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MOVEMENT METHODS FOR 3D MODEL INTERACTION IN VIRTUAL REALITY

A User Study

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ABSTRACT

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Medical imaging, including Computed Tomography (CT) or Magnetic Resonance (MR), is used for verifying diagnoses and planning treatment. Compared to 2D medical images, 3D medical images have been found to increase spatial understanding of human structures in certain contexts. Emerging technologies, including viewing 2D medical images as 3D models in Extended Reality (XR), add interaction possibilities. Specifically, Virtual Reality (VR) allows medical professionals to view images in an immersive environment, without worrying about the limitations of the real environment (e.g., bad lighting). In addition, AI-generated segmentation of medical images allows the automation of a labor-intensive task usually done by radiologists.

Movement, also called locomotion, is a necessary part of VR interaction. Movement methods allow the user to adjust their location in the virtual environment. The context of the VR environment can influence the suitability of a movement method, while the choice of the movement method can impact user experience. The context of 3D model interaction differs from typical VR interaction, as the user needs to inspect the model from close with small-scale, detailed movements.

For research gap verification, a methodological review was conducted. 42 papers on 3D-XR model interaction found in Andor and Google Scholar were included. Even though half of the papers mentioned using movement methods, an experiment comparing them was not included in any of the papers. In the current study, an experiment was conducted to compare three movement methods, Diving, Grabbing, and Teleporting, regarding their suitability for 3D-VR image interaction. Diving was found to be significantly more successful than Teleporting. Diving and Teleporting were found equally fast compared to Grabbing, which was significantly slower. Diving, the less-studied method, received the best scores in most ratings. However, the opinions varied. Therefore, a VR system for 3D-VR medical image interaction should include multiple movement methods.

Key words and terms: medicine, 3D model, 3D image, medical image, movement method, locomotion, virtual reality, extended reality, interaction technique, segmentation, radiology

PREFACE

I remember when I was still a bachelor's student struggling with many personal issues. Too many times I felt like I would never be able to finish my studies. All my life I have been an underachiever at school and in my studies because as a child I was never pushed to study for exams – I was often told to find my *inner motivation*. Yet, when I had my child, something unexplainable happened to my brain. I still feel like they were rewired. The underachiever suddenly started getting top grades and then became so obsessed about grades, that they started to put a lot of effort (a little too much effort at times) into their studies. Probably the fondest memories from my studies will always be from those two literature exams in Prof. Veikko Surakka's courses. I still use Scott MacKenzie's book *Human Technology Interaction an Empirical Research Perspective* in my work. In fact, you might find some references to the book in this thesis as well. I sometimes read it and simultaneously explain to my mother how brilliant it is. Literature exams – something that was always considered a *Mission Impossible* to the underachiever, lit up my passion and confidence to pursue a career in academics.

I owe most of this work to my child, without whom I would still be the underachiever I was before them. Every day you push me to my limits, which might be annoying at times, but by doing so you boost my confidence and ability to handle stress and hard work. You might not yet know it, but you are my biggest mentor. Even now when I am writing this text, you train my ability to multi-task and stay calm in a stressful situation.

I would like to thank both of my supervisors Prof. Roope Raisamo and Jari Kangas for allowing me to learn from the knowledge they have gained throughout the years and helping me with my thesis work. I would also like to thank each professor who gave me interesting knowledge to utilize and reflect on. I would like to thank the members of the MMIG group, as well as the TAUCHI Research Center. I am also grateful for my colleagues: my work roommates (who make me feel like I live in a sort of wholehearted comedy about three research assistants), my colleague who has given me help and much-needed socializing throughout the start of my career (I will miss you), as well as Jari Kangas again for interesting conversations, be they work-related or not. Finally, I would like to thank my spouse for celebrating the end of my thesis journey with me, and my mother for always believing in me and encouraging me to pursue an academic career ever since you took me with you to lectures at Tampere University while I was still a baby – I have finally found that *inner motivation* you have told me to find.

USE OF AI-BASED TOOLS

AI-based tools are emerging, and it is important to be transparent about their use. These tools will likely become the norm in the near future. Therefore, sharing our methods of AI use can help others as well. In this thesis, Chat-GPT 3.5 was used to fix grammar as well as rephrasing text. Grammarly was used to fix grammar, and Microsoft Bing was used in literature searching.

Contents

1. Introduction

Medical imaging, such as Computed Tomography (CT) or Magnetic Resonance (MR), is necessary for confirming diagnoses (Bipat et al., 2005) and treatment planning, including surgical preparation (Karkos et al., 2009). Therefore, medical imaging is an essential part of healthcare. However, medical images reduce three-dimensional (3D) body structures into two-dimensional (2D) slices, leading to a loss of information (Maken & Gupta, 2023). It has been found that interacting with 3D medical visualizations can increase knowledge of anatomical structures compared to traditional 2D methods (Triepels et al., 2020). Additionally in some contexts, 3D medical imaging methods have been found to increase spatial knowledge of three-dimensional structures, compared to 2D methods (Aluwee et al., 2015). Spatial knowledge is defined in Buttussi & Chittaro (2023) as gaining and retaining spatial understanding by acquiring information about the spatial properties of either a real or virtual environment.

Attempts have been made in the medical field to increase 3D information on body structures with new technology, like 3D printing. Although 3D-printed medical models can increase spatial understanding, they limit interaction with the model to the outside structures. 3D printing can also be time-consuming and costly due to the needed materials (Chen et al., 2017). Additionally, surgeons cannot interact with 3D-printed models while operating, as they are unable to touch anything else than the surgical tools.

Thanks to previous research efforts (Zuiderveld et al., 1996), new developments in medical imaging allow the construction of realistic 3D models from 2D medical images (Pessaux et al., 2015). This makes it possible to view all the structures of the model – by going “inside” the model. However, these models are often used with already existing computer software made for conventional desktop systems, limiting possible interaction methods (Zawy Alsofy et al., 2020).

In addition, recent advancements in Artificial Intelligence (AI) algorithms have made it possible to automatically segment anatomical structures. This reduces the time to analyze medical imaging data, lessening the need for time-consuming manual segmentation (Charbonnier et al., 2016). Virtual Reality (VR) has generally been the environment for AI segmentation analysis due to the developments in 2D-to-3D image conversion (Bakhuis et al., 2022).

Extended Reality (XR) can increase possible interaction methods for 3D-model interaction (Rakkolainen et al., 2021). XR is often used as an umbrella term for all the terms under the Virtuality Continuum, excluding real environment (LaValle, 2023, p. 6). The Virtuality Continuum is a concept first described in Milgram & Kishino (1994). According to this concept, virtuality creates a spectrum. The real environment exists on one end of the spectrum, where reality is only constructed of physical objects. VR exists on the other end of the spectrum, where reality is purely constructed of digital objects. This makes it possible for the user to immerse in the virtual environment. Within the spectrum, Augmented Reality (AR) is positioned near a real environment, and Augmented Virtuality (AV) is near a virtual environment, while Mixed Reality (MR) combines both terms. Let an example of a chair be used to illustrate the concept. AR implies that the real world is augmented with digital objects. In AR, a digital chair could be added to the real environment. AV on the other hand means that the virtual world is augmented with physical objects. In this case, a physical chair would be added to the virtual environment. Finally, MR combines AR and AV to construct an environment where physical and digital objects interact in real time. In the context of chairs, a digital chair could be rendered to the same location in the virtual environment, as a physical chair in the real environment, combining digitality and physicality to make it possible for the user to sit on the chair. Another example is that both digital and physical chairs are used in the environment.

In this thesis, the term “3D-XR” is used to generally describe 3D models in VR, AR, and MR, while the terms “3D-VR” and “3D-AR” are used to describe models in either environment specifically. Even though 3D-XR medical models are broadly discussed in the thesis, the focus is on 3D-VR medical models specifically. This is done as VR offers total immersion compared to other XR types. Additionally, the term “3D model interaction” is used to generally describe interaction with 3D models, whereas the term “3D image interaction” focuses on interaction with 2D-to-3D-converted medical images.

In VR, a necessary part of interaction is movement, also called “locomotion” (e.g., Cardoso & Perrotta, 2019), or “travel” (Bowman et al., 1998). Bowman et al. (1998) define movement (travel) as “the control of the user’s viewpoint motion in the three-dimensional environment”, one of VR applications’ most fundamental and widespread interactions. The user often needs movement to adjust their location in the VR environment (Rantala et al., 2021). Movement methods, or “locomotion techniques” (e.g., Rantala et al., 2021) allow this movement to happen. Movement in VR is expected to influence important aspects of the user experience, including enjoyment, frustration, effort, presence, and motion sickness (Hale & Stanney, 2014). Additionally, it has been demonstrated in the movement method studies that the choice of movement method affects user experience (e.g., Bozgeyikli et al., 2019) and that the context of the VR environment affects the suitability of the movement method (Drogemuller et al., 2020).

The framework introduced in Ragan et al. (2015) outlines three distinct types of VR fidelity, of which two of them, interaction fidelity and display fidelity, are discussed here. Interaction Fidelity pertains to the realism of the input devices used and how effectively they replicate real-world interactions (also discussed in McMahan et al., 2016). Display Fidelity instead focuses on the realism of the output devices employed and their ability to reproduce visual sensory stimuli accurately. Two things can be pointed out from this framework, in the context of 3D-VR medical image interaction. One, hardware and software impact the realism of the 3D image. As earlier discussed, current technology is capable of converting 2D medical images into 3D without sacrificing quality. Despite significantly depending on the display device (especially in VR), achieving a high level of display fidelity in medical 3D image interaction is indeed possible. Regarding interaction fidelity, it is important which movement methods are used for interacting with 3D medical images, as they can increase or decrease the realism of the interaction. An example could be given from the context of assessing AI-created segmentation results from 3D medical models. For segmentation assessment, the user needs to be able to explore the 3D model easily from each angle and to investigate the segments from a short distance, by using small, detailed movements.

While there is comprehensive research available concerning VR movement methods in the field of HCI, no previous research was found focusing on movement methods used for interacting within a virtual environment where the focus is on the 3D model itself. For the present study, 42 papers from Andor and Google Scholar were found with the search query "(virtual reality OR vr OR augmented reality OR ar OR mixed reality OR mr) AND 3d model" and further analyzed. The methods for the methodological analysis are discussed in detail in Chapter 2. A 3D model in XR was investigated in each of the papers. Most of the studies were done from a medical perspective. In the medical studies, XR (mostly VR) was used to convert 2D medical images into 3D. These findings suggest that specifically in the medical field, there seems to be interest in small-scale, refined 3D-XR model interaction, particularly in 2D-to-3D medical image conversion.

The ability to explore 3D models relies on two fundamental components: the navigation within the virtual space through movement methods, and the manipulation of the 3D model itself through methods of object manipulation. Therefore, these methods must be researched from an HCI perspective. Object manipulation of medical 3D-XR models has been studied in Rantamaa et al. (2023). However, it was found that besides a conventional mouse, input methods used for object manipulation had difficulties in precision. Therefore, in the thesis, VR movement methods are investigated instead.

For the thesis, an experimental study was conducted comparing three movement methods, Diving, Grabbing, and Teleporting. The aim of the study was to find out which movement methods (if any) are best suitable for 3D-VR image interaction. Diving was considered significantly more successful compared to Teleporting. Diving and Teleporting were equally fast, whereas Grabbing was significantly slower compared to the two movement methods. It was found that the less-studied movement method Diving was rated the best in most of the rating scales. However, there were variations in participants' subjective opinions, supporting the design conclusion that a VR system for investigating medical 3D models should utilize multiple movement methods.

The structure of the thesis is as follows: for background information, first, 3D-VR medical images are discussed in Chapter 2 “3D-VR Medical Models”, to present a methodological review of papers where the focus is on 3D-XR model interaction in VR, AR, and MR. The aim of the review is to demonstrate a research gap that is addressed in the thesis, as well as to show, that a specific interest in medical 3D-VR images was observed across the studies found for the review. Additionally, a discussion on the benefits of 3D-VR medical images is included in Chapter 2. Second, a new taxonomy for movement methods is proposed in Chapter 3 “Movement Method Taxonomy”, extending the work done in Cherni et al. (2020) and Boletsis & Chasanidou (2022). This is done to fill the gaps in previous research and to place the movement methods used in the current study under a theoretical framework. Third, movement method categories along with their example methods are discussed in Chapter 4 “Movement Method Categories”. This is done to elaborate the new taxonomy further. Fourth, the research methods used for the experiment are explained in Chapter 5 “Methods”, where the movement methods, participants, apparatus, and experimental design are elaborated. Fifth, the study results are explained in Chapter 6 “Results”, where quantitative and qualitative results are presented separately. Sixth, the discussion based on the study is presented in Chapter 7 “Discussion”, with additional discussion on the limitations of the current study as well as on the future 3D-VR model interaction studies. Finally, the conclusions of the paper are presented in Chapter 8 “Conclusions”.

2. 3D-XR Medical Models

In this chapter, 3D-XR models are discussed, which generally describe 3D models in VR, AR, and MR. More specifically, the focus is on 3D-XR medical models, meaning that the 3D-XR models are used for medical purposes (e.g., displaying an organ, or a part of the body).

In Section 2.1, a methodological review of papers investigating 3D-XR models is presented, to suggest (1) that 3D-XR image interaction and more specifically 2D-to-3D medical image conversion has been an interest in the medical field, (2) with most of the studies investigating 3D-VR model interaction specifically, and (3) that there is indeed a research gap in 3D-VR model interaction studies from an HCI-perspective. Methods of literature retrieval are discussed in Section 2.1.1. In Sections 2.1.2–2.1.5, the findings of the methodological review are examined. In Section 2.2, the benefits of using 3D-XR medical models are discussed. In Section 2.2.1, the focus is specifically on the benefits of 3D-VR medical images compared to their original 2D versions. The aim is to claim that the use of 3D-XR medical models can be important in the field of medicine and that in particular, 3D-VR medical images have additional benefits over 2D medical images. A summary of the chapter is included in Section 2.3.

2.1. Analysis of Papers Investigating 3D-XR Models

The aim of a methodological review is to find out how research is conducted rather than focusing on the research findings (Chong & Reinders, 2021). For the thesis, a methodological review was used to reveal potential research gaps regarding how 3D-XR model interaction research has previously been conducted. Additionally, the main perspectives of the reviewed research are identified.

Four research questions (RQ), as well as four sub-questions (SQ), were addressed in the review. These questions are not to be mistaken for the research questions of the experimental study explained later, as answers to these questions produce the main findings for the thesis. The research questions and the sub-questions for the review were the following:

RQ1: From which scientific perspective are 3D-XR model interaction studies conducted?
    SQ1: If papers from the medical field are retrieved, what detailed perspectives do they include?
    SQ2: If papers from the medical field are retrieved, how many of them involve the use of 2D-to-3D medical image conversion?
RQ2: What XR types are used in 3D-XR model interaction studies?
RQ3: Are movement methods used in 3D-XR model interaction studies?

- SQ1: If papers utilizing movement methods are retrieved, what movement methods are used?
- SQ2: If papers utilizing movement methods are retrieved, how is the use of movement methods justified?
- SQ3: If papers utilizing movement methods are retrieved, how many of them involve an experimental study to compare the movement methods?

RQ4: Do the 3D-XR model interaction studies describe controls of the XR software in detail?

With the first research question along with its sub-questions, the aim was to find out whether medical papers occur more often than non-medical papers (RQ1), what detailed perspectives of the medical papers (e.g., radiology) occur most often (SQ1), and whether 2D-to-3D image conversion is utilized in most of the medical papers (SQ2). These questions were used to justify the medical perspective of the thesis. With the second research question, the goal was to find out whether VR is the most utilized XR type in the 3D-XR model interaction papers (RQ2). The question was applied to validate the use of VR in the thesis. With the third research question along with its sub-questions (RQ3, SQ1, SQ2, SQ3), the aim was to validate the use of movement methods and the HCI perspective of the thesis. Finally, the fourth research question (RQ4) was used to further justify the HCI perspective.

2.1.1. Retrieval of literature

Half of the papers (n=21) were retrieved from Andor and the other half (n=21) from Google Scholar, with the search query "(virtual reality OR vr OR augmented reality OR ar OR mixed reality OR mr) AND 3d model". The papers were retrieved during the timeframe from December 13th to 14th.

There were several inclusion criteria for the papers. Regarding the topics of the papers, the focus needed to be on investigating one or two 3D models at a time or a single 3D visualization of a three-dimensional structure. If the user needs to focus on multiple different 3D models simultaneously, they would not be able to carefully investigate the 3D models, thus being out of scope for the current study. In the case of 3D models, they needed to be large enough for the user to move and visualize them from different angles (not small, grabbable VR objects), but small enough for the user to inspect them in a smaller area (not room-sized or larger architectural structures). This is due to the context of the 3D-XR model interaction of interest. Papers where 3D modeling and model assembly tasks were mainly involved were not accepted, as these represent a different type of 3D-XR model interaction. Finally, the papers needed to include some kind of depiction of how the user uses the XR software – therefore, papers where the focus was only on technical details were excluded from the analysis.

Related to hardware-specific details with AR and MR, the 3D models or visualizations needed to be displayed with a head-mounted device (HMD) or another device where the user looks through two lenses to see the content. This was required because some studies that utilized AR and MR used a tablet or a mobile device to display the content. This is out of the scope of the current thesis, where precise interaction is needed.

Related to the general requirements of the papers, all papers needed to be peer-reviewed, non-duplicate, and published in an academic journal or a conference. Review papers were not included, as they do not focus on producing state-of-the-art.

Even though there was a total of 31 233 papers in Andor and 1 440 000 in Google Scholar, only the first 21 papers that filled the above criteria were retrieved from both databases. This was due to the vastness of the search results. A total of 186 papers were excluded from the analysis based on the inclusion criteria. In addition, two papers were excluded as they were not publicly available. In **Table 1** (p. 8), the papers found for the analysis are presented.

2.1.2. From which scientific perspective are 3D-XR model interaction studies conducted?

In this Section, the first research question of the review “From which scientific perspective are 3D-XR model interaction studies conducted?” is addressed, along with its sub-questions “If papers from the medical field are retrieved, what detailed perspectives do they include?”, and “If papers from the medical field are retrieved, how many of them involve the use of 2D-to-3D medical image conversion?”.

Most of the papers were done from a medical perspective. This suggests an interest in 3D-XR model interaction specifically in the medical field – at least when the context is small-scale interaction without the focus on 3D modeling and assembly tasks.

All medical papers were centered on the medical professional point-of-view. It is particularly interesting, that an HCI perspective was not employed in any of the studies. For the thesis, only three papers focused on small-scale 3D-XR model interaction from an HCI perspective were found (Li et al., 2021; Sousa et al., 2017; Rantamaa et al., 2023), but none of these papers were included in the current analysis. This indicates a research gap in small-scale 3D-XR model interaction from an HCI perspective, where the focus is on the interaction methods rather than on field-specific information.

The most prevalent themes of the medical papers (themes can co-occur in some of the papers) were “Medical education” (n=12), “Surgical planning” (n=10), and “Surgical training” (n=6). Additional themes were “Radiology” (n=4) and “Intraoperative guidance” (n=2). From the non-medical papers, the most prevalent theme was “Art and Archeology” (n=3), followed by “Experimental media archeology” (n=1), “Neuroscience” (n=1), “Geology” (n=1), “Engineering” (n=1), “Science education (n=1), and “Forensics” (n=1). Therefore, 3D-XR models have been mostly developed and studied for use in the field of surgery as well as for medical education purposes in the analyzed studies. There also seems to be some interest in 3D-XR models from a radiological perspective.

In most of the medical papers, converting 2D medical images (such as Computed Tomography, Magnetic Resonance, and Echo Imaging) into 3D representations was involved. Therefore, regarding 3D-XR model interaction, it seems that especially 2D to 3D-XR image conversion is of medical field's interest.

ANDOR					**GOOGLE SCHOLAR**				
Number and name of the paper	**Theme**	**XR type**	**Medi-cal paper**	**MM used**	**Number and name of the paper**	**Theme**	**XR type**	**Medi-cal paper**	**MM used**
1. Awori et al. (2023)	Medical education	**VR**	**X**		1. Ammanuel et al. (2019)	Medical education	**VR**	**X**	**X**
2. Aydin et al. (2023)	Surgical training	**VR**	**X**		2. Barsanti et al. (2015)	Art and Archeology	**VR**		
3. Bairamian et al. (2019)	Surgical training and -planning	**VR**	**X**		3. Boedecker et al. (2021)	Surgical planning	**VR**	**X**	**X**
4. Banfi et al. (2023)	Art and Archeology	**VR/ AR**		**X**	4. Calì et al. (2016)	Neuroscience	**VR**		**X**
5. Barber et al. (2018)	Surgical training	**MR**	**X**		6. Fairén et al. (2017)	Medical education	**VR**	**X**	**X**
6. Benmahdjoub et al. (2022)	Intraoperative guidance	**AR**	**X**		7. Falah et al. (2014)	Medical education	**VR**	**X**	
7. Burström et al. (2019)	Intraoperative guidance	**AR**	**X**		8. Frajhof et al. (2018)	Surgical planning	**VR/ MR/ AR**	**X**	
8. Cho et al. (2021)	Surgical planning	**MR**	**X**	**X**	9. Horvat et al. (2019)	Engineering	**VR**		**X**
9. Greuter et al. (2021)	Medical education	**VR**	**X**	**X**	10. Izard & Mendez (2016)	Medical education	**VR**	**X**	**X**
10. Harkema & Rosendaal (2020)	Experimental media archeology	**VR**			11. Izard et al. (2017)	Medical education	**VR**	**X**	
11. Janeras et al. (2022)	Geology	**MR**		**X**	12. Izard et al. (2018a)	Radiology	**VR**	**X**	**X**
12. Jo et al. (2021)	Surgical planning	**VR/ AR**	**X**		13. Izard et al. (2018b)	Surgical training	**VR**	**X**	
13. Karmonik et al. (2018)	Surgical planning	**AR**	**X**	**X**	14. Izard et al. (2019)	Radiology	**VR/ AR**	**X**	**X**
14. Krause et al. (2023)	Medical education	**VR**	**X**		15. Izard et al. (2020)	Radiology	**VR/ AR**	**X**	
15. Mahrous et al. (2021)	Medical education	**AR**	**X**		15. Koller et al. (2019)	Forensics	**VR**		**X**
16. McJunkin et al. (2018)	Surgical training	**MR**	**X**		16. Liou & Chang (2018)	Science education	**VR**		
17. Moro et al. (2017)	Medical education	**VR/ AR**	**X**		17. Nicholson et al. (2006)	Medical education	**VR**	**X**	
18. Van Nguyen et al. (2022)	Art and Archeology	**VR**			18. Ong et al. (2018a)	Surgical planning	**VR**	**X**	**X**
19. Santa-Bárbara et al. (2023)	Surgical planning	**VR**	**X**	**X**	19. Ong et al. (2018b)	Radiology	**VR**	**X**	**X**
20. Towers et al. (2022)	Medical education	**VR**	**X**		20. Roh et al. (2021)	Surgical training	**VR**	**X**	
21. Zari et al. (2023)	Surgical planning	**MR**	**X**	**X**	21. Stadie et al. (2008)	Surgical planning	**VR**	**X**	

Table 1. Summary of the papers retrieved for the methodological analysis.

2.1.3. What XR types are used in 3D-XR model interaction studies?

In this Section, the second research question of the review "What XR types are used in 3D-XR model interaction studies?" is answered. VR was the primary focus among XR types in most papers. AR, MR, or combinations such as VR & AR and VR, MR & AR were discussed in the rest of the papers. The findings suggest that VR specifically seems to be the main reality type in 3D-XR model interaction. The reason for this could be that VR head-mounted displays have been generally available for commercial use (Cipresso et al., 2018). Another reason might be that in many of the papers, the focus was on medical education, surgical planning, or -training. Therefore, it might be relevant to fully block the real environment to either simulate a specific scenario or to fully focus on the 3D model by reducing other visible stimuli.

2.1.4. Are movement methods used in 3D-XR model interaction studies?

In this Section, the third research question of the review "Are movement methods used in 3D-XR model interaction studies?" is addressed, along with its sub-questions "If papers utilizing movement methods are retrieved, what movement methods are used?", "If papers utilizing movement methods are retrieved, how is the use of movement methods justified?", and "If papers utilizing movement methods are retrieved, how many of them involve an experimental study to compare the movement methods?". Movement methods were utilized in approximately half of all the papers (n=18). The movement methods that could be recognized as existing methods (can co-occur in papers where more than one movement method is used) were Real walking (n=9) and Teleporting (n=3). The frequent use of Real walking is probably due to two factors: (1) it allows interaction using real body movements, making it suitable for people who have less XR experience (Cardoso & Perrotta, 2019), and (2) it is easy to provide, as the needed sensor-tracking sometimes comes automatically with XR systems (N. Rasouli, personal communication, June 2023). Teleporting on the other hand is a commercialized VR movement method (Prithul et al., 2021), therefore many of its implementations are available for use by people with basic programming knowledge.

Additionally, the utilization of a movement method was mentioned in some studies, yet it was not possible to categorize any existing movement methods due to the generic description of the method (n=6). In one of these papers, the movement method was generally described as "gaze-controlled" without further description (Ammanuel et al., 2019). It was also mentioned that it was possible to "go inside" the 3D model (Izard et al., 2018a), or "move around" it (Izard et al., 2019). The lack of description of the movement method could result from the unfamiliarity with XR technologies as well as due to field-related differences. For example, authors from the medical field probably do not see the used interaction techniques as relevant as authors from the field of Human-Computer Interaction (J. Kangas, personal communication, May 2023).

The use of a movement method was mainly justified in some of the papers by being able to go inside the 3D model or move around it. Therefore, some of the benefits related to movement methods appear to be acknowledged in the papers. Nevertheless, reasoning for the use of a specific movement method, such as Teleporting, is not provided in these papers. In a paper that was not part of the current analysis, reasoning was given for why a specific movement method was used (Liimatainen et al., 2021). In the study, Teleporting was meant to allow long-distance movement while preventing motion sickness, while Joystick was used for small-scale movement within the model. This aligns with movement method studies, where continuous artificial movement (such as Joystick) has been found to increase motion sickness, whereas Teleporting has been rarely found to cause motion sickness (e.g., Christou & Aristidou, 2017, discussed further in Chapter 7). All the movement methods mentioned here are explained more in Chapter 4.

Although movement methods were mentioned in nearly half of the analyzed papers, an experiment to test the utilized movement methods was not conducted in any of them. Therefore, it is impossible to know, whether the movement methods that were used in the studies are suitable for refined, small-scale interaction with a 3D model. In addition, only three papers focusing on small-scale 3D-XR model interaction from an HCI perspective were found (Li et al., 2021; Sousa et al., 2017; Rantamaa et al., 2023), but none of these papers were found from the current analysis.

2.1.5. Do the 3D-XR model interaction studies describe controls of the XR software in detail?

In this section, the fourth research question of the review “Do the 3D-XR model interaction studies describe controls of the XR software in detail?” is addressed. The phenomenon of interaction methods’ vague descriptions was also visible by looking at the extent to how in detail the controls were described. Only in a few of the analyzed studies, the controls for the commands were described in enough detail. The controls were seen as described in detail if all the commands were mentioned along with their controls. Vague control descriptions, such as “using the right controller” were not seen as enough. Imprecise depictions of the controls could also be caused by unfamiliarity with XR technologies and field-related differences.

2.2. Benefits of 3D-XR Medical Models

There were several promising results of medical teaching with 3D-XR models. In Alfalah et al. (2019), it was found that the VR system significantly improved participants’ anatomy learning experience compared to the traditionally used models. Additionally, the VR manipulation methods enhanced the understanding of heart anatomy within participants.

In two studies, using XR was found to help the participants achieve higher test results on medical exams. The group with 3D-VR training was found to succeed better on a test, compared to the control group (Maresky et al., 2019) It should however be noted that the control group had less training before the experimental task compared to the 3D-VR group. On the other hand, in Bogomolova et al. (2020), differences in overall test results were not found among the 3D-AR, 3D-desktop, and 2D groups. However, the students with the most difficulty in visual-spatial ability performed better in the 3D-AR group, highlighting the value of XR in understanding spatial relations (as also reported in Molina-Carmona et al., 2018).

In Moro et al. (2017), groups who learned with 3D-VR and 3D-AR applications reported enhanced engagement, enjoyment, and participation compared to group learning with a tablet-based application. Additionally, 3D-VR and 3D-AR-based learning were as effective as tablet-based learning – however, some participants experienced blurred vision, disorientation, and motion sickness with the 3D-VR group. A suitable movement method can reduce experiences of disorientation (Bhandari et al., 2018) and motion sickness (Prithul et al., 2021). In Nakai et al. (2022), it was found that providing access to course materials in a VR environment was highly beneficial for medical students. The ability to manipulate anatomical structures by moving and modifying them was also appreciated.

Promising results were also visible in surgical training. In Siff & Mehta (2018), it was reported that the introduction of an AR surgical training program led to a notable increase in trainee satisfaction when compared to their conventional preparation methods. In Roh et al. (2021), it was discovered that the participants preferred photographic 3D-VR models over traditional models. Practicing virtual surgery with photographic 3D models was thought to enhance the participants' surgical skills and facilitate the development and exploration of new surgical techniques. In Santa-Bárbara et al. (2023), 3D-VR models were found to be equally capable as 3D-printed models for classifying proximal humerus fractures. VR was also found suitable for providing training in orthognathic surgery in a clinical setting (Pulijala et al., 2018).

Regarding presurgical planning, an evaluation of a VR system for liver surgery was conducted in Boedecker et al. (2021). The evaluator group consisted of five surgeons who had expertise in hepatobiliary surgery. The surgeons found the VR system to be helpful and easy to use. Additionally, it was reported in Reinschluessel et al. (2019), that surgeons found it very useful to transform 3D-printed organ models into VR. VR made it much easier to understand spatial relationships, which could greatly enhance surgical planning. The results in Frajhof et al. (2018) demonstrate, that the 3D model used in a medical case was seen as precise. The used model greatly aided in planning and performing the surgery. Therefore, it was concluded in the paper that the utilization of XR to display a patient's

3D data is proven to be a valuable tool for surgical planning, providing surgeons with an accurate representation of the patient's anatomy in a spatial context. Finally, it seemed that XR systems originally made for surgical training, had additional potential in presurgical planning in urogynecology (Siff & Mehta, 2018) and in orthopedics (Santa-Bárbara et al., 2023).

2.2.1. Benefits of 3D-VR medical images

One of the benefits of 3D-VR medical images is that they are commonly converted from 2D slices into more realistic 3D models (Bakhuis et al., 2022). 3D-VR images aid medical professionals by allowing intuitive manipulation with VR controllers (Gao et al., 2012; Bakhuis et al., 2022), including rotation and dissection (Gao et al., 2012).

In Gao et al. (2012), converting High-Resolution Computed Tomography (HRCT) images to 3D-VR was studied in the context of 9-19-year-old Congenital Aural Atresia (external auditory canal development failure, CAA) patients. It was suggested that 3D-VR images could illustrate spatial relationships between ear structures in treating CAA. The authors found that both HRCT and 3D-VR images give important information concerning the preoperative planning of CAA patients. From a single 3D-VR image, various factors, such as the complete lengths of the tympanic and mastoid segments could be determined, in addition to the morphological differences of the small ossicles. This highlights the usefulness of 3D-VR HRCT images in understanding spatial relationships.

3D-VR medical images have been studied for use in surgical training. In Hosoya et al. (2022), it was found that the subjective understanding of paranasal sinus anatomy was significantly higher when learning with CT and VR images than by solely using CT images. Participants without VR experience (70% of 27) did not have problems in operation and found the learning experience efficient and enjoyable. Additionally, it was discovered in Agarwal et al. (2012) that by using volume segmentation to highlight object vascular pathology and combining CTA and MRI images, trainees can better grasp patient-specific anatomy and challenges in aneurysm surgery from various angles. This approach also enables neurosurgery residents to practice surgical planning and visualize the procedure.

Additionally, 3D-VR medical images have been found potential for use in presurgical planning. In the context of cardiology, utilizing existing imaging data for presurgical planning through VR is both feasible and practical (Ong et al., 2018a). Regarding radiology, using VR for viewing CT-scan images improves the understanding of radiological findings (Oulefki et al., 2022). This makes the use of 3D-VR images promising for medical treatment planning.

With the current general interest in AI, automated segmentation of 3D-VR images is the focus of several studies. In Bakhuis et al. (2022), AI segmentation with 3D-VR-converted Contrast-Enhanced CT (CECT) images was investigated in the context of child patients with Congenital Lung Abnormality (CLA). The authors elaborated on how pre-operative conventional 2D CECT imaging might result in imprecise localization of CLA lesions, consequently contributing to incomplete resections. After the 3D-VR visualization, a greater level of agreement on the localization of CLA in lung segments was reached by the surgeon and radiologist. Hence, 3D-VR CECT images can provide both the radiologist and surgeon with more precise details regarding the extent of CLA segment involvement.

2.3. Summary

The analysis done in the chapter gives validation for the context of the current research. Firstly, most 3D-XR model interaction studies that involve the investigation of smaller 3D models without focusing on 3D modeling or assembly tasks, seem to be conducted from a medical perspective. Additionally, most of these studies seemed to specifically focus on VR use. Almost half of all the 3D-XR model interaction papers included the use of at least one movement method. However, no studies were found that compare the used movement methods for this specific context.

Secondly, 3D-XR model interaction seems to have different benefits. It increases spatial learning ability, which is needed for the full understanding of human structures (e.g., organs, veins). 3D-XR models seem to produce effective tools for surgery planning and teaching. More specifically, 3D-VR medical images appear to further the understanding of anatomy and radiological findings. One reason for this could be that in VR, it is possible to block all the visual distractions in the real environment and only focus on the 3D model itself. Therefore, 3D-VR models are fitted for scenarios of medical planning where the patient is not physically involved, as well as self-learning or remote teaching about human structures.

3. Movement Method Taxonomy

In the thesis, the term “movement” is used to describe adjusting the user’s viewpoint in the VR environment, and the term “movement method” is used to describe the technique that allows this adjustment to happen. This is justified due to the term “travel” being often associated with long distances (Razzaque, 2005), and the term “locomotion” being often associated with longer distances than in 3D-VR image interaction. Movement methods belong inside the umbrella term “interaction technique”. Foley et al. (1990) define interaction technique as the method or approach used to facilitate engagement between a user and a system. It involves the combination of physical devices, the actions performed by the user (whether physical or mental) while using those devices, and the system's response. This response can be in physical form or entirely digital, encompassing the feedback necessary for the user to understand the outcomes of their actions within the system. Thus, in the context of 3D-VR image interaction, both the movement methods and the image manipulation methods (e.g., slicing or rotating the model) are considered interaction techniques.

As there are an extensive amount of movement methods, classifications have been created for them in some studies. However, these classifications are often too narrow or imprecise. This is discussed in Section 3.1 “Earlier Categorizations”. Therefore, a new taxonomy is presented in Section 3.2 “Updated Taxonomy”.

3.1. Earlier Categorizations

Regarding movement method studies, a challenging factor for establishing solid categorizations is that the terminology of different movement methods varies substantially. For example, in this study, the term “Grabbing” is used, whereas in Rantala et al. (2021) the term “Grab” is used, and in Zhang et al. (2019) the term "Swimming” is used, even though all three closely related movement methods.

Another challenge is the variability of closely related interaction techniques. To use the same studies as demonstration (current study; Rantala et al., 2021; Zhang et al., 2019), “Grabbing” in this study, would be classified under the same final category as “Grab” and “Swimming”. However, full 3D flight (discussed later in the chapter) is possible with “Grabbing”, whereas “Grab” and “Swimming” are described to only include forward movement. Some interaction techniques might use the same name even though the movement is produced differently. For example, “Flying” is often used with a body gesture or with a button of a controller (Bozgeyikli et al., 2019).

In addition to the variation of the movement commands, there is variability in the input methods between closely related interaction techniques. “Grab” uses a single VR controller for the movement, whereas “Grabbing” and “Swimming” use both VR controllers. “Grabbing” involves grabbing the controllers (discussed in Chapter 5) for registering movement, whereas “Grab” uses a trigger button, or both trigger buttons in the case of “Swimming”, to register movement. As hybrid movement methods (combining two or more movement methods) are emerging, further classification problems appear (Boletsis & Chasanidou, 2022).

Additionally, different results are presented by the studies focusing on establishing categorizations. For example, Boletsis & Chasanidou (2022) focus on creating a taxonomy based on three attributes (interaction type, VR motion type, VR interaction space), which sort each movement method into different categories (VR locomotion type). Cherni et al. (2020) on the other hand split movement methods into groups based on the movement type (e.g., is the movement based on leaning of the body, or artificial methods, such as a VR controller). Due to different categorizations, researchers might have problems distinguishing which should they use in which situation.

An issue with categorizations in Boletsis & Chasanidou (2022) and Cherni et al. (2020) is that they lack some information. Therefore, neither establishes a complete categorization for existing movement methods. For argumentation, categorizations done in both papers are presented along with a discussion of their issues.

3.1.1. The taxonomy in Boletsis & Chasanidou (2022)

Figure 1 (p. 16) presents the movement method taxonomy proposed in Boletsis & Chasanidou (2022), which is based on the previous work done in Boletsis (2017). The movement methods are divided into three attributes: interaction type, VR motion type, and VR interaction space. Interaction type is categorized as either "physical", based on body movement, or "artificial," reliant on external output methods, typically a VR controller. Regarding VR motion type, both physical and artificial movement methods are labeled as "continuous" or “non-continuous”. Continuous VR motion refers to uninterrupted motion where the user must control the movement to reach the desired destination. Non-continuous VR motion on the other hand refers to motion where the user instantly moves from one location to another. VR interaction space is divided into two groups: “open” and “limited”. Open VR interaction space implies that the VR environment is wider than a physical room, while limited space means that the environment is equal to a physical room, or smaller.

Finally, five VR movement method types are distinguished from the taxonomy: Motion-based, Motion-based Teleporting, Room-scale-based, Controller-based, and Controller-based Teleporting. Motion-based methods have a physical interaction type, continuous motion type, and open interaction space. Examples of methods include Walking-in-place, Redirected walking, Gesture-based movement, and Arm-swinging. Motion-based teleporting methods have the same attributes, except the motion type is non-continuous. Gesture-, Gaze-, and Redirected teleportation are mentioned as examples of methods. Room-scale-based methods have a physical interaction type and, a continuous motion type, but a limited interaction space. The only movement method mentioned as an example is Real walking. Controller-based methods have an artificial interaction type, continuous motion type, and open interaction space. Examples mentioned are Joystick-based movement, Human joystick, Chair-based movement, and Head-directed movement. Finally, methods of Controller-based Teleportation have the same attributes as Controller-based methods, but the motion type is non-continuous. Joystick-based Teleportation is mentioned as an example of this category.

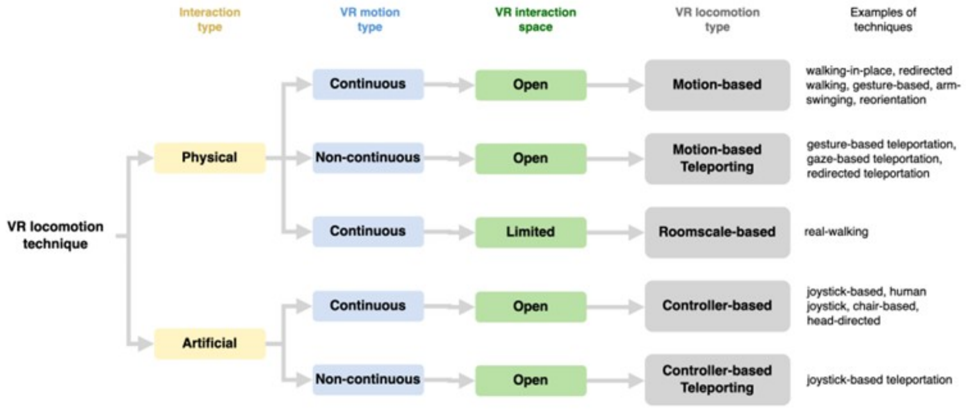

Figure 1. A movement method taxonomy in Boletsis & Chasanidou (2022).

The taxonomy in Boletsis & Chasanidou (2022) can certainly distinguish most movement methods, and the attributes used in the categorization process are relevant. However, issues can be found in taxonomy as well. While Real walking can only be used in a limited VR environment, Motion-based-, and Controller-based methods, as well as methods of Motion-based-, and Controller-based Teleporting can also be used in a limited VR environment[1]. Findings from the methodological review discussed in Chapter 2 indicate that although Real walking was often used for 3D-XR model interaction done in limited space, other movement methods were also utilized (although fewer in number). Drogemuller et al. (2020) state, that when navigating extensive graphs within a room-scale VR setup, relying solely on walking to reach a particular point in the graph may be insufficient due to spatial limitations. The same applies in the context of 3D-VR interaction. Additionally, wired VR headsets are still frequently used, which restricts the use of Real walking.

There are issues between Motion-based and Controller-based movement method categories as well. The Motion-based category is too broad: there are walking simulation methods along with gesture-based techniques, although it would be logical to separate them. Regarding the Controller-based category, there are movement methods that according to the taxonomy in Cherni et al. (2020) are based on physical, leaning-based body

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[1] However, as with open VR environments, some movement methods are expected to work more efficiently in limited VR environments than others.

movements (Human joystick, Head-directed methods, Chair-based methods), even though the category should only include movement methods based on artificial interaction.

Finally, as the movement methods are only divided into continuous and non-continuous, where does Jumping (Weißker et al., 2018), which is located in between the two movement types, belong? The taxonomy is not able to answer this question. Jumping as explained in Weißker et al. (2018) implies that between beginning and destination points, the user is instantly transported along multiple points. This differs from continuous motion, where movement is constantly perceived, and from non-continuous, where the user instantly transports from the beginning to the destination point.

3.1.2. The taxonomy in Cherni et al. (2020)

Figure 2 (p. 18) presents the movement method taxonomy done in Cherni et al. (2020). The movement methods are divided into three main categories: User-body-centered, External peripheral-centered, and Mixed movement methods.

"User-body-centered" implies that the movement is initiated by the user's body movement (Cherni et al., 2020). This category is divided into two subcategories: leaning-based and walk simulation. Movement in leaning-based methods is accomplished by tilting the body or certain body parts in the chosen direction, with various body parts being monitored to detect motion in the user. Therefore, leaning-based movement methods are divided into three subcategories: head-based-, trunk-based-, and arm-based motion capture. Examples of each subcategory include Walk-in-place (Lee et al., 2018; head-based motion capture), NaviChair (Kitson et al., 2017b; trunk-based motion capture), and Point and teleport with arm gestures (Bozgeyikli et al., 2016b; arm-based motion capture). In the walk simulation category, Redirected walking (Razzaque, 2005) is the only movement method mentioned. It allows the users to move in a broader VR environment like with Real walking, but within a limited physical environment. This is done by rotating the view in HMD so that the user walks in a circular motion (rather than straight) to avoid physical obstacles.

External peripheral-centered movement methods utilize an external input method to initiate movement in VR. These methods are divided into two subcategories: semi-natural and non-natural. Semi-natural movement methods aim to remind Real walking as much as possible. This is achieved by using different devices where walking is registered, such as an Omnidirectional treadmill (Warren & Bowman, 2017), or the Virtusphere device (Nabiyouni et al., 2015). Non-natural movement methods essentially combine both Controller-based and Controller-based Teleporting categories in Boletsis & Chasanidou (2022). Non-natural movement methods do not rely on physical movement but use an external controller instead to initiate VR translations. Examples include Point and Teleport with a VR controller (Habgood et al., 2018), and World-in-miniature (Berger & Wolf, 2018).

Mixed movement methods combine leaning-based and External peripheral-centered methods. Examples included in the paper combine trunk leaning with Joystick (Kruijff et al., 2015), and head-tilting with Stepper machine (Bozgeyikli et al., 2016a). Additionally, head-tilting combined with Walk-in-place (Ohshima et al., 2016) is mentioned, even though both seem to be categorized as leaning-based methods in the taxonomy. Thus, there seems to be some unclarity regarding the category.

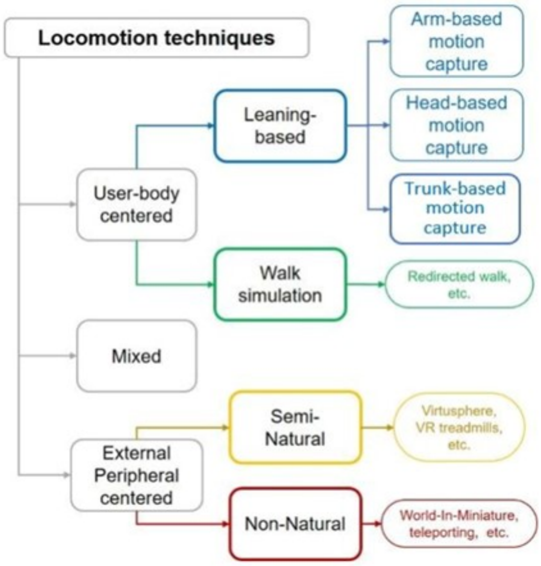

Figure 2. A movement method taxonomy in Cherni et al. (2020).

As with the taxonomy done in Boletsis & Chasanidou (2022), the taxonomy in Cherni et al. (2020) includes many positive aspects. The categorization of movement methods based on the type of motion offers a different approach compared to the taxonomy in Boletsis & Chasanidou (2022). It also partially addresses concerns within both Motion-based and Controller-based categories (Boletsis & Chasanidou, 2022), as well as acknowledges hybrid methods. However, the taxonomy proposed in Cherni et al. (2020) does present certain issues.

Regarding leaning-based methods, it can be argued that some of the mentioned methods are not leaning-based (e.g., Point and teleport with arm gestures, Arm swinging, and Walk-in-place). According to the taxonomy, a movement method is considered "leaning-based" when motion capture is used to distinguish movement. However, Cherni et al. (2020) describe: "In leaning-based locomotion techniques, walking is achieved by leaning the whole body or just parts of it into the desired direction". This implies that leaning-based methods are (1) based on continuous movement and (2) based on tilting of the body or specific body parts in the wanted direction. Therefore, Point and teleport would not be considered leaning-based as it is not a continuous movement method. Additionally, Walk-in-place would not be a leaning-based method as it only relies on head tracking to determine rotation translation, and both Walk-in-place and Arm swinging utilize repetition of a gesture to achieve simple forward movement, rather than tilting the body per se.

For walk simulation methods, the category seems to only include Redirected walking. However, many other movement methods simulate walking, including Walk-in-place, Omnidirectional treadmill, and Virtusphere device. Therefore, the category does not seem logical. Another question regarding the User-body-centered category is where Real walking belongs. The authors seem to categorize Real walking as a leaning-based method (Cherni et al., 2020; Table 2, p. 17), even though the movement is not mainly achieved by body tilting.

Regarding external peripheral methods, the categorization between semi-natural and non-natural does not seem logical, as the movement producing differs quite substantially in both categories. Even though semi-natural methods use external methods of giving movement input, they are still centered on body movement produced by the user, differing from non-natural methods. Another issue lies in the names of the categories: semi-natural and non-natural. It should be asked when a movement method can be considered "natural". As Real walking is the only movement method that uses the same movement as in a real environment without the need for learning, it is also the most "natural". However, to which methods should "semi-natural"- and "non-natural" methods be compared for them to be classified as such? If compared with each other, using a game controller for VR translations could feel more "natural" to the user as it can resemble playing video games, while walking inside a big sphere or on an Omni-treadmill with a restricting harness might feel more "unnatural" for the user. In the context of movement methods categorized as "semi-natural" and "non-natural", both represent a learned relationship, rather than a natural one. Therefore, the word "natural" should not be used.

Finally, Cherni et al. (2020) lack a clear description of the differences between leaning-based Point and teleport and non-natural Point and teleport. It is not said in the text, what is the difference. Only at the end of the paper, a table is found (Cherni et al., 2020; Table 2, p. 17), where Point and teleport is classified as leaning-based, when it only relies on arm gestures, and non-natural, when it relies on VR controllers. This categorization is only visible from the font colors of the movement method names, which were used in the movement method taxonomy (Figure 2).

This section ends by concluding that as movement methods are becoming increasingly more complex due to emerging hybrid forms and diversity, the classifications of the movement methods must include this complexity as well. Therefore, modern movement method taxonomies cannot be made too simple. In the context of 3D-VR model interaction and the studied movement methods of Diving, Grabbing, and Teleporting, there is a need for a new taxonomy, as the taxonomy in Boletsis & Chasanidou (2022) does not include all the possible movement methods for interaction in a limited VR environment, and some of the categories in the taxonomy presented on Cherni et al. (2020) lack clarity. Finally, both taxonomies do not distinguish the movement methods between movement preciseness nor whether the movement method is ground-based (no vertical movement) or flight-based (additional degrees of freedom with vertical movement).

3.2. A New Taxonomy

Figure 3 (p. 21) displays a new movement method taxonomy, based mostly on the earlier contributions in Boletsis & Chasanidou (2022) and Cherni et al. (2020). Additionally, some of the used terminology comes from the work done in Cardoso & Perrotta (2019) and Adhikari et al. (2021). It should be noted that the taxonomy is made to include the movement methods that already exist – therefore, some of the sub-categories are further divided while others are not.

Movement methods are divided into three main groups (displayed in yellow) based on interaction type: Body-based-, Artificial-, and Hybrid movement. Body-based methods specifically utilize the body movements of the user for VR translations. Artificial methods utilize external input methods for VR translations, most commonly VR controllers. Hybrid methods on the other hand combine both body-based and artificial movement for producing VR translation. An example of this could be that the user uses a VR controller for forward and backward translations but rotates their body to achieve rotation translation in VR. Each main category is divided into a set of sub-categories (displayed in green), and final categories (displayed in purple). Each final category has a set of example movement methods, labeled by their suitability for 3D-VR image interaction. Movement methods presented with green font are assumed to be suitable for 3D-VR image interaction, while movement methods presented with red font are not. It should however be noted, that since movement methods have not been studied for 3D-VR model interaction, these assumptions do not have any scientific validation. Some of the movement methods are discussed later in Chapter 4, along with the speculation of 3D-VR image interaction suitability.

The main categories are further categorized based on different attributes (displayed with rough-edged square background): motion type (displayed in blue) with values ‘continuous’, ‘instant’, and ‘hybrid’, and movement range with values ‘ground-based’ and ‘flight-based’. Furthermore, some categories use specific attributes (displayed in red) in labeling. These include movement type, use of external devices, as well as optical flow cues, and are explained later in Chapter 4.

Regarding motion type, continuous and instant types are the same as in the taxonomy proposed in Boletsis & Chasanidou (2022), although the original paper used the term ‘non-continuous’ instead of ‘instant’. Continuous motion is smooth, it gives optical flow

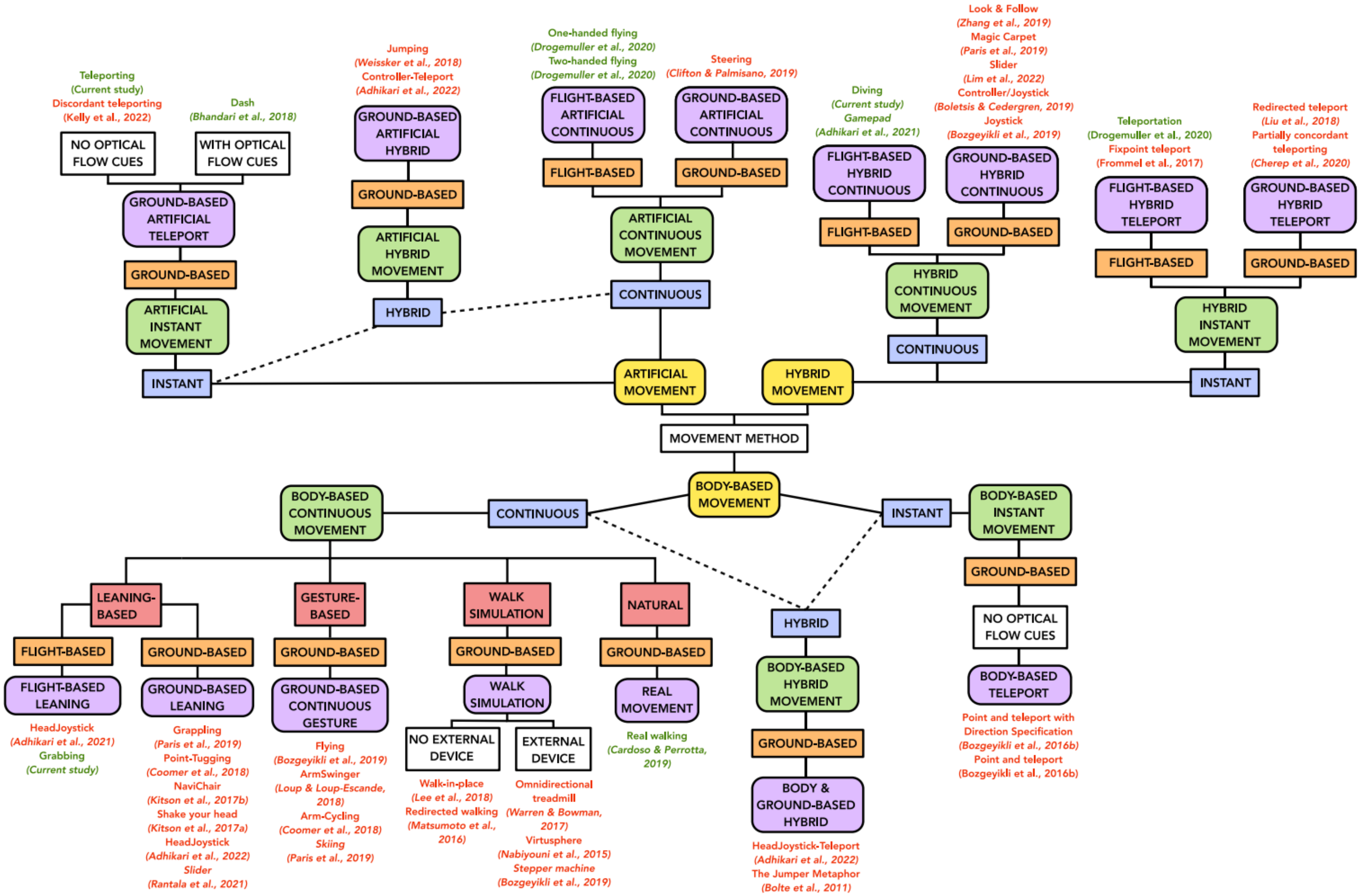

Figure 3. A new movement method taxonomy.

cues as well as the ability to control the movement to reach the destination point, like in real-world motion. However, instant motion is achieved by “jumping” between locations. Hybrid motion is between both motion types. Instead of moving on a continuum or between two points, the user moves between multiple different points in the VR environment, making it possible to control the movement in another direction without giving as many optical flow cues as in continuous motion.

The new taxonomy differs from previous taxonomies in multiple ways. Firstly, the new taxonomy categorizes movement methods by movement range. This is based on the contributions in Adhikari et al. (2021), where the term “ground-based” is used to describe movement methods that solely use z- and/or x-axis -motion (forward, backward, and/or left, right) for movement, and the term “flying” when vertical movement (up, down) is included. However, as there is also a movement method called Flying (Bozgeyikli et al., 2019), the term is changed to “flight-based” in the new taxonomy. Categorization by movement range is necessary for 3D-VR image interaction, as flight-based movement methods include more Degrees of Freedom (DoFs) to allow more refined movement. Four DoFs are needed for full control of 3D flight, although there are limited flying interfaces using two DoFs (Adhikari et al., 2021).

Secondly, the new taxonomy does not categorize the movement methods based on whether the VR interaction space is open or limited, as was done in Boletsis & Chasanidou (2022). This is justified because all the movement methods *can* be used in a limited VR interaction space, although some methods might not be as suitable for movement as others. Thirdly, the new taxonomy is made to include hybrid movement methods, either combining physical and artificial interaction, or continuous and instant motion. Finally, the sub-categories differ from previous taxonomies. This is elaborated in the following chapter, where the main categories, sub-categories, and final categories along with their example movement methods are presented.

4. Movement Method Categories

In this chapter, the movement method categories of the new taxonomy are introduced thoroughly. Additionally, examples of movement methods are explained in detail when resembling the methods (Diving, Grabbing, and Teleporting) used in the current study. Special focus is on movement methods resembling Diving, due to the method's novelty. The chapter is divided into sections based on main categories: Body-based movement is discussed in Section 4.1, Artificial movement in Section 4.2, and Hybrid movement in Section 4.3. Additionally, movement methods' suitability for 3D-VR image interaction is discussed based on the new taxonomy. However, this is based on mere assumption, as the topic has not been studied previously. Finally, in Section 4.4, the contents of the chapter are summarized.

4.1. Body-based Movement

Body-based movement methods are divided into three sub-categories discussed in separate sections. Section 4.1.1 focuses on Body-based continuous movement, Section 4.1.2 on Body-based instant movement, and Section 4.1.3 on Body-based hybrid movement.

4.1.1. Body-based continuous movement

Body-based continuous movement is further divided into five final categories based on movement type (leaning-based, gesture-based, walk simulation, or natural) and -range (flight- or ground-based). The final categories are titled Flight-based leaning, Ground-based leaning, Ground-based continuous gesture, Walk simulation, and Real movement.

Leaning-based movement methods utilize the tilting of the body or certain body parts for VR translations. For example, a user tilting their body forward could be interpreted as forward translation in VR. Grabbing, a method used in the current study, is also based on leaning. This is discussed further in Chapter 5. Promising findings in support of leaning-based approaches have been reported in some of the movement method studies. These findings include improved accuracy (Miehlbradt et al., 2018), ease of use (Higuchi & Rekimoto, 2013; Hashemian et al., 2022), and enjoyment (Higuchi & Rekimoto, 2013; Hashemian et al., 2022).

It is possible to distinguish both flight- and ground-based leaning-based methods. For example, different versions of HeadJoystick have been made to either utilize ground-based movement (Adhikari et al., 2022) or flight-based movement (Adhikari et al., 2021). In the HeadJoystick method, the upper body tilts in the direction of the simulated motion. This reduces the visual-vestibular cue conflict by helping align vestibular cues with the virtual translation (Adhikari et al., 2021). In **Figure 4** (p. 24, left), the commands for flight-based HeadJoystick are displayed (Adhikari et al., 2021). The user's head position controls the velocity, while rotational translations are achieved with the user's body rotation in a swivel chair. The interface sets a starting point (zero-point) each time it is used.

When the user moves their head in any direction from this point, it causes them to move in the same direction in the VR environment. The further they move their head from the zero-point, the faster the VR translations. Leaning forward or backward makes the user move in those directions in the VR space while leaning left or right produces side-to-side movements, and stretching up or slouching down produces up or down movements. To stop the movement, the user must return their head to the zero-point.

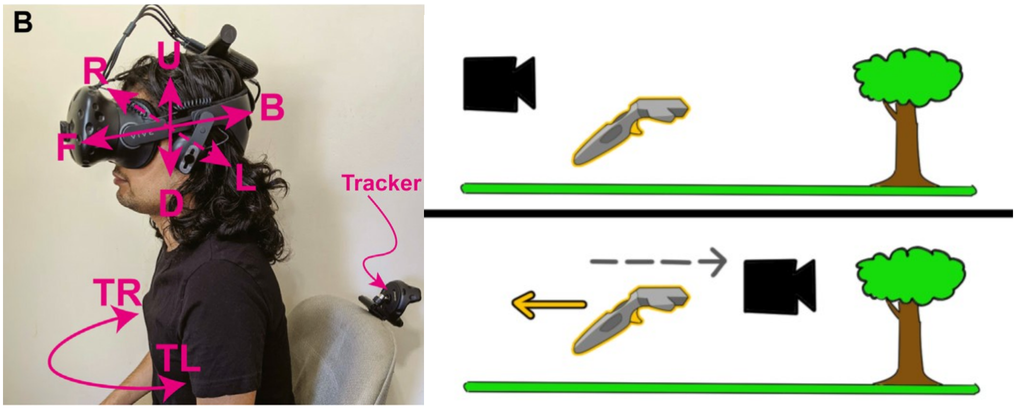

Figure 4. Left: Commands for HeadJoystick. Right: Forward command for Point-Tugging.

Adhikari et al. (2021) compared HeadJoystick to a flight-based hybrid continuous movement method Gamepad. As the body movement translated to a similar VR translation in HeadJoystick, the participants reported less motion sickness and a stronger sense of self-motion compared to the participants using Gamepad.

HeadJoystick is a feasible movement method due to its inexpensiveness and simplicity of setup (Adhikari et al., 2021). However, it is not suitable for 3D-VR image interaction due to head-controlled velocity. For 3D-VR image interaction, the doctors need to be able to turn their heads to analyze the medical image in detail. Another flight-based method utilizing leaning is Grabbing used in the current study. This method is seen as suitable for 3D-VR image interaction and is further explained in Chapter 5.

Besides HeadJoystick (Adhikari et al., 2022), methods of ground-based leaning mentioned in the taxonomy include Grappling (Paris et al., 2019), Point-Tugging (Coomer et al., 2018), NaviChair (Kitson et al., 2017b), Shake your head (Kitson et al., 2017a), and Slider (Rantala et al., 2021). Out of these methods, Grappling, Point-Tugging, and Slider are explained further due to the resemblance of Grabbing. In **Figure 4** (right), the command for moving forward with Point-Tugging is illustrated (Coomer et al., 2018). The user presses the trigger button of the VR controller to grab a point in the VR environment. Next, the user pulls the arm closer to move forward in the VR space. Similarly, the user can push the arm further to move backward. To stop the movement, the trigger button is released. Even though the movement sequence is registered with a VR controller, the actual movement still utilizes arm-based leaning.

Slider, as illustrated in **Figure 5** (left), is a movement method based on a single VR controller (Rantala et al., 2021). A horizontal beam is trajected from the controller in the virtual space. This beam demonstrates the direction of the movement and can be altered by moving the controller. When the user presses down the touchpad, the desired location of the beam is locked. The user can then "slide" forward or backward within the direction of the beam. To move forward, the user brings their arm closer to the body. To move backward, the arm is moved further from the body. The movement is stopped by releasing the touchpad.

Methods of ground-based leaning are not seen as suitable for 3D-VR image interaction. This is due to the lack of detailed movement with the methods.

Gesture-based movement methods are based on repetitive gestures that induce simple, continuous forward movement. Therefore, gesture-based movement methods are ground-based (hence the name "ground-based continuous gesture"). The word "repetitive" implies that the gesture inducing the movement is always the same. In the taxonomy, examples of Ground-based continuous gesture include Flying (Bozgeyikli et al., 2019), ArmSwinger (Loup & Loup-Escande, 2019), Arm-Cycling (Coomer et al., 2018), and Skiing (Paris et al., 2019). From these movement methods, Flying is further discussed.

Flying is a movement method based on continuous movement, e.g., Steering (discussed later). However, with Flying, the movement is simpler, often based on a gesture (Ground-based continuous gesture) or a button click (Ground-based artificial continuous) that initiates the movement (Bozgeyikli et al., 2019). In **Figure 5** (right), the forward command for gesture-based Flying is displayed (Bozgeyikli et al., 2019). The user raises their hand to induce a forward motion in the VR space. To stop the forward motion, the user needs to lower their hand.

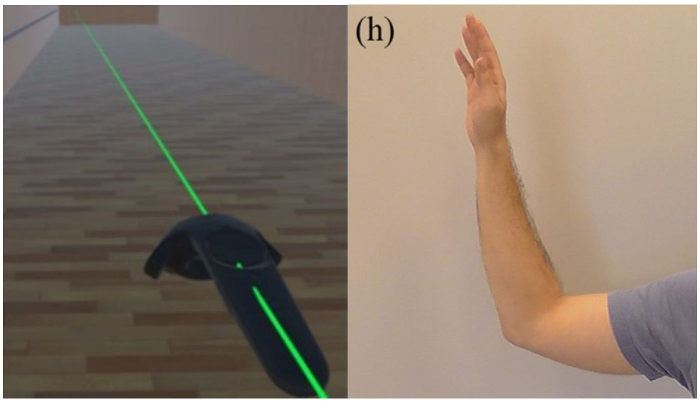

Figure 5. Left: Use scenario for Slider. Right: Forward command for Flying.

Movement methods belonging to the category of Ground-based continuous gesture are not suitable for 3D-VR image interaction. This is due to the simplicity of the commands, as they are only capable of producing forward translations (Flying, Arm-Cycling, Skiing), or forward and backward translations (ArmSwinger).

Movement methods based on walk simulation aim to mimic Real walking (discussed later) in a limited space. These methods can be divided into two groups based on whether an external device is used for body movement input. In the taxonomy, Walk-in-place (Lee et al., 2018) and Redirected walking (Matsumoto et al., 2016) are mentioned as examples of walk simulation without an external device. Regarding the methods relying on an external device, the Omnidirectional treadmill (Warren & Bowman, 2017), Virtusphere (Nabiyouni et al., 2015), and Stepper machine (Bozgeyikli et al., 2019) are mentioned. Movement methods relying on walk simulation are not seen as fit for 3D-VR model interaction as they do not have enough precision. In addition, the feasibility of many walk simulation methods using an external device is low due to the high costs of the required hardware.

The real movement category and the name of the movement method called “Real walking” are based on the review done in Cardoso & Perrotta (2019). In the review, the term “real locomotion techniques” was used to describe how to move in the virtual environment, the user needs to physically move from one point to another in the real environment. The movements are translated the same way in the virtual environment, as they are done in the real environment. Therefore, real movement methods are the most “natural” regarding VR interaction. Movement methods utilizing real movement mostly include Real walking, but vehicles can also be included (Cardoso & Perrotta, 2019). Even though as of now the category only includes one movement method, real movement is different from other body-based movement methods. Therefore, having a category with one movement method is justified here.

Regarding 3D-VR model interaction, Real walking is suitable for refined investigation of the 3D model. However, it is not always a feasible movement method, as it requires a wide physical space for tracking.

4.1.2. Body-based instant movement

Body-based instant movement methods are solely based on using body movements for teleporting from one point to another. The current methods under the category are ground-based. No optical flow cues are utilized, meaning that after teleporting, the user is instantly teleported to the destination point without a sense of continuity in the movement. The only examples under the category are Point and Teleport with Direction Specification and the original Point and Teleport. Both are explained more in detail due to the resemblance of Teleporting.

In **Figure 6**, the commands for Point and Teleport with Direction Specification (Bozgeyikli et al., 2016b) are illustrated. The user uses their finger to point to a preferred location in the virtual environment and rotates their wrist (while pointing) to rotate the view angle of the destination point. In Bozgeyikli et al. (2016b), Point and teleport with Direction Specification was compared with the original Point and teleport, where the rotational translations were made using body rotation. It was found that the original Point and Teleport outperformed Point and Teleport with Direction Specification. Therefore, the authors suggested avoiding the use of Point and teleport with Direction Specification.

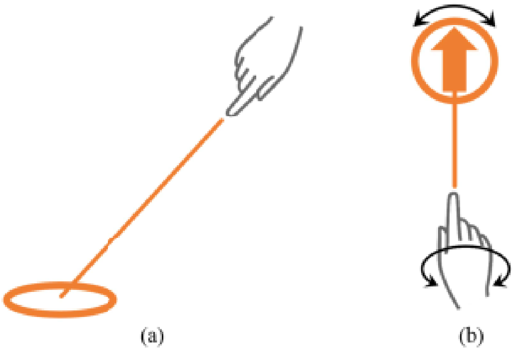

Figure 6. Commands for Point and Teleport with Direction Specification. (a) The user points to a location of preference and (b) rotates their wrist while pointing to rotate the view angle where the user is teleported.

Even though there could be body-based instant movements that are suitable for use in 3D-VR model interaction, Point and teleport with Direction Specification have been found imprecise in adjusting the rotation angle (Bozgeyikli et al., 2016b). Therefore, the method is too imprecise for interacting with 3D-VR models. Additionally, for the original Point and Teleport, rotational VR translations are only done with body rotations. This makes the interaction too simple for 3D model interaction, as the user can only teleport horizontally and rotate with their body.

4.1.3. Body-based hybrid movement

Body-based hybrid movement methods combine continuous and instant movement. The movement methods belonging to this category fall somewhere between both movement types. Therefore, they cannot be solely connected to either attribute. Current body-based hybrid movement methods are ground-based. Examples in this category include Head-Joystick-Teleport (Adhikari et al., 2022), and the Jumper Metaphor (Bolte et al., 2011). Neither of these methods is seen as suitable for 3D-VR image interaction due to the impreciseness of the movement.

4.2. Artificial Movement

In Artificial movement, external input methods are utilized to produce VR translations. Artificial movement can be considered the opposite of Body-based movement, as the translations themselves do not involve the use of body movements – although hand movements are usually required for pointing with a VR controller. Artificial movement methods are divided into three sub-categories discussed in separate sections. Artificial continuous movement is discussed in Section 4.2.1, Artificial instant movement in Section 4.2.2, and Artificial hybrid movement in Section 4.2.3.

4.2.1. Artificial continuous movement

Techniques utilizing either artificial- or hybrid continuous movement (which involve steering a joystick or a controller) have been found to increase motion sickness compared to other movement methods (Zhang et al., 2019). Additionally, in Bozgeyikli et al. (2016a), a drifting effect was observed: the participants moved forward while turning, causing them to move more than needed.

Artificial continuous movement is further categorized into flight- and ground-based methods. Examples of flight-based artificial continuous movement methods include One- and Two-Handed Flying (Drogemuller et al., 2020). These methods are discussed in more detail due to the resemblance of Diving.

In **Figure 7** (right), One-Handed Flying is illustrated (Drogemuller et al., 2020). One-Handed Flying is a technique used in Google Earth VR (Google, 2018). A single VR controller is used for the translations. To move in the VR space, the participant needs to point the controller in the preferred direction and press the trigger button. A blue arrow coming from the controller in the virtual space indicates the direction where the user is heading. Movement speed depends on how far the controller is being held from the user's body.

In **Figure 7** (left), Two-Handed Flying is displayed (Drogemuller et al., 2020). The movement method utilizes two VR controllers to cast an arrow where the movement is directed. For example, when the left controller is located on the left, the right controller

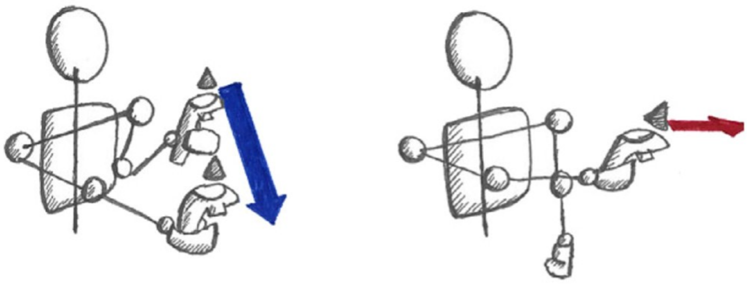

Figure 7. Left: Illustration of Two-handed Flying. Right: Illustration of One-Handed Flying.

is located on the right, and both trigger buttons are held down, the user moves to the right. The distance of the controllers determines the movement speed.

In Drogemuller et al. (2020), One- and Two-Handed Flying, Teleport, and World-in-Miniature were compared in the context of 3D-graph interaction. Two-Handed Flying received the best scores overall. It was also deemed the most accurate (with One-Handed Flying as the second).

Flying-based movement methods based on artificial continuous movement are well-suited for 3D-VR model interaction. These methods offer enough control and precision for the movements. However, the findings in Drogemuller et al. (2020) indicate that compared to One-Handed Flying, Two-Handed Flying could have more potential in 3D-VR model interaction due to the experimental findings on accuracy.

Regarding ground-based artificial continuous movement methods, Steering (Clifton & Palmisano, 2020) is mentioned as an example in the new taxonomy. Steering is discussed further due to its resemblance to Diving.

In Steering, a single-hand VR controller is utilized for simple commands. To move forward in the VR environment with Steering, the user needs to use the hand holding the VR controller to horizontally point an area they want to move towards. Then, they need to press and hold the trigger button to initiate the movement. The movement stops when the trigger button is released. Due to the lack of detailed translations, the method is not seen as suitable for 3D-VR model interaction.

4.2.2. Artificial instant movement

Methods belonging to the category of artificial- or hybrid instant movement do not usually cause motion sickness (Prithul et al., 2021). These methods have also been found easy to use (Bozgeyikli et al., 2016a, Langbehn et al., 2018) and efficient (Prithul et al., 2021). However, instant movement has been found to cause lower presence due to spatial disorientation (Prithul et al., 2021). Spatial updating is a cognitive process that automatically maintains the spatial relationship between an individual and their surroundings as they move and interact with the environment. It can be seen as a mental mapping system, keeping track of one's position and surroundings without conscious effort (Wang, 2016). Instant movement methods allow “jumping” from one point to another without optical flow. This can make it harder to estimate the distance traveled, leading to spatial disorientation (Bhandari et al., 2018).

In artificial instant movement, ground-based artificial teleport is included as the final category. Regarding ground-based methods, Teleporting (Current study), Discordant teleporting (Kelly et al., 2023), and Dash (Bhandari et al., 2018) are mentioned as example techniques in the new taxonomy. From these methods, Discordant teleporting and Dash are discussed further due to their resemblance to Teleporting.

In Discordant teleporting, the joystick of the VR controller is tilted to display a beam representing the destination point. By rotating the joystick, the user can adjust the view angle of the destination point. This enables the user to make artificial rotational translations in the VR space. When the joystick is released, they teleport to the destination.

Discordant teleporting does not include optical flow cues, whereas Dash includes them to reduce spatial disorientation. Dash, as displayed in **Figure 8**, is implemented so that when the user teleports to the destination point, they are moved from the starting point to the destination with a continuous flow (Bhandari et al., 2018). This makes it possible to determine the distance of the movement.

Figure 8. Left: Illustration on how Dash (a, c) can reduce spatial disorientation compared to conventional instant VR movement (a, b).

Regarding 3D-VR image interaction, Teleporting, and Discordant teleporting can be seen as suitable methods, as it is possible to rotate without physically turning around. Dash, however, does not include artificial rotation. Therefore, it is not suitable for 3D-VR model interaction, due to limited movement commands.

4.2.3. Artificial hybrid movement

As with body-based hybrid movement, artificial hybrid movement combines continuous and instant movement. Example techniques include Jumping (Weißker et al., 2018), and Controller/Teleport (Adhikari et al., 2022). However, neither of these techniques is seen as appropriate for 3D-VR image interaction, as the movement combining continuous and instant movement involves small jumps. This causes problems in small-scale VR interaction, as the user cannot move to an exact point.

4.3. Hybrid Movement

Hybrid movement methods combine body-based and artificial techniques to produce VR translations. This category is divided into two sub-categories. In Section 4.3.1, Hybrid continuous movement is discussed while Hybrid instant movement is addressed in Section 4.3.2.

4.3.1. Hybrid continuous movement

Hybrid continuous movement methods resemble artificial continuous movement methods. However, artificial continuous movement methods either offer at least one artificial method for the rotational translations or do not involve rotation at all. In Hybrid continuous methods, rotational translations are only achieved by utilizing body movement (relying on head- or controller-tracking). Hybrid continuous movement methods are categorized into two final categories, Flight- and Ground-based hybrid continuous, which both are discussed in this section. Examples of Flight-based hybrid continuous movement methods include Gamepad (Adhikari et al., 2021) and Diving (current study). While Diving is presented in Chapter 5, Gamepad is further discussed due to its resemblance to Diving.

With the Gamepad method, two joysticks of a game controller are utilized for VR translations. In **Figure 9**, the commands for Gamepad are illustrated (Adhikari et al., 2021). The left joystick controls horizontal movement (forward, backward, left, right) while the right joystick controls vertical movement (up, down). The head direction of the user determines the area where the movement is targeted, and the rotational translations are done with a swivel chair.

Regarding 3D-VR image interaction, flight-based hybrid continuous methods are well-suitable, as they allow enough detail to the movements. As vertical movement is included, the user can move lower or higher in the VR space. This makes the 3D model investigation more efficient.

Figure 9. Commands for Gamepad.

Ground-based hybrid continuous movements include Look & Follow (Zhang et al., 2019), Magic Carpet (Paris et al., 2019), Slider (Lim et al., 2022), Controller/Joystick (Boletsis & Cedergren, 2019) and Joystick (Bozgeyikli et al., 2019) as examples in the new taxonomy. All the following movement methods are discussed further due to their similarity with Diving.

With Magic Carpet (Paris et al., 2019), a single VR controller is used to signify movement. The user needs to press and hold the trigger button of the controller to initiate the movement, while the movement direction is based on the controller tilt. When the controller is tilted forward, the user moves forward in the VR space, while tilting backward causes the user to move backward. The movement speed is determined by how much the controller is tilted by the user. For example, a slight tilt would cause the user to move slower, while a more exaggerated tilt would make the user move faster.

Slider (Lim et al., 2022) is a movement method that uses a single VR controller for translations. The user points the controller toward the preferred direction. A beam is cast from the controller to signify the direction to the user. To initiate movement, the user presses the trigger button of the controller. The movement stops when the trigger button is released. Look & Follow (Zhang et al., 2019) is a similar method, except that rotational translations are based on head-tracking rather than tracking the controller.

Regarding Controller/Joystick, two VR controllers were utilized in the method. In **Figure 10** (left), the use scenario for the movement method is displayed (Boletsis & Cedergren, 2019). To move in the VR space, the user needs to press the touchpad of either controller to initiate movement. The movement speed can be controlled by altering the position of the thumb on the touchpad. The movement direction is based on the direction of the VR controller.

In the Joystick method, a physical joystick is utilized for the VR translations. In **Figure 10** (right), the use scenario for the method is displayed (Bozgeyikli et al., 2019). To move forward, the user needs to tilt the joystick forward. Additionally, the user can tilt the joystick to either left or right to move sideways. Rotational translations are based on head direction.

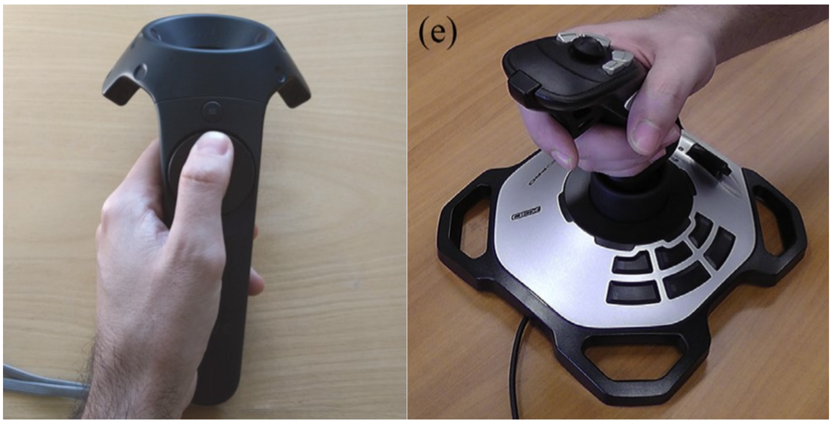

Figure 10. Left: Use scenario for Controller/Joystick. Right: Use scenario for Joystick.

Currently, ground-based continuous hybrid methods are not suitable for 3D-VR model interaction, as the methods only allow simple forward-, backward-, and sideways-commands. In addition, many of the methods involve changing the movement speed. This is not beneficial for small-scale VR interaction, as the user does not need to move longer distances.

4.3.2. Hybrid instant movement

As with Hybrid continuous movement, Hybrid instant movement currently combines body-based rotational translations with horizontal and vertical artificial translations. Hybrid instant movement is divided into two final groups: Flight- and Ground-based hybrid teleport.

Regarding flight-based methods, Teleportation (Drogemuller et al., 2020) and Fixpoint teleport (Frommel et al., 2017) are mentioned as examples in the new taxonomy. From these methods, Teleportation is further described due to its resemblance to Teleporting.

In **Figure 11**, the use of Teleportation is displayed in the VR environment (Drogemuller et al., 2020). A beam is projected from the right VR controller which determines the destination point where the user will be teleported. Additionally, the user can control the distance of the beam by either touching the upper part of the touchpad (to move the beam further) or by touching the lower part of the touchpad (to move the beam closer). To instantly move to the destination point, the user needs to press the trigger button. To reduce disorientation, the screen fades in and out (in black) for one second.

Some methods utilizing flight-based hybrid instant movement can be seen as suitable for 3D-VR model interaction. For example, Teleportation allows detailed movement to interact with the 3D model. Even though rotational translations are not included in the artificial commands, vertical translations allow the 3D model to be investigated from different positions. However, Fixpoint teleport is not suitable for 3D-VR model interaction, as it only allows teleportation on fixed locations. This greatly limits the interaction.

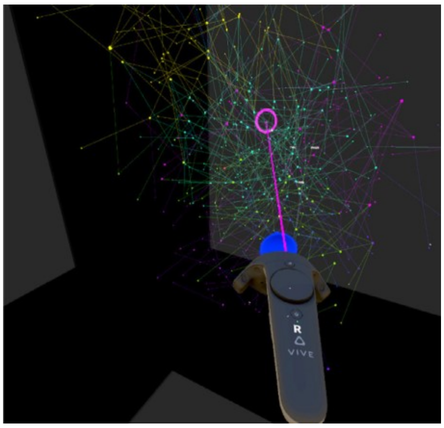

Figure 11. The use of Teleportation is displayed in the VR environment.

Regarding ground-based methods, Redirected teleport (Liu et al., 2018) and Partially concordant teleporting (Cherep et al., 2020), are mentioned as examples in the new taxonomy. From these methods, Partially concordant teleporting is further discussed due to its resemblance to Teleporting.

In Partially concordant teleporting, translations are made with artificial methods, while body movements are used for the rotations. The body-based rotation in a real environment is consistent with movement in the VR space.

Current ground-based methods of hybrid instant movement are not seen as suitable for 3D-VR model interaction, as they require frequent turning. In addition, unfeasible movement for small-scale interaction is included with Redirected teleport.

4.4. Summary

In this chapter, different movement methods were described along with their categories under the new taxonomy. Most example movement methods were not seen as suitable for 3D-VR model interaction, as they do not fulfill the needed requirements of preciseness. From the movement methods seen as suitable for 3D-VR model interaction, many are flight-based. Flight-based movement methods can offer more movement commands due to the addition of vertical translations.

5. Methods

In this chapter, the methods used in the study are described. Experimental research, also known as the “scientific method” (MacKenzie, 2013, p. 130), was used as the main research method. Experimental research is the only method of empirical research that makes it possible to determine causal relationships between variables (MacKenzie, 2013, p. 132). A causal relationship means that when one of the variables is manipulated, it leads to a response in the other variable. The manipulated variable is called the independent variable, while the response variable is called the dependent variable (MacKenzie, 2013, p. 131). At least one dependent variable and one independent variable with two levels are required for a controlled experiment. Without determining the causality between variables, it is not possible to know whether external factors have caused the change in the dependent variable (MacKenzie, 2013, p. 145-146).

In experimental research, balancing between internal and external validity is crucial for the quality of experimental research (MacKenzie, 2013, p. 142). Internal validity is the level of certainty that there is a causal relationship between the independent and dependent variables (MacKenzie, 2013, p. 141). A high level of internal validity is achieved by controlling the experimental conditions in a precise manner, to avoid any confounding variables. A confounding variable is any external factor that interferes with the relationship between the independent and dependent variables (MacKenzie, 2013, p. 166). An example of a confounding variable could be interference if the facilitator interferes with the participant while the experimental task is conducted. The experiment is controlled by careful experiment design. This can be done by assuring two factors. First, the experimental conditions should not change between participants. This means, that the experiment is conducted in controlled laboratory settings (MacKenzie, 2013, p. 130), and that the experiment is done as similarly as possible for each participant. One solution is to treat the factors that could interfere with the experimental results (e.g., instructions, facilitator’s role, seat position, hardware) as control variables (MacKenzie, 2013, p. 166). Second, each participant should only be exposed to one of the experimental conditions, referred to as between-subjects (MacKenzie, 2013, p. 175), or counterbalancing is used to balance the order of the conditions if within-subjects is used instead (MacKenzie, 2013, p. 177). Within-subjects implies that each participant is exposed to all the experimental conditions (MacKenzie, 2013, p. 175).

External validity is the level of generalizability of the research results. Even if the experiment is conducted with high internal validity, the experimental conditions can differ greatly from real-life conditions. (MacKenzie, 2013, p. 141) Additionally, if there are too many prerequisites for the participants, the experimental findings can become less generalizable (MacKenzie, 2013, p. 166). External validity can be considered in the experiment design by adding random variables to the study (MacKenzie, 2013, p. 166). A random variable is any variable that can add variety to the study without significantly interfering with the internal validity of the research. An example of a random variable could be participant performance, as there is a naturally occurring variance in human performance.

A comparative evaluation of movement methods for 3D-VR model interaction is done in the thesis. As was demonstrated in the methodological analysis in Chapter 2, almost half of the studies included the use of a movement method, yet no studies have been found that compared movement methods for 3D-VR model interaction. If a single interaction method is evaluated, it is not possible to know whether Method X is more efficient than Method Y, for example (MacKenzie, 2013, p. 143).

This chapter is divided into several sections. The movement methods are described in Section 5.1. The experimental design used for the study is elaborated in Section 5.2. In Section 5.3., the focus is on the participants who took part in the experiment, while the apparatus used in the experiment is introduced in Section 5.4. Finally, in Section 5.5, the experiment procedure is explained.

5.1. Movement Methods

The three movement methods that were selected for the study were Diving, Grabbing, and Teleporting. In addition, the participants could also use limited Real walking (e.g., taking a few steps, crouching, turning, and head-turning) to address the limitations of the chosen movement methods and make the VR system more intuitive.

Grabbing and Teleporting were selected because they were moderately common movement methods (Cherni et al., 2020; Langbehn et al., 2018; Rantala et al., 2021; Zhang et al., 2019; Paris et al., 2019; Coomer et al., 2018). Diving has not traditionally been used in practical tasks. It was of the research group’s interest to study how the diving metaphor would perform compared to the traditional movement methods. The main criterion for all the movement methods was that they allow small, detailed movements around an object. In the following sections, the commands for each movement method are introduced. Diving is discussed in Section 5.1.1, Grabbing in Section 5.1.2, and Teleporting in Section 5.1.3.

5.1.1. Diving

Diving is illustrated in **Figure 12** (p. 37, left). In the new taxonomy presented in Chapter 3, Diving belongs to the final movement method category of “Flight-based continuous hybrid”. The method allows vertical translations (up, down), and the movement is based on controllable, linear forward movement. Diving is considered a hybrid because it combines both artificial and body-based methods. Diving utilizes the left-hand VR controller (artificial method) for linear translations. As rotational translations are not included in the artificial controls, body rotations (body-based method) are used for these translations.

Diving is based on commonly used continuous movement methods called “Flying” (Adhikari et al., 2021; Bozgeyikli et al., 2019), “Steering” (Buttussi & Chittaro, 2023; Clifton & Palmisano, 2020), “Joystick” (Bozgeyikli et al., 2019), as well as on a novel movement method referred to as “Slider” (Rantala et al., 2021). The movement direction is based on the controller’s direction. The commands (for controller facing forward or upward) are the following:

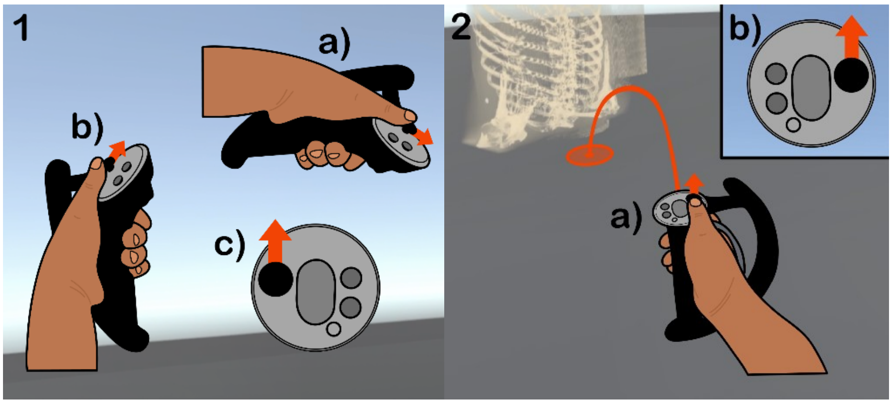

Figure 12. Left: Commands for forward and upward movements in the Diving method are illustrated: (a) hold the left controller horizontally and (c) tilt the joystick up to move forward. (b) Hold the left controller vertically and repeat (c). Right: The command for the Teleporting method is illustrated: (a) Tilt the joystick of the right controller up to activate a teleport beam. (b) Use your arm to select a target location. Release the joystick to teleport to the target at the beam’s end.

- **Moving forward:** (1) Holding the left VR controller in a horizontally linear position (facing forward). (2) Tilting the joystick upwards.
- **Moving backward:** (1) Holding the left VR controller in a horizontally linear position (facing forward). (2) Tilting the joystick downwards.
- **Moving to the left:** (1) Holding the left VR controller in a horizontally or vertically linear position (facing forward or upward). (2) Tilting the joystick to the left.
- **Moving to the right:** (1) Holding the left VR controller in a horizontally or vertically linear position (facing forward or upward). (2) Tilting the joystick to the right.
- **Moving upward:** (1) Holding the left VR controller in a vertically linear position (facing upward). (2) Tilting the joystick upward.
- **Moving downward:** (1) Holding the left VR controller in a vertically linear position (facing upward). (2) Tilting the joystick downward.

5.1.2. Grabbing

Grabbing also resembles "Swimming" in Zhang et al. (2019), "Point-Tugging" in Coomer et al. (2018), "Grab" in Rantala et al. (2021), and "Grappling" in Paris et al. (2019). However, like Zhang et al. (2019), Grabbing utilizes both left and right VR controllers for movement. Out of the mentioned movement methods, Grabbing is the only one that is flight-based. Therefore, it can be considered somewhat novel. In **Figure 13**, the forward command for Grabbing is illustrated. The commands for the movement method are the following:

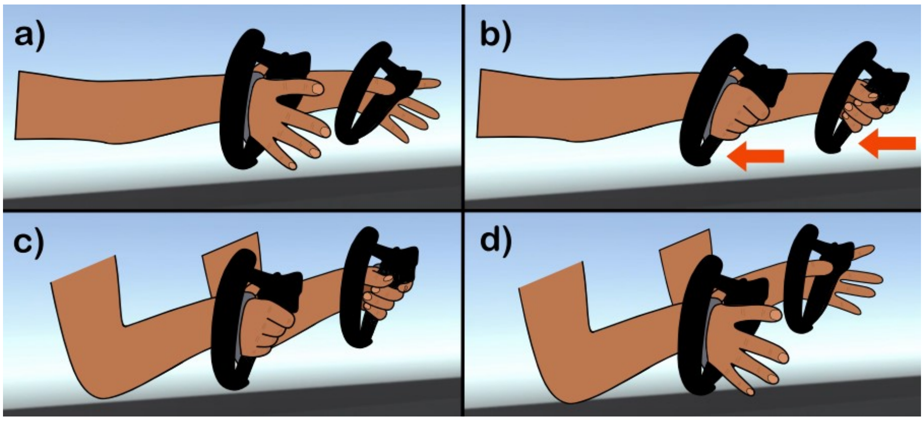

Figure 13. Movement sequences needed for moving forward with Grabbing: (a) With hands released from the controllers, spread arms forward close to each other. (b) Grab both controllers. (c) Start pulling both arms closer to the body. (d) Release controllers.

- **Moving forward:** (1) With controllers released and elbows open, place both arms at the front. (2) Grab both controllers. (3) Pull both arms closer to the body in a Z-axis motion. (4) Releasing controllers.
- **Moving backward:** (1) With controllers released and elbows closed, place both arms at the front of the body. (2) Grab both controllers. (3) Move both arms at the front of the body in a Z-axis motion. (4) Releasing controllers.
- **Moving to the left:** (1) With controllers released, place both arms close to each other at the center or the left side of the body. (2) Grabbing both controllers. (3) In the X-axis, move both arms to the right. (4) Releasing controllers.
- **Moving to the right:** (1) With controllers released, placing both arms close to each other at the center or the right side of the body. (2) Grabbing both controllers. (3) In the X-axis, move both arms to the left. (4) Releasing controllers.
- **Moving upwards:** (1) With controllers released, place both arms up. (2) Grabbing both controllers. (3) In the Y-axis, begin moving both arms downwards. (5) Releasing controllers.

- **Moving downwards:** (1) With controllers released, placing both arms downwards. (2) Grabbing both controllers. (3) In the Y-axis, begin moving both arms upwards. (4) Releasing controllers.
- **Rotate to the left:** (1) With controllers released, place both arms to the front of the body, so that there is at least 30cm of space between the arms. However, the arms should not move too far from the body. (2) Grabbing both controllers. (3) Begin doing a circular motion, where both hands start at the same level from the Z-axis but end up at the same level front and center of the body on the X-axis. The right-hand moves to the front, while the left hand moves to the back. (4) Releasing controllers.
- **Rotate to the right:** (1) With controllers released, place both arms to the front of the body, so that there is at least 30cm of space between the arms. However, the arms should not move too far from the body. (2) Grabbing both controllers. (3) Begin doing a circular motion, where both hands start at the same level from the Z-axis but end up at the same level front and center of the body on the X-axis. The left hand moves to the front, while the right hand moves to the back. (4) Releasing controllers.

Additionally, in the video tutorial, it was also instructed that the participants could do a longer forward/backward move sequence, resembling "zooming in and out" from the 3D model:

- **"Zooming in":** (1) With controllers released, place both arms close to each other to the front of the body. (2) Grabbing both controllers. (3) Begin moving the arms further from each other along the X-axis so that the body eventually forms a T-shaped position. (4) Releasing controllers.
- **"Zooming out":** (1) With controllers released, place both arms to the sides of the body so that the body forms a T-shaped position. (2) Grabbing both controllers. (3) Begin moving the arms closer to each other along the X-axis. (4) Releasing controllers.

5.1.3. Teleporting

Teleporting is illustrated in **Figure 12** (p. 37, right). Teleporting belongs to the final movement method category of "Ground-based artificial teleport", without the use of optical flow cues. The movement is instant, based on setting a remote target in the VR space. As Teleporting is a ground-based movement method, vertical movement is not included. The right VR controller is utilized for movement. Teleporting has only one command:

- **Teleport to a location:** (1) Facing the direction where the instant movement is wanted to be performed. (2) Tilting the joystick of the right controller upwards, so that a teleport beam is showing. (3) Changing the location of the teleport beam by moving the right arm while keeping the joystick tilted upwards. (4) Rotating the joystick of the left controller to adjust the preferred view angle for the location. (5) Releasing the joystick to teleport.

5.2. Experiment Design

For the current study, the goal was to determine whether the independent variable (Movement method) causes a change in the dependent variables. A within-subjects design was used for the experiment as the independent variable was not a naturally occurring variable (e.g., gender identity, handedness), therefore it was not necessary to separate participants into different groups (MacKenzie, 2013, p. 175). As within-subjects design enables the use of the same participant for all conditions, fewer participants are needed for credible results.

A 3 × 1 within-subjects design was followed in the experiment, with the independent variable being the movement method with three levels: (1) Diving, (2) Grabbing, and (3) Teleporting. A balanced 3 × 6 Latin square design was used to counterbalance the movement method conditions so that each condition precedes and follows each other equally (MacKenzie, 2013, p. 178).

In the study, various subjective and objective dependent variables were measured. The subjective variables included Successfulness, Confidence, Efficiency, Easiness, Motion sickness, and Preference. "Successfulness" assessed participants' level of accomplishment. "Confidence" measured the perceived confidence in using the movement method. "Efficiency" and "Easiness" evaluated the perceived ease and efficiency of using the movement method (see Table 1). All these variables produced interval data (MacKenzie, 2013, p. 136), as the participants rated them using a 7-point Likert scale ranging from "1" (Not at all) to "7" (Very). "Preference", an ordinal variable (MacKenzie, 2013, p. 136) referred to the participants' ranked preferences for each movement method, with "1" being the most preferred and "3" being the least preferred method.

The objective variable, Completion time, measured the time (in seconds) taken for the participants to complete the task. This variable produced ratio data (MacKenzie, 2013, p. 137–138). The completion time was measured with two decimal points precision. The measurement started when the participant clicked the "Next" button after the training session and ended when the last green-colored segment was turned red by the facilitator. Aside from training, the total amount of visited segments was 24 participants × 3 models × 6 segments = 432 segments.

5.3. Participants

Altogether 28 participants took part in the experiment. Four participants were excluded from the data: two did not see the segment tags due to unexpected blurriness, one did not see a segment tag due to height-related issues, and one accidentally clicked a button that ended the experiment before visiting all segments.

Of the remaining participants, 17 were recruited from Tampere University's DMLab subject register and the Orsee system, one participant from an e-mail list of the TAUCHI research unit, and the rest through personal affiliations. 14 participants identified as male and 10 as female. The mean age of the participants was 32.5 years. 22 participants were right-handed, one was left-handed, and one considered themselves as equally-handed. To assure the generalizability of the findings, participants with different levels of VR experience were included in the study. 17 participants reported having some experience of using VR (used VR a few times), while 6 participants had no experience. This also included participants, who had used VR once a long time ago, and felt that they related more with having no experience than some experience. One participant reported having a long VR experience.

The participants in this experiment had to have normal or corrected-to-normal vision. The use of varifocal glasses was not possible, as it was found to reduce the accuracy and speed of reading the segment tags. Additionally, the participants were instructed to avoid wearing hair accessories made from hard material in the back of their heads (e.g., hair clips), as it could reduce their comfort with the VR headset (if the accessory presses against the VR glasses). It was also instructed to avoid wearing oversized hair accessories and eyeglasses, as they might not fit inside the VR glasses. All participants signed a consent form before the experiment and were compensated with a movie ticket.

It is important to note that for the current study, it was not necessary to involve participants who were medical professionals. It was important to compare traditionally used movement methods for 3D-VR model interaction before including solely radiologists as participants, as they might not even be compatible for this specific context. There are only a few radiologists in Tampere, and many if not all of them have a busy work schedule. Therefore, a valid experimental study would be difficult to conduct.

5.4. Apparatus

The apparatus used for the current study is discussed in this section. Experimental software and hardware are described in Section 5.4.1. For the experiment, the participant had to move around the VR object and observe targets. This is explained further in Section 5.4.2.

5.4.1. Software and hardware

The software for the experiment was developed with the Unity Game engine (Unity, 2020), the OpenXR Plugin (OpenXR, 2023), and the Unity Volume Rendering Plugin (mlavik1, 2022). The most frequently used rendering method is direct volume rendering, which involves ray-casting through the data. Additionally, direct volume rendering uses transfer functions where the X-axis correlates with density and the Y-axis with alpha (opacity). These functions make it possible to change the color and the opacity of 3D objects.

In **Figure 14** (left), the experimental hardware is illustrated. Varjo Aero headset with a high-resolution display (Varjo, 2020) was used along with left- and right-hand Valve Index controllers (Valve, 2021). The positions of the devices were tracked with SteamVR Base Stations 2.0 (Vive, 2021), which were positioned around the area of the experiment.

5.4.2. Moving around and observing targets

During the task, the participant moved around the VR object using the specified movement method, looking for six targets in total. When a target was found, the participant inspected it from different sides to find a label (a letter-number pair), which they were asked to report to the facilitator (see **Figure 14**, right). The order in which the targets were found did not matter.

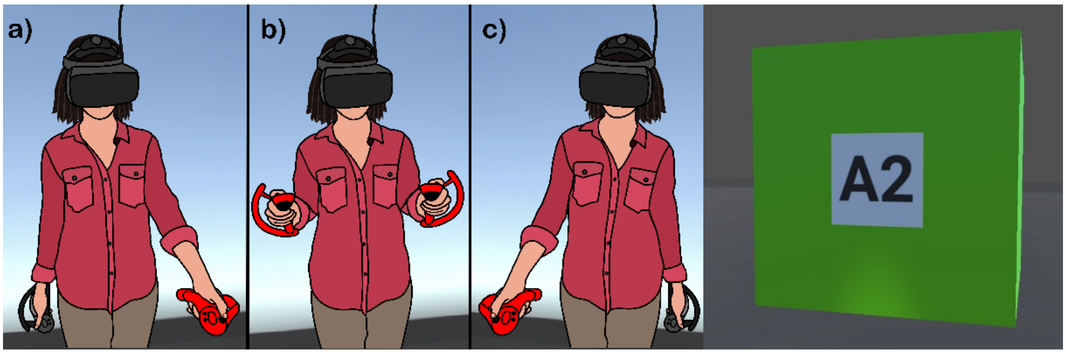

Figure 14. Left: Use scenario for the experiment, Varjo Aero headset with two Valve Index controllers was used. The controller used for each method is illustrated and highlighted in red: (a) for Diving, (b) for Grabbing, and (c) for Teleporting. Right: A cubic target that the participant was looking for with a character-number label on one side.

As the participants searched for the targets and moved around the ones they found to observe the label, they had to make several small, deliberate movements. This enabled a thorough evaluation of the appropriateness of their chosen movement method.

5.5. Procedure

In this section, the experimental procedure is described. The preparations before the experiment are discussed in Section 5.5.1, the video tutorial and practice session in Section

5.5.2, and the experimental task in Section 5.5.3. Finally, the procedure after the experimental task is elaborated in Section 5.5.4.

5.5.1. Before the experiment

In the beginning, the participants were asked to read the subject information sheet and sign an informed consent form, then complete a background questionnaire with the following information:

- Age
- Gender (Male, Female, Other, Prefer not to say),
- Dominant hand (Left, Right, Equal),
- VR experience (No experience, Some experience – has tried a few times, Long experience).

The general description script was read out loud by the facilitator in English, but the participants could ask questions either in English or in Finnish. The general description of the experiment is included in Appendix A. The facilitator started reading the instructions for the experiment in phases, reading from a paper so each participant got identical instructions. After this, the facilitator answered the participant's questions (if any).

5.5.2. Video tutorial and practice session

The facilitator instructed the participant to sit next to the computer screen and wear headphones to watch two video tutorials. The first of the tutorials addressed how to wear VR controllers. The second tutorial was about the first movement method. After completing the first condition, a video tutorial of the following movement method was watched.

Once the participant had watched both tutorials, the facilitator helped them to stand on the floor in an area marked with tape. This ensured that the participants had equal space to move when they started the practice session. Then, the participant was given VR controllers and -glasses. The facilitator fastened the devices and made sure that they were worn correctly and comfortably. The participant was instructed to turn towards (if not already facing) the 3D model. The facilitator then read the instructions for the practice session: "Now we will start the *(first/second/third)* practice session. Remember that you need to find the segments which are the green cubes and say the tag visible on one of their sides out loud so I can verify that you have visited them."

For the practice session, the participant had to find two cube-shaped, green targets (referred to as "segments") within and around a 3D model of a lung area. The segments had a tag on one of the sides, with the letter "P" (for "Practice") followed by a number starting from one (e.g., "P1") to identify it. Using the given movement method, the participant had to get close to the segment, read the tag aloud, and the facilitator would check the segment as visited in two ways. First, the facilitator marked an “X” on a paper sheet, next to the segment tag. Then, they clicked a corresponding number button (e.g., “1” for “P1”) on the keyboard to turn the segment’s color red. These steps verified the successful completion of the task. Additionally, the color change of the segment helped participants to keep track of visited segments. It also helped to log the task ending time.

The reason why the facilitator needed to verify the segment was that the task needed to include enough detailed movement around the 3D model. If the participants themselves had been able to verify the segment, the experimental software would have needed to include more details, such as making sure that the participants could only register the segment from a certain angle. Additionally, they would need to get close enough to the segment to make sure that they cannot register it from afar. Implementing these restrictions could make the experimental task harder for the participants. Therefore, to limit any facilitator-induced errors, two-step segment verification (checklist and button click) was used by the facilitator.

After finding both segments, the facilitator asked the participant to click a button with the label “Next” on the opposite side of the 3D model to start the experimental task as soon as they felt ready with the movement method.

Some participants needed more help than others while training with the movement methods. The study aimed to include people who were not familiar with VR. Therefore, the facilitator assisted (as needed) during practice sessions, ensuring all participants could complete the three experimental tasks.

5.5.3. Experimental task

The VR environment for the experiment is displayed in **Figure 15**. For each of the three experimental tasks, the instructions were the same as with the practice session, except the participant was to find six segments. There were three different 3D models: jaw and neck

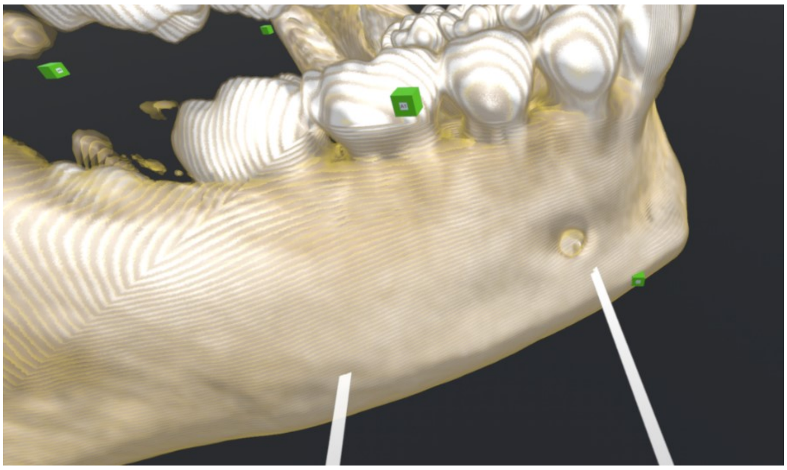

Figure 15. A screenshot of the VR space, displaying Model 1 and four visible targets.

area (Model 1), skull area (Model 2), and face and neck area (Model 3). The segments were positioned differently in each of the models to hinder possible effects of learning. As with the practice session, each segment had a letter-number tag on one side. The letter tag was “A” for Model 1, “B” for Model 2, and “C” for Model 3, while the number was between “1” and “6”.

When the segments were found, the participant clicked the “Next” button to move forward, either to the next practice session or a space with no 3D objects after the final condition. Then, the facilitator helped remove the VR glasses and -controllers.

The participant filled in a movement method evaluation questionnaire for the given movement method (Appendix 1). The participant needed to rate their Successfulness, Confidence, and Motion sickness with the movement method. In addition, they needed to rate the movement method’s Efficiency and Easiness. The participant could also optionally answer an open-ended question: "Any specific problems with ergonomics?"

5.5.4. After the experimental task

When the participants had completed all three movement method tasks, they filled in a final questionnaire about the VR system and the movement methods in general (Appendix 2). First, the participant needed to rank the three movement methods by their personal preference (1 being the most preferred movement method, 3 being the least preferred movement method). The facilitator had marked down the order in which the participant had done the movement method conditions. This prevented participants from relying only on the movement method names.

Then, the participant could optionally answer three open-ended questions: (1) "How did you feel about the VR system?", (2) "Do you have any proposals on how to improve the VR system or the movement methods?", and (3) "Is there anything else about the movement methods you want to share?"

6. Results

In this section, the findings of the study are reported. First, the quantitative results (Section are presented in Section 6.1. Second, the qualitative results from the open-ended questionnaire answers are presented in Section 6.2.

6.1. Quantitative Results

The quantitative results of the study are presented in this section. The objective results involving Task completion time are introduced in Section 6.1.1. The subjective results (involving Successfulness, Confidence, Efficiency, Easiness, Motion Sickness, and Preference) are described in Section 6.1.2.

6.1.1. Objective results (Task completion time)

The results for task completion times with each movement method are shown in **Figure 16**. As the task completion times were not normally distributed, Friedman's test for non-parametric statistical significance was also used. Nevertheless, since the patterns of significant differences (*p* < .05) for the task did not differ for the ANOVA and the Friedman's test, the results for the ANOVA are presented, as done in Perugini et al. (2007) and suggested in MacKenzie (2013, p. 227).

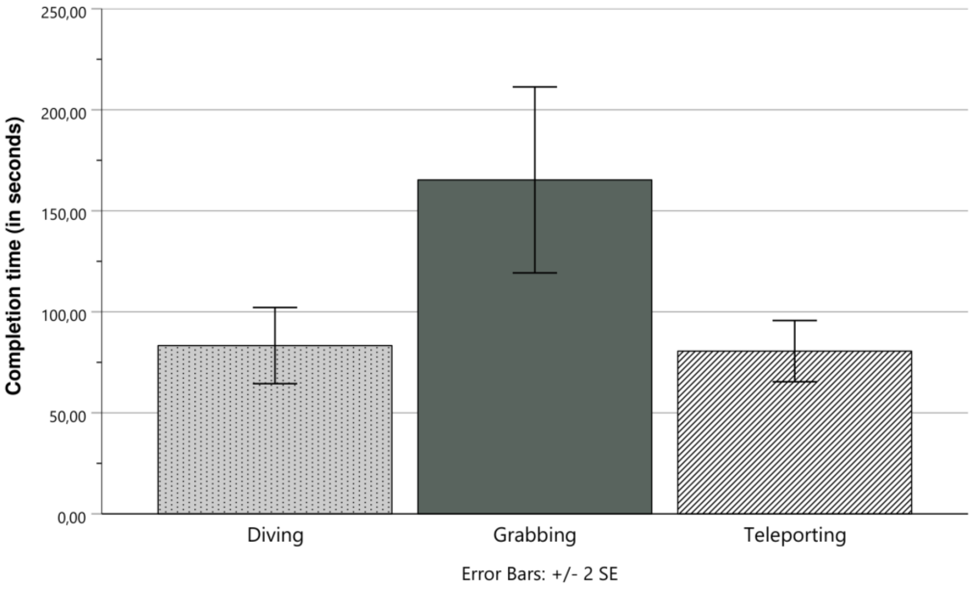

Figure 16. Task completion time averages for each movement method. Grabbing was the most time-consuming movement method.

One-way within-subjects ANOVA was used with the movement method as a factor. The ANOVA showed a statistically significant effect of the movement method, *F*(1.3, 30.3) = 11.1, *p* < .05. Post hoc pairwise comparisons for the movement method showed that the participants completed the task significantly faster with Diving compared to

Grabbing, *t*(23) = -3.5, $p < .05$, and with Teleporting compared to Grabbing, *t*(23) = 3.5, $p < .05$. The pairwise comparison between Teleporting and Diving was not statistically significant.

6.1.2. Subjective results

Figure 17 shows the results of the Likert scale subjective evaluations. Related to Successfulness, Friedman's test showed that there was a statistically significant effect of the movement method, X^2 (2) = 8.8, $p < .05$. Post hoc pairwise comparisons with Wilcoxon signed-rank tests showed that the participants rated Diving as significantly better than Teleporting, *Z* = -3.35, $p < .05$. Other pairwise comparisons were not statistically significant.

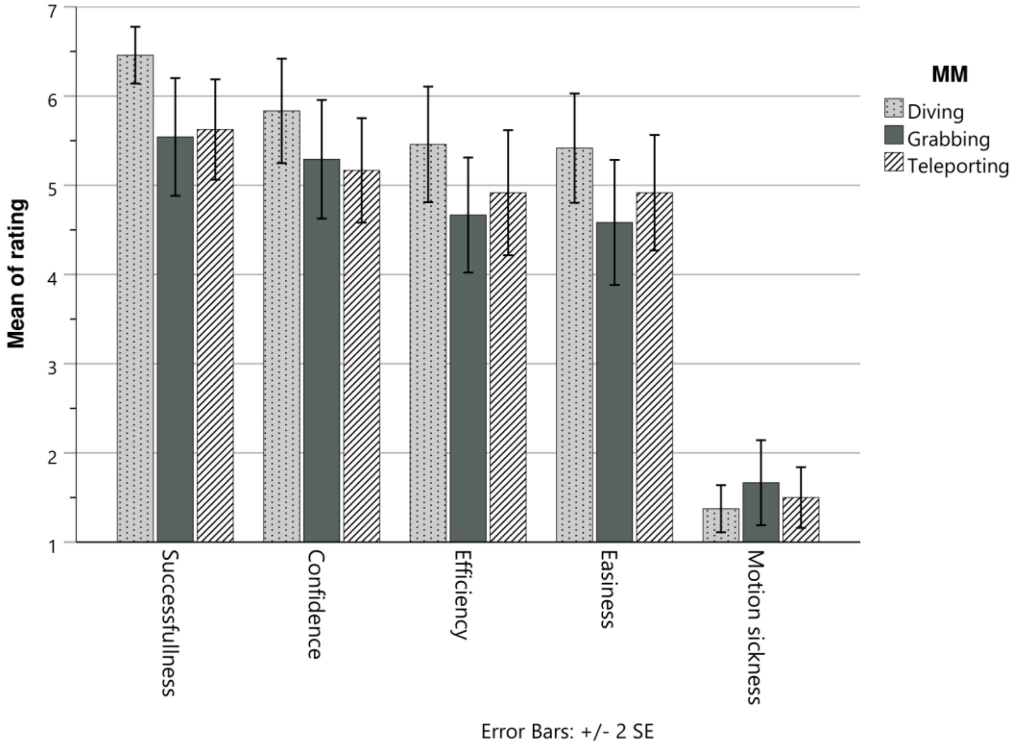

Figure 17. The subjective evaluation results of experienced Successfulness, Confidence, Efficiency, Easiness, and Motion sickness attributes with each movement method.

There was no statistical significance regarding Confidence, Efficiency, Easiness, and Motion sickness. However, Diving was ranked the highest in Successfulness, Confidence, Efficiency, and Easiness – whereas Grabbing was ranked the lowest in Successfulness, Efficiency, and Easiness. Diving was also ranked the lowest in Motion sickness (less motion sickness), and Grabbing was ranked the highest (more motion sickness).

Condition	Mentions		
	1st	2nd	3rd
Diving	12	9	3
Grabbing	8	4	12
Teleporting	4	11	9

Table 2. The number of movement method preferences' mentions (1st = Most preferred, 3rd = Least preferred).

The results for movement method preference are presented in **Table 2**. While not statistically significant, Diving was the most preferred among the three movement methods. Post hoc test showed that between Diving and Teleporting, significance was approaching (p = .019, Bonferroni-adjusted p-value < .017).

6.2. Qualitative Results

For qualitative analysis, the participants' answers were grouped into tables based on questions and categorized into subcategories by topic. The anonymized tables were sent to GPT-3.5 (Brown et al., 2020), and the AI chatbot was asked to distinguish the main themes from them. AI was used merely as a tool to make the qualitative analysis more effective. The main themes that the AI chatbot recognized were inspected in detail, and any errors were resolved by the researcher. The main themes were then reduced to four categories, and their results are discussed in the following sections: "Diving" in Section 6.2.1, "Grabbing" in Section 6.2.2, "Teleporting" in Section 6.2.3, and "VR system" in Section 6.2.4.

6.2.1. Diving

Four participants reported positive attributes with Diving, such as easiness to use (2 participants), fastness (1 participant), as well as realism and naturalness (1 participant). One participant described using Diving as "like playing video games", which emphasized that they connected the movement method to an already known mental model. Another participant expressed that they preferred Diving the most.

However, a total of nine participants expressed some negative attributes. Two participants mentioned that it was hard to rotate the 3D model. One of these participants emphasized that rotation was needed to see behind them. A negative effect of the lack of rotation was recurring head-turning, as that was the only way to rotate the view angle. To improve the movement method, a rotation feature was proposed (2 participants). One participant described the idea more in detail: the user could keep a certain button pressed to activate rotate mode. Joystick movement would then be converted into rotation at different angles.

Two participants expressed the need to have a better solution for vertical movements. It was mentioned that moving vertically with Diving caused challenges when a segment was behind a bone structure of the 3D model (1 participant). One participant expressed difficulty in displaying the segment tag when a segment was close to the model, as they did not have much space. This could imply, that Diving was a difficult movement method for viewing segments in hard-to-reach areas.

Additionally, two participants reported non-intuitive movement directions. One of these participants explained that the reversed order of the left and right movements in Diving felt strange and complicated. Some participants addressed issues in using a single controller with Diving. One participant found that the movement method was limited to four actions with a single controller. Another participant suggested making use of both controllers, like playing a video game: the left joystick would be used for moving around the object while the right joystick would be reserved for moving forward and backward.

6.2.2. Grabbing

Three participants mentioned positive attributes with Grabbing. The movement method was described as easy to use (1 participant) and the most intuitive of the methods (1 participant). One participant expressed how they found their way to navigate and move by using the movement method. They also felt that "zooming" was the most beneficial ability in Grabbing, and even emphasized "loving" it.

However, 11 participants described different negative attributes of the movement method. Grabbing was described as "slow" (2 participants), "clumsy" (1 participant), and the most challenging movement method to adopt (1 participant). Three participants mentioned problems related to moving with Grabbing. One participant expressed moving to be challenging in general. Another participant described that their movements became slower when the 3D model was closer – as if they were "stuck". It was also mentioned that the distance was harder to control with Grabbing (1 participant).

Four participants brought out issues related to the "zooming" ability. Zooming was found not to work well (1 participant). Another participant could not differentiate between zoom in/out and move forward -movements. Two participants expressed problems in zooming on a precise point. One of these participants described that the zoom-in/out commands made the 3D model also move up/down, which was not seen as user-friendly.

In addition, two participants described issues related to rotation ability. It was suggested that the user should be able to rotate easily, as rotating required more than one movement (1 participant). Another participant suggested adding the ability to rotate the 3D model. Rotation ability was possible with Grabbing – however, this ability was not described in the video tutorial. This is explained further in Chapter 7.

Three participants expressed problems related to the lack of intuitiveness with the movement method. One participant described: "When I want to move the model up, it goes down”. It also felt difficult to remember how the commands were executed (1 participant) and release the hands from the controllers to stop them from grabbing (1 participant). Furthermore, one of the participants expected more consistency with the movements. They explained that during zooming, for example, they expected the VR object to enlarge instead of getting closer by zooming in.

Regarding accessibility and physical straining, three participants expressed their concerns. One participant found Grabbing challenging, especially if the user’s hand movements are limited. This participant suggested using a controller to adjust the movement range: a slighter hand movement could cover a greater distance. Additionally, two participants proposed that Grabbing could be physically straining to use for extended periods.

6.2.3. Teleporting

With Teleporting, three participants reported positive attributes: fastness (2 participants), realism and naturalness (1 participant), and easiness to use (1 participant). However, 10 participants stated various negative attributes of the movement method. Three participants found Teleporting generally challenging to use. In addition, the target point location was found inaccurate (4 participants), and the rotating feature was found difficult (2 participants). One participant mentioned having to turn around frequently to fix the rotation angle. One participant mentioned that Teleporting involved excessive physical actions, which reduces efficiency.

In this regard, another participant reported encountering unexpected obstacles when moving around the virtual space while using Teleporting. This participant also reported difficulties with the wire of the HMD when using the movement method, as it hindered their movements. Lastly, one participant highlighted the lack of vertical movement in the movement method.

Three participants suggested improving Teleporting overall, as they found it could be effective. One of them suggested implementing an undo feature for Teleporting. This would allow users to self-correct their movements using the movement method itself.

6.2.4. VR system

A total of 20 participants expressed having positive experiences with the VR system. 12 participants found positive instrumental qualities, including the ease of using the VR system (5 participants) or movement methods (3 participants), as well as quickness to learn (1 participant). Two participants also expressed not being overwhelmed by the VR system. Additionally, eight participants reported positive non-instrumental qualities of the VR system. For example, the experience was stated as fun (3 participants) and interesting (4 participants).

However, 10 participants expressed having different negative experiences with the VR system. One participant mentioned that the movement methods were not easy to use.

Also, it was suggested that moving around the models was sometimes challenging (1 participant). Two participants addressed the need to integrate multiple movement methods. One of these participants wanted more variation in choosing the preferred method depending on the situation. One participant suggested that using haptic gloves would increase overall efficiency. One participant would have preferred to manage the VR object with the movement methods instead of the virtual space.

Regarding the VR objects, five participants mentioned blurry graphics and two of these participants explicitly emphasized blurriness within the object. One participant expressed the need to enhance the realism of the 3D models. Another participant recommended improving rendering speed for quick movements to prevent motion sickness. They suggested introducing a high-quality 3D or custom-made model would be easy for the system to render. In terms of hardware, three participants expressed that the cable of the HMD was either uncomfortable or restricted their movement. One of these participants suggested using a wireless HMD instead.

7. Discussion

This chapter is divided into three sections. The results regarding the movement methods are discussed in Section 7.1. Limitations of the study are addressed in Section 7.2. Finally, the future of 3D-VR model interaction studies is discussed in Section 7.3.

7.1. Movement Methods

In the thesis, a research gap was addressed in movement (locomotion) method studies focused on small-scale interaction with a 3D model. Additionally, the current study answers the need for experiments in the field of medicine, where there has been a growing interest in (1) converting 2D medical images into 3D models in VR and (2) using AI methods for segmenting these models, as demonstrated in Chapter 2.

In the current study, the less-known method of Diving was seen as significantly more successful than Teleporting. In a study that compared movement methods for viewing 3D graphs, Teleporting was found less preferred than the other methods (Drogemuller et al., 2020). Although in the current study, no significance was found regarding movement method preferences, significance was approaching between Diving and Teleporting. Teleporting relies on spatial cues from the VR environment (e.g., shading). In VR environments lacking these cues due to visualization design (as in the current study and Drogemuller et al., 2020), Teleporting could be harder to use. The qualitative results demonstrated that some participants had to use more physical movements to fix errors made with the movement method. The lack of shading in the floor of the VR environment might have caused difficulties for the participants in estimating the location of the VR object, as the object was floating in the VR space.

Participants' frequent need for physical movements in Teleporting may also have been caused by the lack of body-based or visual self-motion cues, which causes disorientation. In the real world, these cues are present while moving (Kelly et al., 2023). The lack of information about one's movement complicates spatial updating, the process of adjusting one's position relative to one's surroundings when on the move. It is reasonable to assume that this phenomenon may also occur in small-scale VR environments, where the focus is on precise interaction with a single VR object, as in our current study.

In Bozgeyikli et al. (2016b), the original Point and Teleport (with rotational translation done with body rotation) was compared to Point and Teleport with Direction Specification (rotational translation done with hand rotation). In the study, it was found that the participants had significantly less feeling of control when using Point and Teleport with direction specification compared to the original Point and Teleport. In the current study, the frequent need for turning could imply that similar effects were observed. Therefore, the participants might have had less control over the direction specification in Teleporting. The authors in Bozgeyikli et al. (2016b) recommended using the original movement method to avoid the found usability problems.

Additionally, some of the participants in the present study addressed the lack of rotational translation with Diving. A fix to the rotational issues in both Teleporting and Diving could be to use a swivel chair, as in Adhikari et al. (2021). Based on the literature review of the thesis, the use of real movement for rotational translations would further improve spatial understanding. However, for a sitting use position, Teleporting would have to be changed from ground-based movement method to flight-based (the participants had to use their body for vertical movements in the current study). In addition, some participants addressed the lack of rotational translation with Diving. A feasible fix could also be to use a swivel chair. Rotational translation done in a sitting position could reduce cord-related problems with the HMD as well, as these problems were reported by some of the participants in the current study.

It has been suggested that the prevalence of Teleporting is due to its easiness of use (Bozgeyikli et al., 2016b; Langbehn et al., 2018). However, this may be just a matter of established ways of implementing movement actions. The present study did not show a statistical significance for Teleporting related to easiness.

Movement methods using artificial or hybrid continuous motion (resembling Diving), such as Steering (Christou & Aristidou, 2017; Clifton et al., 2020), Slider (Rantala et al., 2021), and Joystick (Coomer et al., 2018; Griffin et al., 2018), have been found to significantly increase motion sickness compared to other movement methods. In contrast, Teleporting has been found to rarely induce motion sickness (e.g., Christou & Aristidou, 2017; Langbehn et al., 2018; Prithul et al., 2021; Weißker et al., 2018). In the current study, however, no difference was found between Diving and Teleporting related to motion sickness. This suggests, that in small-scale interaction with a single VR object, continuous movement methods such as Diving rarely cause motion sickness. This could be explained by the small motions needed, which keep the effects reasonable.

Grabbing was found significantly more time-consuming than Diving and Teleporting; this is in line with previous research (Zhang et al., 2019). In the present study, Diving and Teleporting were found to be equally fast, which is inconsistent with previous studies where Teleporting has typically been the fastest movement method (e.g., Boletsis & Cedergren, 2019; Bozgeyikli et al., 2019; Griffin et al., 2018; Langbehn et al., 2018). The result that Teleporting was significantly faster than Grabbing, however, suggests that the findings between Diving and Teleporting may be considered accurate. Although in one paper Teleporting has been found to take more time compared to other methods in investigating a 3D graph (Drogemuller et al., 2020), the present study suggests that Teleporting allows quick movement in single VR object investigation.

In previous work, a controller-assisted version of Grabbing (Swimming) was preferred to its original version (Zhang et al., 2019). In the current study, an assisted version of Grabbing was not included. Nevertheless, some participants addressed potential straining and accessibility issues related to Grabbing, which suggests the need for a controller-assisted version. With movement methods based entirely on body-based movements like Grabbing, physical straining becomes a possible concern. In Bozgeyikli et al. (2019), it was found that another body-based movement method, Walk-in-place, required significantly more effort and caused significantly more increased tiredness compared to the artificial movement method Joystick. Even though physical straining was not observed in the current study, some participants felt that Grabbing could cause straining if used for longer periods.

Some participants in the current study found Grabbing as clumsy, hard to adopt, unintuitive, and difficult for moving. This suggests that the movement method was difficult to understand and operate for these participants and might be one factor causing the increased task completion times.

Additionally, Grabbing was classified as a “natural” movement method in Zhang et al. (2019). However, the results of the present study suggest that even though Grabbing was intuitive for some, it was a learned relationship for many — as is the case with all three movement methods studied.

Diving was seen the most positively of the three movement methods. However, the opinions concerning the movement methods varied, supporting the design conclusion that a VR system for investigating medical 3D models should provide more than one movement method. This allows the user to switch between the movement methods depending on their personal preferences and the situation. For example, Teleporting could be used for transporting into a further location within the 3D model, Diving for general movement along X, Y, and Z axes, and Grabbing for close, refined investigation of the segments.

7.2. Limitations

The discussion regarding limitations of the current study is divided into two sections. In Section 7.2.1, internal validity of the study is addressed, while external validity is discussed in Section 7.2.2.

7.2.1. Internal validity

At the beginning of the experiment, four participants had Model 3 placed at a higher altitude. The model was lowered because some participants using the Teleporting method could not see a segment tag due to their height. Possible group effects were tested for each dependent variable – no statistical difference was found, and thus, we have included their data in the analysis.

The lack of instructions for rotating using Grabbing was mentioned in Chapter 6. This could have made some participants view the movement method less positively, as one person expressed the need for rotation while using Grabbing.

Finally, in the experiment, participants could ask questions in Finnish or English, to which the facilitator answered in the language that the question was proposed. As Finnish was the native language of the facilitator, it could be, that the help offered in Finnish was of higher quality than the help offered in English. Therefore, the authors acknowledge that the disproportionate offering of help (time spent helping, language in which the help was provided) might have some effects on the internal validity of the study.

7.2.2. External validity

It was found that most participants only experienced low levels of motion sickness with all the movement methods. However, the research invitation mentioned that the study could lead to VR-related motion sickness. As most of the participants already had some VR experience, they might have been able to evaluate their level of motion sickness as low. Therefore, people who experience more motion sickness might have wanted to refrain from participating in the study, to avoid nausea and discomfort – reducing the external validity of the study. Future studies should include a background question related to whether the participants have previous experiences of VR-related motion sickness, as now it is merely possible to make presumptions from the study data.

Additionally, one participant reported that it was hard for them to come up with improvement suggestions for the VR system, as they did not have much VR experience. The findings suggest that this is the case: only one out of six participants who categorized themselves as having “No VR experience” gave an improvement suggestion – whereas out of the rest 18 participants, 16 gave improvement suggestions.

7.3. Future

The results add to the knowledge of movement methods in VR. Diving as a less-known method was supported, which suggests that the industry-standard method of Teleporting may still be challenged. There is still room for innovation and further experiments in different contexts of use. It is expected that the selection of the most optimal movement method depends on the scale of movements required in interaction.

It was clear that a VR system for investigating 3D medical models should provide more than one movement method. This would allow the user to switch between the movement methods depending on personal preferences and the situation. For example, Teleporting could be used to quickly transport into another location of the 3D model; Diving for generally moving along X and Y axes; and Grabbing for close and refined investigation of the segments. It would be interesting to study the preferred combinations of such methods in different classes of tasks when they would all be available to the user at any time. This would require careful user interface design to make the selection of each method as fluent as possible so that they are available but not mixed.

Some of the participants in this study addressed that using movement methods for 3D-VR model investigation did not seem intuitive. Instead, they thought that the model itself could be manipulated with manipulation methods. This highlights the need for further 3D-VR model interaction studies, where movement methods and manipulation methods could be compared to see which is more intuitive – or whether a combination of both methods would be the most beneficial for medical professionals.

8. Conclusion

Three movement methods, Diving, Grabbing, and Teleporting, were compared in the thesis. The subjective comparisons focused on the experienced successfulness, confidence, efficiency, easiness, motion sickness, and movement method preference. Diving, the novel movement method, was deemed significantly more successful compared to the well-researched method of Teleporting. Although significant differences were not found regarding the rest of the subjective comparisons, Diving was received as the best among the participants. Artificial and hybrid continuous movement methods have generally been found to induce a substantial amount of motion sickness. However, the results of the current study indicate that the amount of experienced motion sickness could be insignificant in small-scale VR interaction.

In the thesis, it was also studied whether there are differences between the three movement methods regarding task completion time. In this comparison, Grabbing was found significantly the slowest, while Diving and Teleporting were found equally fast. The results suggest that although in many studies Teleporting has been the fastest movement method, its performance depends on the context of the VR application.

Even though Diving was generally seen the most positively by the participants, the opinions about the movement methods varied. Therefore, the study supports the design conclusion that a VR system for medical 3D-model interaction should utilize more than one movement method. This allows the user to switch between different movement methods, depending on personal preferences and use context.

Although there seems to be interest in 3D-VR model interaction in multiple areas in the medical field, no papers that involved comparison of movement methods for investigating 3D-VR models were found in the methodological review done in the thesis. Therefore, a research gap in 3D-VR model interaction studies seems to be filled in the current study.

As promising results for the novel method of Diving were shown, further studies could investigate the method in different VR contexts. In addition, it would be beneficial to compare which of the two techniques is more suitable for 3D-VR model interaction: manipulating the 3D model itself with manipulation methods or adjusting the user’s viewpoint in the VR space with movement methods. It could also be, that the combination of both techniques is most useful for medical professionals.

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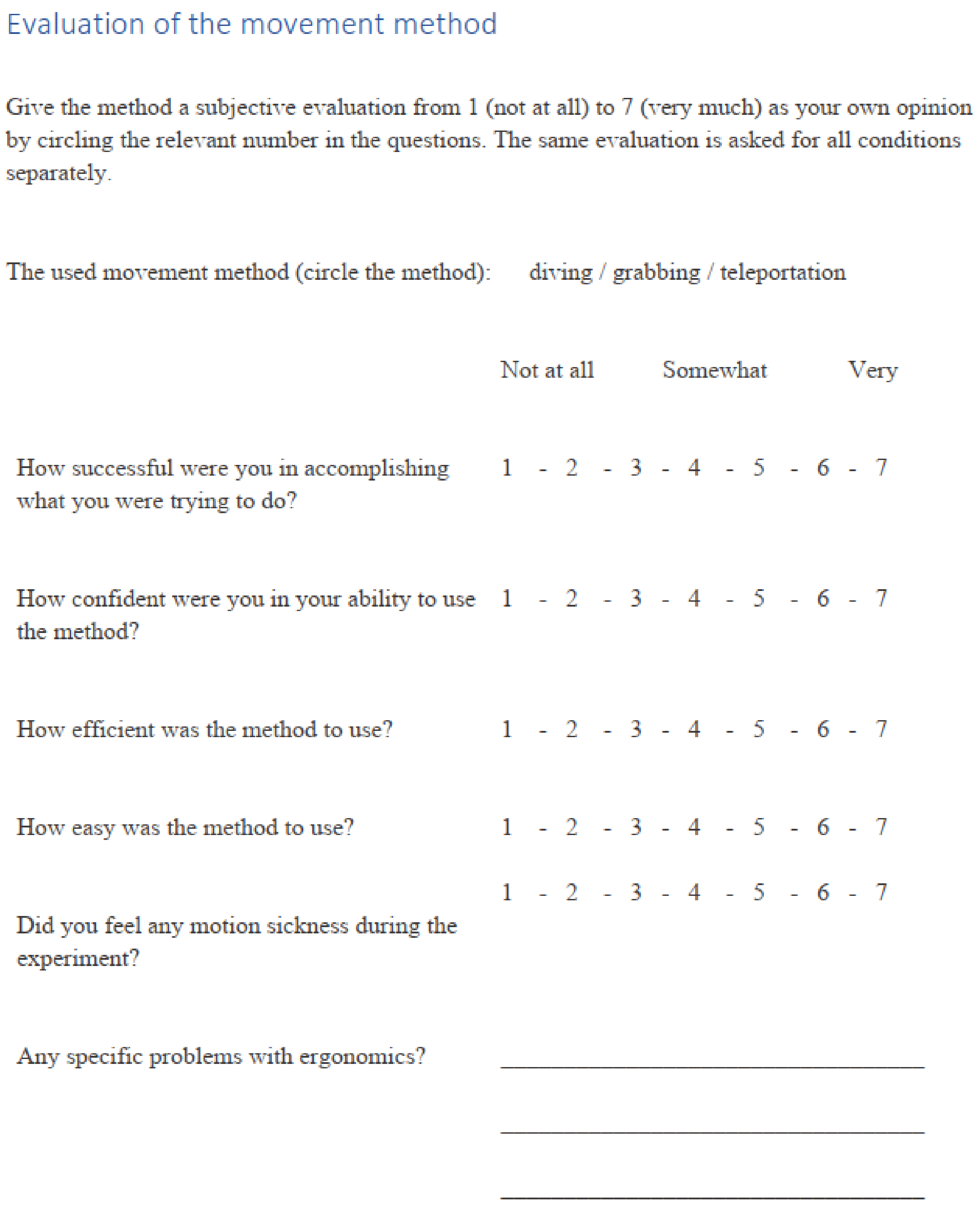
Appendix 1

Movement Method Evaluation Questionnaire



Evaluation of the movement method

Give the method a subjective evaluation from 1 (not at all) to 7 (very much) as your own opinion by circling the relevant number in the questions. The same evaluation is asked for all conditions separately.

The used movement method (circle the method): diving / grabbing / teleportation

	Not at all Somewhat Very
How successful were you in accomplishing what you were trying to do?	1 - 2 - 3 - 4 - 5 - 6 - 7
How confident were you in your ability to use the method?	1 - 2 - 3 - 4 - 5 - 6 - 7
How efficient was the method to use?	1 - 2 - 3 - 4 - 5 - 6 - 7
How easy was the method to use?	1 - 2 - 3 - 4 - 5 - 6 - 7
Did you feel any motion sickness during the experiment?	1 - 2 - 3 - 4 - 5 - 6 - 7

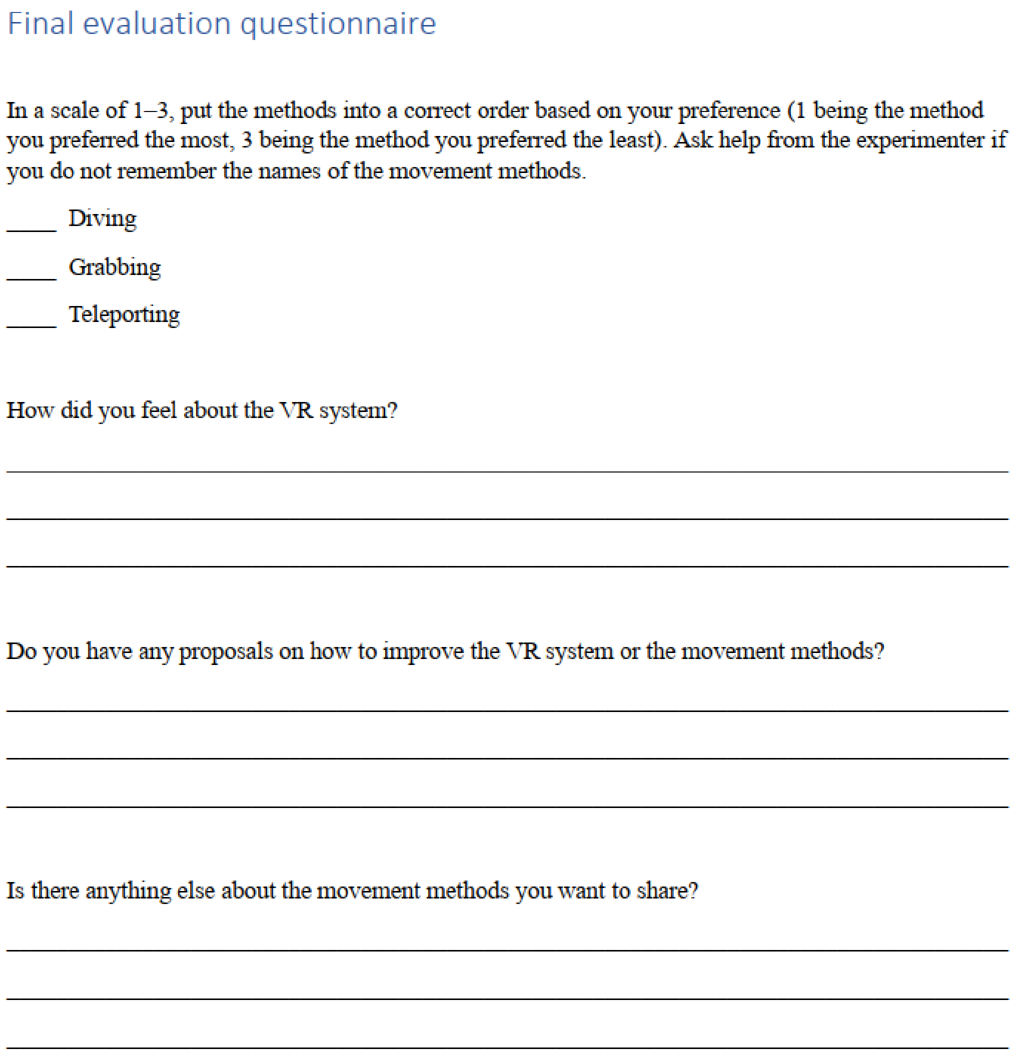
Any specific problems with ergonomics? ________________________________

____

____

Appendix 2

Final Evaluation Questionnaire



Final evaluation questionnaire

In a scale of 1–3, put the methods into a correct order based on your preference (1 being the method you preferred the most, 3 being the method you preferred the least). Ask help from the experimenter if you do not remember the names of the movement methods.

____ Diving

____ Grabbing

____ Teleporting

How did you feel about the VR system?

____

____

____

Do you have any proposals on how to improve the VR system or the movement methods?

____

____

____

Is there anything else about the movement methods you want to share?

____

____

____