021 20:05:06	RENAN MAGALHAES	Aceito
Outros	Curriculo_Lattes.docx	22/05/2021 20:02:24	RENAN MAGALHAES	Aceito
Solicitação Assinada pelo Pesquisador Responsável	Carta_Encaminhamento_InvestigacaoVR.pdf	22/05/2021 19:56:39	RENAN MAGALHAES TREVIA	Aceito
Cronograma	Cronograma.pdf	09/05/2021 18:22:38	RENAN MAGALHAES	Aceito
Folha de Rosto	folhaDeRosto.pdf	03/05/2021 18:34:27	Marcio Sarrogli Pinho	Aceito
Solicitação registrada pelo CEP	Carta_de_Aprovacao_da_Comissao_Cientifica.pdf	29/04/2021 13:37:42	RENAN MAGALHAES	Aceito
TCLE / Termos de Assentimento / Justificativa de Ausência	TCLE_InvestigacaoVR.pdf	29/04/2021 12:35:36	RENAN MAGALHAES TREVIA	Aceito
Projeto Detalhado / Brochura Investigador	Documento_Unificado_do_Projeto_de_Pesquisa.pdf	29/04/2021 12:32:44	RENAN MAGALHAES TREVIA	Aceito

**Situação do Parecer:**

Aprovado

**Necessita Apreciação da CONEP:**

Sim

PORTO ALEGRE, 11 de Junho de 2021

\_\_\_\_\_  
**Assinado por:**  
**Paulo Vinicius Sporleder de Souza**  
**(Coordenador(a))**

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## ATTACHMENT B – SYSTEM USABILITY QUESTIONNAIRE

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



**ATTACHMENT C – SYSTEM USABILITY SCALE (SUS)**

<b>System Usability Scale (SUS)</b>		
<b>#</b>	<b>Description</b>	<b>Value</b>
1	Strongly Disagree	1
2	Disagree	2
3	Neutral	3
4	Agree	4
5	Strongly Agree	5

**ATTACHMENT D – LIKERT SCALE**

<b>Likert Scale</b>	
<b>#</b>	<b>Description</b>
1	Very Bad
2	Bad
3	Neutral
4	Good
5	Very good

## ATTACHMENT E – NASA TASK LOAD INDEX (NASA-TLX)

NASA Task Load Index (NASA-TLX)				
#	Scale Description	Description	Score Range	Score Value
1	Mental Demand	How much mental and perceptual activity was required? Was the task easy or demanding, simple or complex?	Low to High	0.0, 0.5, 1, 1.5... 9, 9.5, 10.0
2	Physical Demand	How much physical activity was required? Was the task easy or demanding, slack or strenuous?	Low to High	0.0, 0.5, 1, 1.5... 9, 9.5, 10.0
3	Temporal Demand	How much time pressure did you feel due to the pace at which the tasks or task elements occurred? Was the pace slow or rapid?	Low to High	0.0, 0.5, 1, 1.5... 9, 9.5, 10.0
4	Overall Performance	How successful were you in performing the task? How satisfied were you with your performance?	Good to Bad	0.0, 0.5, 1, 1.5... 9, 9.5, 10.0
5	Effort	How hard did you have to work (mentally and physically) to accomplish your level of performance?	Low to High	0.0, 0.5, 1, 1.5... 9, 9.5, 10.0
6	Frustration Level	How irritated, stressed, and annoyed versus content, relaxed, and complacent did you feel during the task?	Low to High	0.0, 0.5, 1, 1.5... 9, 9.5, 10.0



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