

Faculty of Cognitive Sciences and Human Development

A Heuristic for Wearable Virtual Reality Educational Applications

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A Heuristic for Wearable Virtual Reality Educational Applications

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DECLARATION

I declare that the work in this thesis was carried out in accordance with the regulations of Universiti Malaysia Sarawak. Except where due acknowledgements have been made, the work is that of the author alone. The thesis has not been accepted for any degree and is not concurrently submitted in candidature of any other degree.



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ABSTRACT

Students frequently encounter difficulties in grasping abstract concepts within the education process, particularly in subjects like science. To address the diverse learning needs of students, educational institutions globally are increasingly adopting advanced technology-based tools. Virtual Reality (VR), transitioning from its origins in gaming, has emerged as a significant tool in education, offering engaging and immersive learning experiences. The usability of VR educational applications is paramount as it directly influences student satisfaction, motivation, and learning outcomes, especially in challenging subjects. However, a notable gap exists in the lack of established guidelines for evaluating the usability of virtual reality educational applications. This research aimed to develop and validate a comprehensive heuristic checklist for evaluating the usability of wearable VR educational applications (WVREA). Employing an eight-step methodology, the study involved expert judgment from academics and industry practitioners (n=25) for the efficacy assessment of the heuristics, followed by heuristic evaluations conducted by academics and industry practitioners (n=15) and schoolteachers (n=15). The findings indicated that the developed checklist effectively identified and addressed key usability issues, with no further heuristics deemed necessary. Positive feedback from HCI experts, VR specialists, and schoolteachers confirmed the effectiveness of the revised heuristics in addressing usability concerns. This research demonstrates the potential of the developed heuristic checklist to serve as a standard assessment tool for WVREA usability. Ultimately, this study lays a crucial foundation for establishing standardised usability practices for WVREA, thereby facilitating the creation of more user-centred and effective VR educational experiences.

Keywords: Wearable Virtual Reality (WVREA), VR education, VR Usability Evaluation, Usability Heuristics, and Standardised Evaluation Practices.

Heuristik untuk Aplikasi Pendidikan Reality Maya Boleh Pakai

ABSTRAK

Pelajar sering menghadapi kesukaran dalam memahami konsep abstrak dalam proses pendidikan, terutamanya dalam mata pelajaran seperti sains. Bagi memenuhi keperluan pembelajaran yang pelbagai dalam kalangan pelajar, institusi pendidikan di seluruh dunia semakin banyak menggunakan alat berasaskan teknologi yang canggih. Realiti Maya (VR), yang pada asalnya dikaitkan dengan permainan, kini telah muncul sebagai alat penting dalam pendidikan, menawarkan pengalaman pembelajaran yang menarik dan imersif. Kebolehgunaan aplikasi pendidikan VR adalah sangat penting kerana ia secara langsung mempengaruhi kepuasan pelajar, motivasi, dan hasil pembelajaran, terutamanya dalam subjek yang mencabar. Walau bagaimanapun, terdapat jurang yang ketara dalam ketiadaan garis panduan yang mantap untuk menilai kebolehgunaan aplikasi pendidikan realiti maya.

Kajian ini bertujuan untuk membangunkan dan mengesahkan senarai semak heuristik yang komprehensif bagi menilai kebolehgunaan aplikasi pendidikan VR boleh pakai (WVREA). Menggunakan metodologi lapan langkah, kajian ini melibatkan penilaian oleh pakar akademik dan pengamal industri (n=25) bagi menilai keberkesanan heuristik, diikuti dengan penilaian heuristik yang dijalankan oleh akademik dan pengamal industri (n=15) serta guru sekolah (n=15). Hasil kajian menunjukkan bahawa senarai semak yang dibangunkan berkesan dalam mengenal pasti dan menangani isu utama kebolehgunaan, tanpa keperluan untuk heuristik tambahan. Maklum balas positif daripada pakar HCI, pakar VR, dan guru sekolah mengesahkan keberkesanan heuristik yang disemak dalam menangani kebimbangan kebolehgunaan.

Kajian ini membuktikan potensi senarai semak heuristik yang dibangunkan sebagai alat penilaian piawai bagi kebolehgunaan WVREA. Secara keseluruhannya, kajian ini meletakkan asas penting ke arah mewujudkan amalan kebolehgunaan yang standard untuk WVREA, sekali gus memudahkan penciptaan pengalaman pendidikan VR yang lebih berpusatkan pengguna dan berkesan.

Kata kunci: *Realiti Maya Boleh Pakai (WVREA), Pendidikan VR, Penilaian Kebolehgunaan VR, Heuristik kebolehgunaan dan Amalan Penilaian Standard*

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LIST OF ABBREVIATIONS

AR	Augmented Reality
BYOD	Bring your own device
CCI	Child–computer interaction
CGS	Centre for Graduate Studies
COVID-19	Coronavirus disease-19
2D	Two Dimensional
3D	Three Dimensional
GUI	Graphical User Interface
HCI	Human-Computer Interaction
HE	Heuristic Evaluation
HMD	Head-Mounted Device
HTC	High Tech Computer Corporation
ICT	Information and Communication Technology
IoT	Internet of Things (IoT)
ISO	International Organization for Standardization
IVR	Immersive Virtual Reality
MAUVE	Multi-criteria Assessment of Usability for Virtual Environments
MUSE	Meta-heUristics uSability Evaluation tool
NIVR	Non-Immersive VR
PC	Personal Computer
PHEG	Playability Heuristic Evaluation for Educational Computer Games
SIVR	Semi-Immersive VR
SMART	Smartphone Mobile Application heuRisTics

SMASH	Smartphone's Usability Heuristics
STEM	Science, Technology, Engineering and Mathematics
SUS	System Usability Scale
TMD	Touchscreen-based Mobile Devices)
UI	User Interface
UNIMAS	University Malaysia Sarawak
VE	Virtual Environment
VLE	Virtual Learning Environment
VLS	Virtual Learning Space
VW	Virtual World
VR	Virtual Reality
WVREA	Wearable Virtual Reality Educational Applications
WVREAUH	Wearable Virtual Reality Educational Application Usability Heuristics

CHAPTER 1

INTRODUCTION

1.1 Study Background

Virtual Reality (VR) is an advanced technology that provides users with an immersive and interactive experience through real time, computer-generated 3D graphics (AlGerafi et al., 2023; Bogusevschi et al., 2020). The artificial environment is meticulously crafted and controlled by a computer to provide a realistic and interactive experience for the user. Furthermore, Kamińska et al. (2019) elaborate that VR environments typically aim to mimic real-world settings, enabling users to navigate and engage with objects and virtual entities like avatars. By simulating the user's physical presence in a digitally created world, VR opens a realm of possibilities for interactive experiences and innovative applications.

VR technology has emerged as a powerful tool due to its ability to transform traditional teaching and learning methodologies, notably through wearable devices such as the Oculus Quest 2 and HTC Vive Pro 2. This technology is innovatively immersing students in interactive digital experiences and simulations and heightens their engagement (Al-Ansi et al., 2023; Almufarreh & Arshad, 2023; Lampropoulos & Kinshuk, 2024). It mimics natural human perception and interaction in experiments by providing a believable environment where users can experience realistic social interactions, facial expressions, and gestures (Partarakis & Zabulis, 2024). These capabilities allow students to explore abstract concepts more effectively than traditional text-based or 2D learning methods (Bogusevschi et al., 2020; Qorbani et al., 2021; Sherman & Craig, 2018; Young et al., 2020).

Many students struggle to comprehend complex issues, especially in science subjects, due to technical intricacies, the need for abstract thinking, and the tangible aspects of these concepts (Byukusenge et al., 2023; Yager, 2000; Zheng et al., 2015). Students struggling with abstract concepts can benefit from this technology's capability to revisit topics, make errors and learn from them. VR overcomes limitations found in traditional classrooms, such as the lack of opportunity to practice outside of laboratory schedules.

VR immerses students in a fully immersive digital world using wearables such as head-mounted displays (HMD) that transport them entirely into computer-generated environments. The application of wearable VR in educational settings has the potential to revolutionise how knowledge is acquired and applied. Within the realm of VR, there exist three distinct types: non-immersive VR (NIVR), semi-immersive VR (SIVR) and immersive VR (IVR) (Salatino et al., 2023). Wearable sensors and devices, in conjunction with hybrid deep learning algorithms, significantly enhance the immersive qualities of VR experiences by collecting real-time physiological data and contextual information from users, enabling more intuitive interactions (Singh et al., 2023). Additionally, the integration of olfactory and haptic devices in VR applications contributes significantly to creating multisensory immersive experiences, impacting users' sense of presence, immersion, and engagement (De Jesus Jr. et al., 2022).

These advancements in wearable technology, from physiological data collection to haptic feedback systems, collectively contribute to creating a more realistic and engaging VR experience, fostering the complex feeling of "being there" within the virtual world. Immersive VR technology, which refers to the utilisation of head-mounted devices, allows

the realistic visualisation of three-dimensional (3D) data and supports an exciting real-time learning experience.

Such technology can improve performance outcomes, facilitate high interactivity with objects and persons, create a virtual environment that resembles the real world, provide feedback from the simulation to the learner, and foster conceptual understanding by providing an effective and unique way to learn while motivating students (Huang et al., 2010). These compelling factors have prompted researchers to incorporate wearables into this study.

In a study by Zhang (2017), HMD-based systems are highlighted for providing a better user experience (UX) and ease of use. These technologies hold the potential to enhance enjoyment, motivation, and achievement of learning objectives, making them favoured by researchers. Users can deeply engage with the content, experiencing a heightened sense of presence (Becker et al., 2023; Lee & Wong, 2014), thus fostering enriched learning experiences and improved information retention using virtual-based wearables in educational settings. Key hedonic properties such as immersion, presence, embodiment, flow, and empathy play vital roles in the utilisation of VR gear. Presence significantly boosts user engagement, especially in VR educational applications. Numerous studies emphasise the importance of presence in driving user interest and immersion (Himmels et al., 2023; Li et al., 2023; Sun, Yilu et al., 2023). Elements such as embodiment, emotional states, user interactions, and spatial enclosure are crucial in influencing presence and engagement within the VR experience. Understanding how user behaviours, emotions, and interactions affect learning outcomes in immersive environments can offer valuable insights for developing effective VR interventions in education. A lack of presence may

indicate reduced engagement with the virtual environment, resulting in disinterest and frustration, affecting UX negatively (Dey et al., 2020). This lack of engagement may lead to decreased motivation to interact with the application, underlining the importance of considering user motivation (Ryan & Deci, 2000).

Nevertheless, the success of teaching and learning depends not only on the level of technological advancement but also on how user-friendly the application is. Evaluating an application's usability is crucial in software development to ensure it is efficient, effective, and ease to use (Figueroa et al., 2019). Usability, as defined by ISO 9241-11(1998), refers to how well specific users can use a product to achieve specific goals with effectiveness, efficiency, and satisfaction in a specified context of use. It is a measure of how easy user interfaces are to use (Baghini et al., 2024; Nielsen, 1994; Rusu et al., 2018), defined by attributes such as learnability, efficiency, memorability, errors, and satisfaction. The usability of a product or software can be evaluated by usability testing, inspection or inquiry. However, usability inspection is often the most cost-effective and efficient technique for identifying usability problems as it evaluates the overall design to pinpoint any problems (Cho et al., 2022; Nielsen, 1994).

HE is among the most widely used usability inspection method in VR-related studies (e.g., Botha et al., 2021; Guo et al., 2023; Jansen et al., 2023; Minocha & Hardy, 2011; Moore et al., 2020; Siso et al., 2022; Stadler et al., 2023; Wang et al., 2019; Young et al., 2020) due to its ability to effectively detect a high proportion of usability problems in applications (Guo et al., 2023; Joyce et al., 2015; Rusu et al., 2011a; Quiñones et al., 2019). By employing established usability heuristics, HE assesses usability in an easily understandable way (Fuller et al., 2023; Quiñones & Rusu, 2017). Despite some criticism

regarding its limitations in detecting problems and the general nature of existing heuristics (Rajanen & Rajanen, 2018), it remains popular due to its cost-effectiveness. Identifying usability issues early in the design process, as highlighted by Fuller et al. (2022), is crucial as it reduces the expenses associated with fixing them. Designers are more receptive to changes during the early stages when the design is not yet finalised. Furthermore, HE involves experts evaluating a user interface against usability heuristics, making it a quick and affordable method to uncover design flaws without requiring many participants or extensive resources (Quiñones & Rusu, 2019). Although Nielsen's usability heuristics are commonly used due to their general applicability and resource efficiency, which focuses on more pragmatic aspects such as information hierarchy, icons, symbols, etcetera, some studies recommend employing domain-specific heuristics for detecting specific system usability issues more effectively (Figueroa et al., 2019; Othman et al., 2018; Young et al., 2020). This study explores the use of HE as a valuable alternative, offering a cost-effective and efficient method for identifying potential usability issues in user interfaces tailored for Wearable Virtual Reality Educational Applications (WVREA).

The purpose of this dissertation is to develop and validate a heuristic checklist specific to educational applications supporting wearable VR applications, referred to as WVREA, to promote a usable and effective VR experience in education. This research aims to uncover how VR features can enhance students' understanding of abstract concepts and achieve meaningful learning outcomes with minimal to no usability issues in virtual environments (VE).

1.2 Research Motivation and Problem Statements

The initial inspiration that led the researcher to explore this topic arose from firsthand experiences in designing VR applications for education. The researcher relied solely on general heuristics when developing the wearable VR applications and utilised a storyboard design by a teacher. Consequently, during user testing sessions, the researcher encountered significant usability issues that profoundly impacted UX. These issues included motion sickness, users getting lost while interacting in the VE, lack of guidance during navigation within the VE, and the presence of unnatural 3D models that hindered users from envisioning the real environment. Comploi-Taupe et al. (2023) and Othman et al. (2018) attributed these issues to poor design and suggested that domain-specific heuristics could offer solutions. Thus, the pursuit of specialised heuristics tailored for educational VR applications began with the goal of improving usability and user satisfaction, enhancing students' performance, and achieving learning objectives. The growing adoption of VR technology in educational institutions underscores the necessity to address its unique challenges. Current usability heuristics often do not comprehensively address the complexity of an educational VR environment. The complexity includes designing content that aligns with curriculum standards and pedagogical aspects and ensuring learning objectives are met and suitable for VR. Moreover, crafting interactive and captivating educational experiences in VR demands an understanding of diverse learning styles and individual user engagement differences, underscoring the need for the development of new domain-specific heuristics.

Moreover, the researcher notes that HMDs have become economically viable for both consumers and educational institutions due to a substantial reduction in prices (Hodgson et al., 2015). Subsequently, VR technology has been widely embraced, with 96% of universities and 79% of colleges in the UK utilising it (UKAuthority, 2019). The

advancement in graphical fidelity, propelled by progress in personal computers and associated hardware, has further spurred the adoption of VR tools (Slater, 2018). The global virtual reality in education market size was valued at USD 14.55 billion in 2023. The market is projected to grow from USD 17.18 billion in 2024 to USD 65.55 billion by 2032 (Fortune Business Insights, 2019).

Additionally, VR's capacity to offer users a sense of presence and immersion has opened up new educational opportunities (Häfner et al., 2018). The increasing academic research on the potential benefits of immersive VR in education (Hodgson et al., 2019) has spurred researchers to develop specific guidelines tailored to the educational field for wearable VR app development (Hodgson et al., 2019).

Given the mobility and portability of wearable VR devices, this study is essential to understand their potential impact, especially in the field of education. The researcher anticipates that VR, combined with these wearable devices, will see extensive utilisation in educational settings (i.e. Attallah & Ilagure, 2018; Cheng & Yao, 2019).

1.2.1 Empirical Gap

The study aims to address the lack of specific heuristics for WVREA. Previous research by Botha et al. (2021) and Moore et al. (2020) has primarily relied on general heuristics from Nielsen (1994) and Sutcliffe & Gault (2004). In Botha et al. (2021), the authors utilised Nielsen & Molich's heuristics (1990) to evaluate a Virtual Clinical Simulation application. However, this evaluation was conducted by only six experts, which limited the generalisability of their findings. Furthermore, some of the issues arise which is related to education during the validation could not be detected by general heuristics used, such as "the patient's face needed a blue discolouration (cyanosis) to indicate that there was

a lack of oxygen" and "The patient saturation did not react accordingly". Additionally, they encountered disorienting and nauseating effects that the existing framework did not address. Similarly, Moore et al. (2020) applied twelve heuristics from Sutcliffe and Gault (2004) in their related study, which also had a small sample size and identified only five design considerations for developing similar VR applications: affordance, agency, diverse input modalities, mental models, and advanced roles. The clinical settings involved in Moore et al.'s study expressed a need for an educational package that allows them to engage in high-fidelity, realistic, and engaging simulations within a clinical context. Specifically, Sutcliffe and Gault's (2004) tenth heuristic, which pertains to learning support, required detailed attention to enhance active learning. This entails encouraging users to engage in activities directly related to knowledge acquisition. Young et al. (2020) proposed eight heuristics for students' attitudes and behaviours towards VR in the classroom, neglecting to measure actual learning outcomes.

In a different case, Stadler et al. (2023) applied Nielsen and Molich (1990) heuristics to evaluate a dynamic guidance system in a VR transit hub. They discovered a critical issue that traditional methods could not, such as cybersickness induced by the immersive environment. This underscores the necessity to thoroughly investigate the suitability of immersive VR across various domains. Castilla et al. (2013) combined Nielsen's (1990) heuristics with 25 principles suggested by the National Institute for Aging (NIA) (Hodes & Lindberg, 2002). These principles are specifically tailored to enhance the usability of the applications for elderly users, ensuring that the design is accessible and user friendly. Their research revealed specific challenges for participants unfamiliar with computers or application metaphors. This finding underlines the importance of developing VR-specific heuristics tailored to these unique scenarios. Hooft et al. (2019) faced challenges in the HE

of adaptive VR due to the complexities of the technology itself, necessitating further refinement of their lightweight rate adaptation heuristics. Van Wyk and De Villiers (2014) also encountered limitations in their Design-based Research (DBR) Heuristics for VR training programs, highlighting the need for VR training programs and underscoring the need for ongoing improvements in VR-specific evaluation methodologies. Their research revealed specific challenges for participants who are unfamiliar with computer or application metaphors. This discovery underlines the importance of developing VR-specific heuristics tailored to these unique situations. Evaluating VR usability involves both challenges and opportunities. While general-purpose heuristics offer a valuable starting point, their limitations become apparent when navigating the unique complexities of the VE (Zhang & Simeone, 2021; Stadler et al., 2023; Frezzo & Waterman, 2020).

The absence of tailored heuristics for addressing usability issues in WVREA is evident. The unique characteristics of VR-based wearables in educational settings require detailed analysis to ensure effectiveness. VR's immersive nature often introduces novel challenges, like motion sickness or discomfort related to 3D spatial interactions (Vi et al., 2019). VR evaluation requires a heightened focus on representation fidelity, encompassing visual elements and other influencing usability (Zhang & Simeone, 2021). WVREA involves user interaction with learning content through gestures or movements, distinguishing it from traditional Graphical User Interface (GUI) (Gao, 2023; Lin et al., 2023). Current general heuristic often overlooks vital hedonic qualities such as immersion, a sense of presence, embodiment, and flow, leading to usability challenges identified in previous studies (Botha et al., 2021; Castilla et al., 2013; Ferracani et al., 2016; Hooft et al., 2019; Hvannberg et al., 2012; Paes & Irizarry, 2018; Slone, 2009; Zhang & Simeone, 2021). To ensure a compelling

UX in WVREA, it is essential to integrate not only pragmatic aspects but also hedonic qualities, making the experience enjoyable (Mohammad & Pederson, 2022).

It is essential to consider additional factors, such as pedagogical aspects aligning with curriculum content and ensuring learning objectives are met, setting them apart from other VR education apps, to develop more comprehensive heuristics for educational VR applications, as recommended for future work (Chen & Huang, 2023; Christopoulos et al., 2020; Qorbani et al., 2021; Smutny et al., 2019; Soliman et al., 2021). Considering pedagogical factors that emphasise active learning in 2020, Qorbani's comprehensive heuristics for educational VR applications are crucial for future research (Chen & Huang, 2023; Christopoulos et al., 2020; Qorbani et al., 2021; Smutny et al., 2019; Soliman et al., 2021). Wang M. et al. (2022) stated that instructional design is one of the major pillars in the discipline of learning design and technology, emphasising the incorporation of theories primarily from education, psychology, and communication in designing and developing learning activities systematically. Moreover, Mallek et al. (2024) emphasise educational theories such as constructivism and a learner-centred approach as key principles for designing an effective real 3-D learning environment. Therefore, the new heuristics would incorporate these aspects to ensure that the VR apps are instructionally sound by aligning instructional strategies with educational goals, allowing learners to construct knowledge rather than passively receive information actively. The contextually rich and immersive simulations provided by the application bridge the gap between theoretical knowledge and practical application, enhancing learner engagement and retention. Furthermore, the application can promote action-oriented learning through interactive experiences that encourage decision-making and problem-solving, fostering critical thinking and self-directed learning. By facilitating collaboration among learners, the platform empowers

students to work together to tackle challenges, enhancing their understanding through peer discussions. Incorporating real-time feedback mechanisms within the application allows learners to track their progress and understand areas for improvement, essential components of a learner-centred approach. Additionally, developing guidelines within the heuristics to ensure accessibility for students with varying abilities can address equity issues in education. Continuous improvement based on user and educator feedback will ensure that the heuristics remain relevant and effective, ultimately creating a more engaging, contextualised, and collaborative learning environment that mitigates the challenges highlighted in the educational literature.

Asad et al. (2021) and Cooper and Thong (2018) describe VR technology as a transformative tool that offers the opportunity to transform teaching pedagogy. Past studies have overlooked instructional design contexts when using immersive VR apps, indicating a lack of foundational design supported by established learning theories in many existing educational VR applications (Lamb et al., 2018; Lege & Bonner, 2020; Makransky et al., 2019; Markowitz et al., 2018). Furthermore, inadequate pedagogical approaches in traditional teaching methods may lead to low motivation and engagement (Bobko et al., 2024). Users might discontinue using VR apps if they have poor experiences, such as finding activities or instructions too complex to understand or facing difficulties in interacting with them, which could lead to demotivation for future use. Poorly designed cognitive aids and user interfaces can hinder UX and potentially harm students, highlighting the importance of a pedagogical approach in wearable VR education apps. Given the findings of previous studies, there is a clear need to ensure that wearable VR applications are not only engaging but also pedagogically sound. Therefore, one of the heuristics in WVREA's emphasis on incorporating pedagogical approaches aligns with previous research that indicates a direct

correlation between well-designed pedagogical frameworks and improved user motivation and engagement. By establishing these heuristics, the researcher directly responds to the identified need for integrating educational theories into VR applications.

The WVREA heuristics integrate ICT tools into pedagogy, aligning with educational frameworks such as The Malaysian Education Blueprint (2013-2025). Therefore, the new heuristics are designed to enrich students' knowledge and skills, guide developers in creating immersive VR experiences for educational settings, and enhance user engagement, interest, and performance. The new heuristics will be based on the important usability characteristics of a VE backed by the pedagogical approach. Therefore, these criteria should be considered while developing VR-based wearable apps to avoid or reduce usability issues when engaging in activities and, most importantly, to increase students' performance and achievement in the examination.

The new heuristics will serve as a valuable guide for VR developers, enabling the creation of tailored VR applications for classroom use. These new heuristics are intended to assist developers in developing suitable VR applications for classroom use, aiding instructors in selecting appropriate applications for classroom use. This comprehensive and coherent heuristics aligns with the shifting educational technology landscape, fostering seamless and productive learning experiences. Adherence to these heuristics promises to enhance student performance and experiences, surpassing the outcomes observed in previous research due to their focus on constructivist pedagogy and UX (Botha et al., 2021; Minocha & Hardy, 2011; Moore et al., 2020; Young et al., 2020). By leveraging the new heuristics, WVREA has the potential to revolutionise traditional pedagogical approaches, offering a

more immersive, interactive, and effective learning experience. As WVREA continues to become more prevalent and complex, a specific evaluation process is needed.

1.3 Objectives

The study aims to achieve the following objectives:

i. RO1: To assess the shortcomings of existing heuristics for evaluating WVREA.

ii. RO2: To develop a novel set of user friendly and effective heuristics for evaluating the UX of educational apps within the WVREA framework, considering pedagogical aspects.

iii. RO3: To assess the effectiveness of a newly developed novel heuristic in identifying issues for WVREA.

1.4 Research Questions

i. RQ1: How can limitations of current heuristics for evaluating WVREA be identified and addressed, considering factors such as effectiveness, user-friendliness, and alignment with the specific goals, tasks and learning contents within the WVREA framework?

ii. RQ2: How can a novel set of user-friendly and effective heuristics be designed to evaluate the UX of educational apps within the WVREA framework, incorporating pedagogical principles to enhance learning?

iii. RQ3: How effectively do the newly developed heuristics, with their potential to significantly improve the usability of educational apps for WVREA, identify and classify usability issues?

1.5 Definition of Terms

Table 1.1 summarises the definition of terms in this study.

Table 1.1 Definition Of Terms

Terms	Conceptual Definition	Operational Definition
1. Wearable	Wearable technology refers to devices that can be worn by users, like smartwatches, wristbands, smart glasses, smart jewellery, electronic garments, skin patches, and more (Seneviratne et al., 2017).	Wearable devices that could enhance virtual reality (VR) experiences by stimulating senses and contributing to a feeling of presence within the virtual world (Radianti et al., 2020), including Meta Quest, Oculus Rift, Oculus Go, and HTC Vive.
2. Wearable Virtual Reality Educational Application (WVREA)	A wearable virtual reality educational application utilises VR technology to immerse students in fully immersive digital worlds through headsets that transport them to a computer-generated environment (AlGerafi et al., 2023).	WVREA is an interactive educational tool that utilises a virtual environment and a head-mounted device to engage students with digital content. It aims to enhance enjoyment, motivation, and learning achievement through an emphasis on both practical and enjoyable UX. Additionally, WVREA integrates constructivist pedagogy to promote learning through experiential exploration.

Table 1.1 continued

3. Usability	Usability refers to the "Extent to which specified users can use a product to achieve specified goals with effectiveness, efficiency, and satisfaction in a specified context of use" ISO 9241-11, 1998). **Effectiveness:** Accuracy and completeness with which users achieve specified goals. **Efficiency:** Resources expended in relation to the accuracy and completeness with which users achieve goals. **Satisfaction**: Freedom from discomfort and positive attitudes towards the use of the product. **Context of use**: User, tasks, equipment (hardware, software and materials), and the physical and social environments in which a product is used.	There are five core usability attributes: learnability, efficiency, memorability, errors, and satisfaction (Nielsen, 2012). Quality in Use Model International Organization for Standardization., 2011: This model focuses on seven key Aspects: effectiveness, efficiency, learnability, Operability, user error protection, freedom from risk, and context completeness.
4. User Experience (UX)	UX includes usability; however, it involves not only the user's satisfaction- such as how pleasant it is to use a product, system or service - but also their emotions and perceptions during the interaction.	This set of factors for immersive VE expands beyond core usability to encompass a broader UX perspective. It includes presence, engagement, immersion, flow, usability,

Table 1.1 continued

		skill, emotion, experience consequence, judgment, and technology adoption (Tcha-Tokey et al., 2018).

1.6 Significance of Research

This research ultimately aims to close the gap that exists in usability heuristics. Previous studies have favoured the use of domain-specific heuristics to prevent experts from misclassifying usability problems or failing to identify existing issues. Therefore, given the unique characteristics of WVREA, this research argues that a distinct set of heuristics is essential for assessing the usability of such applications. The newly developed heuristics will aid VR education developers in creating suitable apps for students and schoolteachers to use.

1.7 Chapter Summary

Chapter 1 provides a general introduction to this research, as well as the supporting theories, objectives, and gaps that support the overall motivation. Chapter 2 will represent a literature review central to this research study. For every subsection in Chapter 2, this research will discuss the related literature and the gaps it intends to fill. Chapter 3 focuses on the development and validation of usability heuristics tailored for WVREA. The primary objective of the chapter is to establish a comprehensive set of usability heuristics for WVREA, followed by a validation process to refine these heuristics for effective evaluation. The research employs a standard eight-stage methodology outlined by Quiñones and Rusu (2019), encompassing exploratory, experimental, descriptive, correlational, selection, specification, validation, and refinement phases. The validation phase includes an evaluation

that involves academicians, industry practitioners and schoolteachers to assess the heuristics' effectiveness in identifying usability issues in WVREA. Chapter 4 will discuss the report's findings. The methodology led to the identification of 14 usability heuristics based on feedback from this evaluation. Key findings revealed that experts found the heuristics to be useful, clear, and user-friendly, suggesting the need for an additional checklist. As a result, the researcher revised the wording and explanations to enhance clarity and reduce ambiguity. Furthermore, the evaluation of the three WVREAs demonstrated that the proposed heuristics effectively identified usability issues, enabling improvements to the applications. Chapter 5 will further expand on the discussion, while Chapter 6 will conclude the study.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

A comprehensive literature review revealed a notable absence of heuristics specifically tailored for educational VR applications, particularly those utilising wearable technology. While VR has gained traction in various fields, such as the gaming industry (Fernandes & Werner, 2019; Hara et al., 2021; Paes & Irizarry, 2018), and across other domains such as tourism (Bugalia et al., 2016; Ferracani et al., 2016; Tehrani et al., 2014; Videva et al., 2019), psychology (Breves, 2021; Lucio-Alonso et al., 2019), training (Belluco et al., 2010; Fajar et al., 2022; Guo et al., 2023; Hvannberg et al., 2012; Van Wyk & De Villiers, 2014), technology (Hooft et al., 2019; Zhang & Simeone, 2021), education (Botha et al., 2021; Hara et al., 2021; Moore et al., 2020; Minocha & Hardy, 2011; Qu et al., 2021; Young et al., 2020), HCI (Alencar et al., 2011; Cardona et al., 2016; Castilla et al., 2013; Chapoulie et al., 2014; Frezzo & Waterman, 2020; Jansen et al., 2023; Junker et al., 2020; Latif & Widyarto, 2004; Martínez et al., 2013; Prachyabrued & Borst, 2012; Siso et al., 2022; Slone, 2009; Stadler et al., 2023), treatment (Langlet et al., 2021) and marine archaeology (Katsouri et al., 2015), research on heuristics for educational VR remains limited. This lack of guidance presents a significant challenge for designers and developers in creating effective and engaging learning experiences. This study seeks to address this research gap by developing a set of heuristics to guide the design and implementation of educational VR applications, ensuring they effectively cater to the diverse learning styles and educational needs of learners and instuctors. The following discussions explore the

evolution of heuristic development, tracing the evolution from early versions to recent advancements.

2.1.1 Application of Virtual Reality in Education

All students have the capacity to learn, but they do not learn at the same pace and may require different methods and strategies to acquire knowledge. Learning and teaching, especially in science subjects, present unique challenges due to students' difficulty in grasping abstract concepts. These challenges arise from various cognitive and educational barriers. For example, students often struggle to reconcile common sense with scientific concepts, leading to misconceptions that hinder their understanding (Osborne, 2023). Osborne added that students often struggle with discrepancies between common sense and scientific ideas about the way the world works. Akram et al. (2023) found that 58% of primary school students faced difficulties with concept-based items in general science, primarily due to insufficient prior knowledge, inadequate teaching aids, language misunderstandings, inadequate physical infrastructure, and parental involvement in their children's education, whilst Uttal et al. (2024) found that spatial thinking and hands-on experience are essential for grasping abstract concepts in science education.

One effective method for bridging the gap between abstract concepts and tangible understanding in science education is by incorporating advanced technology such as VR. VR is a rapidly evolving technology that creates immersive digital environments, allowing users to interact with simulated worlds. Ramkrishna et al. (2024) and Natasha and Suresh (2024) reported a significant increase in VR-related publications, particularly post-pandemic, indicating a growing interest in its educational applications. Xingrui (2024) defined VR as a computer simulation system that generates VEs, enabling user immersion

through sensory experiences such as visual, auditory, and tactile cues. Research indicates that practical, experiential learning is essential for grasping scientific concepts, as students perform better when they can apply knowledge in real-world contexts (Venkatesh & Dhivya, 2023). By transforming abstract concepts into tangible experiences, VR facilitates dynamic exploration and understanding of various subjects. Students can engage in virtual worlds that simulate real-life scenarios, bridging the gap between theoretical knowledge and practical applications (Byukusenge et al., 2023; Kim et al., 2023; Li, Ziming et al., 2023; Parmar et al., 2023). VR is a beneficial teaching resource (Nesenbergs et al., 2021) and integrating VR into primary school lesson plans offers significant educational benefits, enhancing engagement and emotional connection in learning. For instance, a study involving 455 school children demonstrated that VR environments effectively engaged students in learning about safe cycling, making the educational experience enjoyable and informative (Vuorio, 2024).

VR allows students to engage in hands-on learning and fosters a deeper understanding of complex ideas through interactive experiences (Panwa et al., 2024). The hands-on experience and active engagement offered by the VR environment create an immersive learning environment (Al-Azawi et al., 2019; Fernandes & Werner, 2019; Maheshwari & Maheshwari, 2020; Pellas et al., 2020; Qorbani et al., 2021; Scavarelli et al., 2021; Segura et al., 2020; Vats & Joshi, 2024; Wang, Annie et al., 2022). Its engaging and interactive content particularly benefits students with learning challenges. Chen et al. (2023) revealed that VR significantly boosts student engagement, demonstrating a large effect size ($g=0.85$), particularly in cognitive engagement and procedural knowledge learning. Additionally, Sui and Sui (2024) conducted an experimental study that found a direct correlation between interactivity and learning effectiveness. Their research showed that

immersive interactive experiences in VR enhance subject understanding and skill mastery among ninth-grade students. Lara-Alvarez et al. (2023) conducted a meta-analysis and revealed that students in VR environments scored significantly higher than those in traditional settings, with a standard mean difference of 0.64, suggesting a strong positive effect on learning outcomes.

Cao et al. (2024) posited the effectiveness of VR in educational settings and demonstrated that VR environments enhance learning performance and problem-solving abilities among primary school students. Furthermore, Chen et al. (2024) compared immersive VR-based 3D modelling to conventional methods and found that the immersive approach significantly improves creative thinking and problem-solving skills while reducing cognitive load. Furthermore, VR has expanded the dimensions and benefits of education by providing a deeper and more effective learning experience for students (Akbar & Djakariah, 2024) while also increasing their motivation (Becker et al., 2023; Byukusenge et al., 2023; Daghriri et al., 2024; Di Natale et al., 2020; Dirin & Laine, 2023; Parmar et al., 2023), fosters deeper comprehension of complex concepts and spatial relationships (Flood, 2024; Norwood et al., 2023; Kim et al., 2023; Villena Taranilla et al., 2022; Hanson et al., 2019; Klippel et al., 2019).

A study on high school physics education demonstrated that a VR experimental learning system improved student satisfaction, achieving a System Usability Scale (SUS) score of 74.38, indicating high usability and engagement (Lim & Al Gavara Ramarao, 2024). “The Virtual Scientist” software allows students to conduct virtual experiments in a gamified environment, effectively engaging learners and providing realistic lab experiences, especially beneficial for those in remote areas (Levonis & Schweiker, 2023). Students who

lack access to traditional classroom settings will have the chance to experience this interactive application (Soliman et al., 2021; Neuwirth et al., 2021; Nesenbergs et al., 2020; Xiaorong, 2018).

The development of VR curricula should consider cognitive processes and collaborative learning to ensure that the content stimulates student engagement and learning outcomes (Horváth, 2019). VR's immersive nature promotes collaborative problem-solving, enabling learners to work cohesively in 3D settings to tackle challenges and develop thinking skills. (Al-Azawi et al., 2019; Almusawi et al., 2021; Concannon et al., 2019; Dalgarno & Lee, 2010; Diederich et al., 2021; Fernandes & Werner, 2019; Maheshwari & Maheshwari, 2020; Makransky et al., 2019; Moore et al., 2020; Pellas et al., 2020; Scavarelli et al., 2021; Segura et al., 2020; Southgate, 2020; Wang, Annie et al., 2022; Werf et al., 2023; Wolfartsberger, 2019).

For example, the concepts of embodied social translucence in VR, as explored by Spike and Xie (2025), facilitate collaborative learning by allowing students to interact and communicate in real time, thereby enhancing their collective problem-solving capabilities. Furthermore, a virtual school system designed for collaborative VR learning demonstrated effective task performance among students, showcasing the potential of VR to create engaging and impactful educational experiences (Sobota et al., 2023).

VR is increasingly recognised as a powerful tool for environmental education, allowing students to explore ecosystems in immersive ways (Ahir et al., 2020; Hills & Thomas, 2020; Jitmahantakul & Chenrai, 2019; Minas et al., 2024; Qu et al., 2021; Quay et al., 2020). A study conducted by Mohamed et al. (2024) shows that VR tools significantly enhance environmental literacy and participation among second-grade students,

demonstrating measurable improvements in their understanding of and attitudes towards environmental issues. Furthermore, students reported positive emotional responses and usability, indicating VR's potential impact on environmental engineering education (Wolf et al., 2023).

Educational wearables in virtual applications for science education offer innovative ways to enhance learning experiences. High fidelity significantly enhances the immersive quality of immersive virtual environments (IVEs). This refers to the realism of both visual and interactive elements. This realism contributes to authentic scenarios that enhance students' understanding and retention of knowledge (Christopoulos et al., 2020; Kadri et al., 2024; Moore et al., 2020; Neuwirth et al., 2021; Pellas, Dengel et al., 2020; Qorbani et al., 2021; Smutny et al., 2019; Vats & Joshi, 2024; Wolfartsberger, 2019). For example, Bogusevschi and Muntean (2019) implemented the "Water Cycle in Nature" application, which combined VR with experimental simulations and found positive results in usability and learner experience among 58 primary school children, with over 74% of participants enjoying the application and finding it helpful for understanding key concepts like vaporisation and condensation.

A key factor in the immersiveness of VR environments is the incorporation of multiple senses, which leads to more engaging and realistic experiences. It engages multiple senses, such as visual, auditory, and tactile, to create a rich educational atmosphere that evokes a profound sense of presence (Alqahtani et al., 2017; Choi & Baek, 2011; Cui et al., 2006; Kadri et al., 2024; Krokos et al., 2018; Neuwirth et al., 2021; Qorbani et al., 2021; Sanfilippo et al., 2022; Sandrone & Carlson, 2021; Vats & Joshi, 2024; Wang, Annie et al., 2022; Wu et al., 2020). This immersive nature encourages learners to actively participate in

the educational process through dynamic interaction and real-time feedback (Al-Azawi et al., 2019; Choi & Baek, 2011; Christopoulos et al., 2020; Concannon et al., 2019; Dalgarno et al., 2002; Dalgarno & Lee, 2010; Fernandes & Werner, 2019; Moore et al., 2020; Pellas et al., 2020; Scavarelli et al., 2021; Segura et al., 2020; Smutny et al., 2019).

Reddy (2023) emphasises that combining visual, auditory, and tactile elements is crucial for achieving a high level of realism and presence in VR, both of which are essential for user engagement. Additionally, Ferrise et al. (2023) introduce olfactory stimuli in VR training, demonstrating that integrating smell can further enhance the immersive experience, providing a more comprehensive training environment. Kim et al. (2023) explore how congruent auditory and visual stimuli can enhance vection perception (a feeling that users are moving, even though users are stationary), suggesting that multisensory stimuli can improve the sense of movement in VR. Lee and Jo (2023) discuss sensory transfer, showing how auditory cues can enhance tactile sensations, which supports the idea that engaging multiple senses can lead to a more immersive experience. Moreover, the structural and functional fidelity of virtual avatars is a key factor in creating immersive learning environments, influencing user engagement and learning outcomes. This underscores the importance of realistic avatars in educational settings (Gaudi et al., 2024).

In education, teachers must consider their students' diverse learning styles, as each learner is unique. Therefore, learning should be a personalised and meaningful process that caters to individual needs (Philippe et al., 2020). Personalised learning considers students' prior knowledge and experiences, allowing more effective learning methods and improved comprehension (Ashurova et al., 2024).

VR can create educational environments that adjust based on individual learning styles. For instance, Ildikó (2021) demonstrated that students in a VR classroom scored 20% higher than those in traditional settings. Furthermore, Lin et al. (2021) found that an adaptive VR learning method which identifies and adjusts to students' learning styles has shown promising results, with accuracy in identifying styles ranging from 74.38% to 80.30%.

The accessibility of VR technology has indeed surged in recent years, driven by the introduction of affordable consumer products like Oculus Rift and Google Cardboard. The development of affordable VR headsets is expected to bridge the gap between early adopters and the broader population, promoting inclusive access to immersive experiences (John et al., 2023).

VR provides immersive and interactive environments that enable students to explore complex scientific concepts actively. For instance, Lin and Cheng (2024) created a mini-VR science to help students learn the Periodic Table in Chemistry. They discovered that VR transforms passive learning into active exploration, encouraging students to become experimenters and problem-solvers. Furthermore, Rajassekharan and Vivekanandam (2024) found that the use of VR in electronic science education fosters a deeper understanding through hands-on activities and real-time simulations.

Akbar and Djakariah (2024) and Gadelha (2018) further describe VR as a future learning tool that has the potential to revolutionise education. However, for VR to be effective, its content must be meaningful, engaging, and easy to navigate to ensure that students retain what they learn (Gadelha, 2018). Specifically, VR content needs to be of high quality and aligned with curriculum standards and pedagogical approaches (Becker et al., 2023; Chen & Huang, 2023; Gadelha, 2018; Surapaneni, 2023; Tudor et al., 2018; Vats &

Joshi, 2024). This alignment ensures that VR is an effective teaching tool rather than merely a technological novelty (Surapaneni, 2023).

Doğan and Şahin (2024) support this notion by highlighting the importance of robust theoretical frameworks in VR research to guide the design of effective educational content. Their research emphasises the critical need for more comprehensive, theory-guided, and design-focused VR studies to facilitate its effective integration within educational settings. Additionally, Hamilton et al. (2021) found that adopting immersive VR as a pedagogical method offered learning benefits in approximately half of the 29 cognitive studies they reviewed, particularly in contexts that required spatial understanding and visualisation of highly complex or conceptual problems.

Integrating technology into schools can significantly enhance student engagement and learning when it is thoughtfully and strategically incorporated into the curriculum in a pedagogically beneficial manner. Nesenbergs et al. (2021) argue that the positive impact of technology on student engagement and learning depends on how educators strategically implement it. Premthaisong and Srisawasdi (2024) conducted a study on a technology-infused active inquiry approach aimed at transforming primary school students' understanding of science. The results showed a noticeable change in students' understanding after the intervention.

Despite the promising advancements in VR technology, it is important to note that many students continue to learn passively during science lessons, even when using technology. This observation underscores the ongoing challenge of effectively integrating technology in the classroom to promote more advanced learning concepts. Jiang and Fryer (2023) stress the need for caution, pointing out that many studies on VR learning fail to

address the novelty effect, suggesting that increased motivation may not lead to improved learning outcomes due to insufficient pedagogical frameworks. Sun and Chen (2023) further emphasise the need for careful consideration, noting that while gamification elements in VR can improve engagement, their effectiveness may diminish without proper educational strategies. Furthermore, Chevalier et al. (2023) found no correlation between the presence of VR and actual performance, indicating that without a structured approach, VR may not significantly enhance learning. These findings highlight the need for educators to approach VR integration with caution and careful planning.

Successfully integrating VR into educational practices requires careful consideration of pedagogical approaches and alignment with curriculum objectives. Educators must recognise that while VR has extraordinary potential, it should not be viewed as a one-size-fits-all solution to educational challenges. Instead, VR represents a valuable resource that, when thoughtfully integrated with traditional teaching methods, can provide a rich, multifaceted learning experience (Huang et al., 2021; Nesenbergs et al., 2021). Salakas (2017) emphasises that VR technology alone does not guarantee a quality lesson, asserting that while it may rate well according to the Substitution, Augmentation, Modification, and Redefinition (SAMR) model (Hamilton et al., 2016), it is ultimately effective pedagogy that makes a difference.

As VR continues to evolve, it offers significant opportunities for reshaping educational practices, driving innovation, and fostering an engaging, effective learning environment for students in diverse educational settings. Careful evaluation is crucial to ensuring the effective integration of VR into educational practices. Assessing wearable and interactive VR applications in education involves various methods, including heuristic

evaluation (HE), user testing, and adaptive learning metrics. Such assessments refine the technology and maximise its potential to create richer and more meaningful learning experiences for students.

2.2 Definition of Wearable Technology

Wearable devices come in various forms, ranging from smart glasses to smart rings (Rani & Chu, 2021). Seneviratne et al. (2017) defined wearable technology as devices designed to be worn by users, typically as accessories such as smart watches, wristbands, smart glasses, smart jewellery, electronic garments, and skin patches. Qu et al. (2021) and Sultan (2015) further describe "wearable technology," "wearable devices," and "wearables" as electronic technologies or gadgets integrated into clothing and accessories which can be worn comfortably on the body. According to Khakurel et al. (2018), wearables are characterised as "smart electronic devices available in various forms that sense and analyse physiological and psychological data such as feelings, sleep patterns, movements, heart rate, and blood pressure, through applications either installed on the device or on external platforms. As highlighted by Almusawi et al. (2021), wearables aim to enhance productivity, improve communication, and increase user satisfaction in daily activities, similar to many technological breakthroughs. They come in various forms and can be categorised based on their proximity to body parts, such as head-mounted, arm-mounted, body-mounted, or placed on other regions such as legs or a combination of multiple locations.

Wearables have garnered significant interest among researchers, developers, and practitioners due to ongoing technological advancements, including miniaturised electronic modules and sensors that improve energy, connectivity, and data storage (Motti, 2019). Regardless of their placement on the body, research indicates that wearable offers innovative

solutions for tracking users' biometric data (Bauer et al., 2019), psychophysiological metrics (Bauer et al., 2019; Vartak et al., 2008), and daily activity and behaviour patterns (Frank et al., 2017) in both formal and informal settings throughout the day (Borthwick et al., 2015). Wearables such as smartwatches and electronic tattoos are increasingly adopted for health monitoring, with over 80% of consumers willing to use them for this purpose (Del-Valle-Soto et al., 2024). They continuously collect data on vital signs, sleep patterns, and physical activity, empowering users to manage their health proactively (Kazanskiy et al., 2024).

In addition to tracking health metrics, wearables support various applications, including VR in education, which immerses students in interactive learning environments and promotes a deeper understanding of complex subjects (Almusawi et al., 2021). They also enhance communication among educators and students, enabling seamless interaction and collaboration (Qu et al., 2021). Furthermore, wearables facilitate remote learning by providing tools for virtual classrooms, thereby expanding educational access (Szeto et al., 2024).

2.2.1 Chronological Overview of Head-Mounted Displays

The history of head-mounted displays (HMDs) and wearable technology has significantly impacted various industries. It began with Ivan Sutherland's invention of the "Sword of Damocles" in 1968, which introduced the foundational concept of VR. Since then, VR technology has evolved through advancements in both hardware and software, enhancing UX in areas such as gaming, education, and healthcare (Chavan, 2024; Datta & Mantri, 2022).

During the 1980s and 1990s, VR technology made notable strides. The 1980s saw the first commercial attempts at creating VEs with products like Visual Programming

Language (VPL) Research's EyePhone and DataGlove. However, these innovations remained largely experimental and primarily used in academic and research institutions due to practical limitations and high costs. Also, Steve Mann made significant contributions during this time by developing head-mounted camera technology, which laid the groundwork for modern devices like Google Glass. In 1981, Mann also created a backpack-mounted computer, further advancing wearable technology (Baumann, 2016; Tröster, 2005). Despite these advancements, early VR applications were predominantly limited to research settings and lacked the consumer engagement necessary for widespread adoption (Long, 2024).

The 1990s marked a pivotal period in the gaming market, marked by attempts like Sega VR that ultimately failed to gain significant traction. This era was characterised by experimental technologies that faced challenges with user accessibility and market viability (Levchenko, 2022).

At the beginning of the 21st century, there was a renewed focus on wearable technology, as evidenced by the first International Symposium on Intelligent Wearable Computers in 1997, co-organised by prestigious institutions, including the Massachusetts Institute of Technology, Carnegie Mellon University, and Georgia Institute of Technology. This event sparked notable interest from both academic and industry sectors (Jiang et al., 2015) and led to a proliferation of scientific publications and practical applications related to wearable technology (Tröster, 2005). Innovations continued to emerge, such as the incorporation of Bluetooth technology for internet connectivity and the introduction of the Nike + fitness tracking kit, which was made possible through collaborations between technology giants such as Apple and Nike (Baumann, 2016).

A resurgence in HMD technology occurred in the early 2010s, notably driven by Palmer Luckey's Oculus Rift. The Oculus Rift emerged following a successful Kickstarter campaign and reignited interest in the VR landscape. The launch of the Oculus Rift showcased VR's potential for applications beyond gaming, such as marketing and rehabilitation (Chen, 2024).

The acquisition of Oculus by Facebook in 2014 underscored the commercial viability of HDMs, leading to products like the HTC Vive and PlayStation VR, which established a competitive marketplace. Facebook's $2 billion acquisition of Oculus highlighted the commercial potential of VR, leading to a surge in market interest and product development (Alsius et al., 2018). The integration of social networking features into VR environments, such as Facebook Spaces, has enhanced user engagement and social interaction (Alsius et al., 2018). By the 2020s, societal shifts, particularly during the COVID-19 pandemic, accelerated the adoption of VR technologies, which were increasingly employed for remote work and social interaction (Ball et al., 2021).

In 2021, the Oculus Quest 2 was released, quickly gaining popularity as a standalone VR device. Other companies like Microsoft advanced AR technologies exemplified by the Hololens 2, which showcases the growing interest in immersive technologies beyond VR (Egliston & Carter, 2020).

Furthermore, the announcement of hybrid devices like Apple's Vision Pro in 2023 indicates a significant shift in the landscape of AR and VR. These devices offer innovative healthcare and medical education applications that enhance digital interactions and training opportunities (Santos & Castillo, 2024). Such capabilities may address clinical challenges, allowing clinicians to engage more effectively with patients (Egger et al., 2023). As of

August 2024, advancements in HMD technology continue to enhance user interaction with digital content.

2.2.2 Understanding Wearable Virtual Reality Technology

Wearable VR technology, represented by head-mounted displays (HMDs), is a primary medium that presents visual content directly to the user's eyes. This technology provides a stereoscopic display capable of generating 3D effects while simultaneously tracking head movements to adjust perspective in real-time. Wearable VR systems rely on several key components to facilitate a fully immersive 3D environment. These include motion tracking sensors that detect the user's head and body movements, audio systems, haptic feedback mechanisms, motion controllers, software and contents, and connectivity and networking.

HMDs are engineered to deliver high-resolution visuals and a wide field of view, thus enveloping users within the virtual space (Guo et al., 2024). The Motion tracking sensors are essential in this process, as they allow for the real-time adjustment of perspective, significantly enhancing the immersive experience (Wang et al., 2023). According to Guo et al. (2024), recent advancements have made HMDs lighter yet more powerful, thereby improving user comfort and experience. Furthermore, high-quality audio is essential for establishing a realistic environment in VR; it provides a spatial sound that complements the visual components, thereby enriching the UX (He et al., 2023).

Motion controllers play a critical role by enabling precise hand tracking and facilitating interaction with virtual elements, thus empowering users with agency within the immersive environment (Neamoniti & Kasapakis (2022). Additionally, haptic feedback devices contribute to immersion by delivering tactile sensations in response to virtual

interactions, allowing users to engage with virtual objects convincingly as if they were real (Deng et al., 2023; He et al., 2023). This technological integration is vital for gaming and plays a significant role in training simulations (Xi et al., 2023).

The effectiveness of VR systems depends on the quality of software and content, which must be meticulously designed to effectively leverage the hardware's capabilities (Tran et al., 2023). Additionally, strong connectivity is essential for enabling multi-user experiences and accessing cloud-based content, which collectively enhances the overall VR experience (Charan et al., 2023). Together, these components produce a powerful sense of presence, classifying wearable VR as immersive VR technology. This classification enables seamless interaction with applications, mirroring real-life experiences.

The integration of these technologies promotes increased cognitive engagement and elicits stronger emotional responses, making IVR particularly effective in domains such as education, training and therapy. By providing a completely immersive environment, IVR effectively eliminates distractions from the physical world, allowing users to focus solely on the task or experience at hand.

This study specifically focuses on immersive virtual reality (IVR) applications that utilise high-performance head-mounted displays (HMDs), including devices like the HTC Vive, Oculus Rift, and Meta Quest. An HMD is characterised by its design, worn on the head or integrated into a helmet and features a wide viewing angle alongside advanced tracking capabilities for head and hand movements, which are essential for creating compelling, immersive experiences in VR (Menzel, 2021; Zhang, 2017).

IVR is often considered superior to non-immersive and semi-immersive VR due to its ability to create a heightened sense of presence, enhanced interactivity, and realistic

simulation. Unlike non-immersive VR, which limits users to a screen-based experience, IVR completely envelops users in a 360-degree environment, fostering an authentic sense of "being there". This sensory-rich interaction is crucial for effective learning and engagement, as demonstrated in studies involving immersive analytics and neuroscience research (Zhou et al., 2024; Peng et al., 2024).

Moreover, IVR facilitates embodied interaction, enabling users to engage more deeply with content. For example, research indicates that nursing students trained within an IVR framework reported substantial improvements in non-technical skills and self-confidence, underscoring the technology's potential for enhancing interactive learning outcomes (Chan et al., 2024).

Research supports the idea that immersive VR fosters a more interactive and realistic environment, which significantly enhances UX and information retention. For instance, Jaruševičius et al. (2024) indicate that IVR facilitates deeper cognitive and emotional engagement, improving educational outcomes. Similarly, Atanasov et al. (2023) emphasise that IVR effectively simulate real-world scenarios, enabling users to practice skills in a safe yet realistic setting. Furthermore, Vergara-Rodríguez et al. (2021) and Cao et al. (2024) reveal that immersive environments inspire active participation among learners, enhancing the overall educational experience and potentially leading to better learning outcomes. Erviana and Sepriansyah (2024) found that VR technology significantly improved primary school students' learning outcomes, with post-test scores rising from an average of 65.07 to 86.03 after VR intervention.

2.2.3 The Benefits of Wearable Virtual Reality Applications in Education

Over the past decade, the adoption of VR technologies has surged, particularly with the emergence of head-mounted display devices, such as the Meta Quest series, which have become accessible to the public (Yeo et al., 2024). A wide range of software applications for VR have been developed, from games to education. These devices are increasingly recognised as effective tools for delivering multimedia content in innovative educational settings. The rapid growth of wearables integrated with VR applications has led to substantial improvements in learning performance, enhanced engagement, and increased interest among students studying science, particularly when compared to the traditional method (Dayag & Faramarzi, 2024; di Lanzo et al., 2020; Makransky & Lilleholt, 2018; Shi et al., 2019; Sun et al., 2023). For example, a study by Martarelli et al. (2023) revealed that students using VR headsets outperformed their peers using traditional computers in understanding the water cycle. The study demonstrated that those using headsets had improved comprehension immediately after the intervention and eight weeks later.

In the field of education, wearable technology holds the potential to fundamentally transform and facilitate a new era of learning (Almusawi et al., 2021). Some areas for this transformation include active and collaborative learning (Dayag & Faramarzi, 2024; de la Guia et al., 2016). Research conducted by Akbar and Djakariah (2024) explored the potential of VR to increase student engagement through more interactive and immersive learning. The study found that VR encourages collaboration among students and facilitates shared experiences that promote teamwork and communication skills. In support of this, Young et al. (2020) assert that collaboration is the primary pragmatic heuristic to consider when integrating VR as a learning tool. Their research emphasises the importance of teamwork-based objectives in lesson design while also addressing logistical challenges, such as

ensuring that every student has access to a headset within the classroom. This arrangement fosters collaboration both inside and outside the VR environment and facilitates remote participation.

The potential of VR to enhance collaborative learning is highlighted by its capacity to increase activity efficiency through the involvement of multiple students, which is particularly beneficial in immersive settings. Interestingly, even when only one student is using the VR headset, others can still participate in the learning experience, mitigating some challenges students reported in their studies. In pairs, learners alternate using the VR headset, with the student wearing it describing what they see while their partner records notes and observations. This approach allows more students to engage with VR while capturing insights during the experience. Sharing the headset encourages the student within the VR space to be more observant and to communicate details with greater care, thereby enriching their learning experience.

Moreover, this approach encourages learners to concentrate on the current task and ask relevant questions, thereby enhancing the learning process. In addition to promoting collaboration, VR technology has been proven to enhance interactive physical activity, as demonstrated in a study conducted by McFadden and Li (2019). Also, Bae (2023) showed that a VR-based physical education program significantly improved health-related physical fitness among elementary students, leading to notable enhancements in cardiorespiratory endurance and muscular strength across genders after an eight-week intervention. Additionally, VR technology serves as a powerful learning incentive, increasing students' motivation and engagement levels (Daghriri et al., 2024; Motti, 2019; Southgate, 2020). It enables students to explore complex scientific concepts interactively, thereby enhancing

their understanding and retention of material (Barrett et al., 2018; di Lanzo et al., 2020; Rajassekharan & Vivekanandam, 2024; Southgate, 2020) Studies have shown that IVR and Immersive-sensory Environments (IME) can effectively reduce anxiety levels and create a tranquil atmosphere by incorporating visual, auditory, and olfactory stimuli Baktash & Shirazi, (2024).

These IVR environments provide risk-free learning opportunities by simulating practical scenarios across various fields, including construction environments (Checa & Bustillo, 2020). Furthermore, IVR has been shown to enhance cognitive outcomes and improve knowledge retention, particularly in educational settings that gave increasingly relied on online learning following the COVID-19 pandemic (Ak, 2024). During the ongoing pandemic, which has significantly impacted education worldwide, VR technology plays a crucial role in supporting teaching and learning activities. By utilising VR, educational institutions can adapt to unforeseen crises and effectively navigate challenges, ensuring a smooth continuation of the educational process even in the face of disruption.

The educational benefits of IVR are extensive and multifaceted. As noted by Guttentag (2010), this technology has the potential to increase student engagement (Alfalah et al., 2017; Vazquez et al., 2018; Young et al., 2020), foster student motivation (Arlati et al., 2019; Bhargava et al., 2018; Tarng et al., 2019), and enhance the overall learning experience (Ali et al., 2017; Chang et al., 2019; Chen et al., 2019; Goedicke et al., 2018; Molka-Danielsen et al., 2018; Rajeswaran et al., 2018). VR offers captivating educational resources in subjects like science and mathematics (Schofield, 2012) that help students develop essential skills, including scientific method skills, critical thinking skills and problem-solving abilities (Cao et al., 2024). This aligns with the goals set forth by the

Malaysian Ministry of Education, emphasising the need for creativity and knowledge application in students' learning (Soid & Umar, 2007).

Previously, the high cost of HMDs was one of the significant obstacles to implementing IVR in educational environments. However, the current availability of low-cost HMDs, particularly in schools that embrace the BYOD (bring your own device) model, has effectively addressed this issue (Olmos et al., 2018). Similarly, wearables have become commonplace, as they are not limited to specific demographics. Research indicates that wearables can yield positive outcomes across various age groups, including those with autism spectrum disorders, intellectual disabilities, and learning disabilities (Daniels et al., 2018).

Learning in a wearable VE enhances engagement, motivation, and retention, positioning it as the fundamental learning tool of the 21st century (Bobko et al., 2024; Thornhill-Miller et al., 2023). Educators and researchers are increasingly interested in these technologies for their ability to seamlessly integrate visualisation and interaction (Radianti et al., 2020). Furthermore, studies have shown that students learn faster in a 3D virtual environment (Alqahtani et al., 2017; Christopoulus et al., 2020; Dalgarno et al., 2002; Scavarelli et al., 2021; Wolfartsberger, 2019) and develop strong mental representations through hands-on and collaborative activities (Concannon et al.,2019; Segura et al., 2020). However, the role of a teacher as a facilitator, rather than a traditional instructor, in using this environment could not be denied as their role is crucial in ensuring the success of learning outcomes and project success.

Several studies have indicated that the use of VR enhances learning effectiveness (Ahmed et al., 2023; AlGerafi et al., 2023; Hsu et al., 2022; Ibrahim & El Shakhs, 2023; Li

et al., 2022; Makransky et al., 2019; Neuwirth et al., 2021; Nuguri et al., 2021; Parmar et al., 2023; Yu & Xu, 2022) and fosters learning engagement (Bernardo & Duarte, 2023; Byukusenge et al., 2023; Cecotti, 2023; Kadri et al., 2024; Junge et al., 2023), leading to a positive attitude towards learning and enhancing overall educational experiences (Byukusenge et al., 2023; Di Natale et al., 2020; Dirin & Laine, 2023; Parong & Mayer, 2018; Parmar et al., 2023). Over the past decade, VR technology has grown significantly, with more affordable devices making it increasingly accessible in education (Pinto et al., 2021; Vergara et al., 2020; Yawson & Yamoah, 2020).

In recent years, there has been a growing interest in using software, particularly educational video games and serious games, as educational tools. Nebel et al. (2016) emphasised the potential of commercial video games for educational purposes and highlighted the educational qualities of Minecraft. They noted that Minecraft promotes creation, collaboration, and distribution, making it a valuable tool for various educational topics. Platforms like Minecraft: Education Edition and Labster are increasingly used for learning in formal educational settings. Minecraft's collaborative features allow students to work together on projects, fostering teamwork and problem-solving skills, which are essential in modern education. Additionally, Nebel et al. (2016) suggested that virtual reality (VR) has the potential to be a disruptive tool for training and education, with global and widespread success when backed by pedagogical innovations.

Young et al. (2020) demonstrated the successful use of immersive technologies in facilitating geography students' experiences of real-world environments that are otherwise difficult, expensive, or unsafe to visit. Their study highlighted the value of VR in exploring geomorphology and allowing students to visualise and interact with complex geographical

formations. Similarly, Markowitz et al. (2018) used HMDs to immerse students in an underwater environment, enhancing their understanding of climate change through direct experience.

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The practical benefits of VR and wearables in education are significant, as they allow students to experience environments and situations that traditional teaching methods cannot effectively replicate, such as lectures, slideshows, or 2D videos. A recent meta-analysis by Havard and Podsiad (2020) suggests that integrating wearable technology in educational contexts is rapidly evolving. Their findings indicate that wearables are becoming more affordable and purposeful, reflecting a broader shift toward mobile and digitally sophisticated learning experiences. Furthermore, focused investigations into wearables in areas such as child-computer interaction (CCI) (Sharma & Giannakos, 2021) and the Internet of Things (IoT) (Al-Emran et al., 2020) reinforce the growing popularity of these technologies. These studies provide clear and coherent guidelines for advancing CCI and IoT applications, further strengthening the case for the increasing popularity of wearables and offering clear and coherent guidelines to advance CCI and IoT for learning and education.

2.3 Usability Evaluation

The concept of usability evaluation involves examining how users interact with a system and emphasises the importance of the context in which these interactions take place. It encompasses multiple perspectives, including user-oriented, performance-oriented, and context-oriented views. These perspectives emphasise the importance of user interaction and the environment in which tasks are performed (Inostroza et al., 2016).

ISO 9241-11 (1998) defines usability as the extent to which specific users can effectively, efficiently, and satisfactorily used a product to achieve goals within a designated context. Usability is a measure of user interface ease of use (Baghini et al., 2024; Nielsen, 1994; Rusu et al., 2018) and is characterised by attributes such as learnability, efficiency, memorability, error frequency, and user satisfaction. The effectiveness of these usability features can differ significantly based on the specific context and the unique needs of the users (Ferreira et al., 2020).

Evaluating a system becomes a crucial step in the design of interfaces and interactive tools before it is delivered to the end users (Paz et al., 2023). For example, evaluating VR applications before their release is crucial to mitigate potential increases in maintenance and training costs (Stefan et al., 2023). Research by Rzig et al. (2023) shows that many VR applications lack adequate testing, with 79% of evaluated projects having no automated tests. This gap can lead to increased maintenance costs due to unforeseen issues that arise after the release. Additionally, an analysis of user reviews has pointed out important quality attributes specific to VR, indicating that neglecting these aspects during evaluation can lead to user dissatisfaction and increased support costs (Li et al., 2023).

Evaluating usability is critical for improving user satisfaction and ensuring product success. Usability evaluation involves systematically assessing a product's user interface and overall UX to determine how well users can achieve their goals in a particular environment. For example, Yoon (2023) proposes a quantitative evaluation method that integrates metrics from the ISO SQuaRE framework, enhancing traditional qualitative observations in usability testing. Moreover, a study of a company website in Indonesia utilised User Acceptance Testing (UAT) to assess user interactions, helping to identify areas for improvement in systems and interactions (Firdaus et al., 2022). Such evaluations enhance user satisfaction and contribute to the product's overall success in the market.

Nielsen and Molich (1990) described usability inspection as a general term for methods in which evaluators examine usability-related aspects of a user interface. Similarly, Nik Ahmad et al. (2021) define usability as addressing user concerns, which can minimise training efforts and improve product quality and satisfaction. This emphasis on addressing user concerns improves usability and underscores the audience's significance in product development. Improving usability can also enhance application accuracy and reduce response times for various user tasks, as noted by Parsazadeh et al. (2018). Key concepts in usability include user, goal, effectiveness, efficiency, satisfaction, and context of use (Bevan et al., 2015). Identifying usability issues is vital to ensure products are user-friendly before they reach the end users. One effective way to ensure the usability of an application is through HE.

Stanney et al. (2003) further classified the usability of VE into two categories: the VE system interface, which encompasses software, hardware, and overall man-machine interaction design, and the VE user interface, which includes physiological, psychological,

and psychosocial aspects. This classification is based on a review and synthesis of findings from Gabbard et al. (1997), along with insights from numerous other studies (i.e., Bowman, 1999; Bowman et al., 2000; Chen & Stanney, 1999; Gabbard et al., 1997; Kaur et al., 1999). These concepts were then combined to develop the Multi-criteria Assessment of Usability for Virtual Environments (MAUVE), an automated approach to assist designers and evaluators in enhancing the usability of VE systems (Stanney et al., 2003). **Figure 2.1** illustrates MAUVE's usability evaluation criteria.

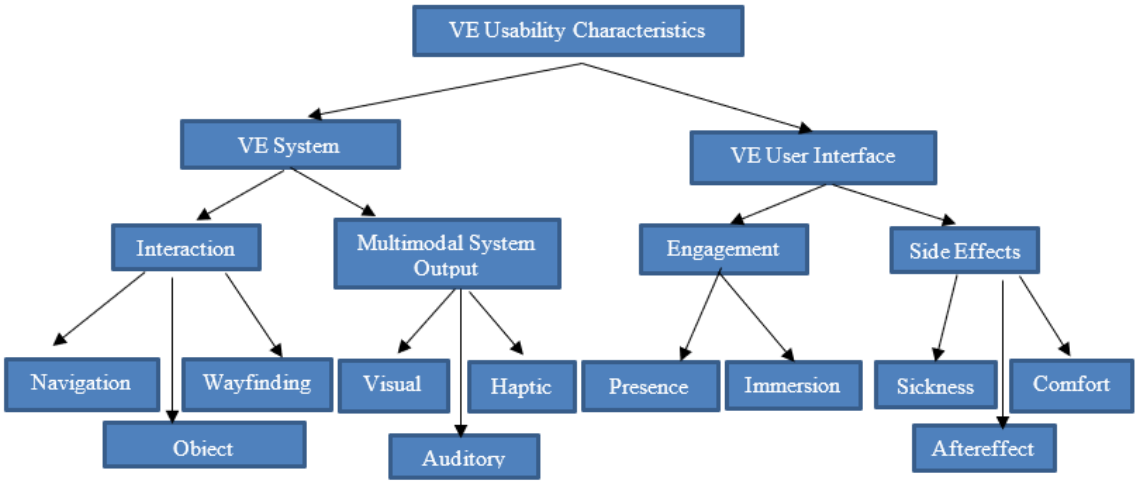


Figure 2.1 Usability Criteria assessed by MAUVE (Adopted from Stanney et al., 2003)

It covers a wide range of multidimensional interaction and multimodal output requirements. According to Stanney et al. (2003), MAUVE's standards can assist VE system designers and evaluators in addressing issues such as motion sickness, discomfort caused by heavy or obtrusive equipment, and a lack of engagement. The researcher discovered that the taxonomy developed by Stanney et al. (2003) bears similarities to that of Gabbard et al. (1997); however, they employ different terminologies. Gabbard et al. (1997) categorise challenges in interactive system development into two main areas: behavioural factors –

encompassing user perception and engagement with the application and constructional factors, which reflect the perspectives of software developers and system design.

2.3.1 Heuristic Evaluation (HE): Key Benefits and Practical Applications

Heuristic Evaluation is a cost-effective method for assessing usability. However, its effectiveness depends on its ability to address the unique needs of a specific domain, in addition to the expertise of the evaluator involved. For example, Bowman et al. (2002) noted that designing 3D User Interfaces (UIs) poses a significant challenge in balancing immersive experiences with intuitive interactions. This complexity can result in either overly simplistic designs or significant usability issues. As highlighted by Reski et al. (2024), incorporating 3D gestural inputs can enhance user interaction but also complicate the design process. A systematic review indicates that while 3D interfaces can improve data visualisation, users often find them intimidating. The perceived ease of use is critical for user acceptance, suggesting that poorly designed interfaces may deter potential users (Veriscimo et al., 2020).

The design of 3D selection and manipulation techniques is crucial; if not implemented properly, it can lead to significant usability problems, including motion sickness and performance degradation (Riecke et al., 2018). Therefore, effective hand interaction with virtual content requires careful consideration of user intent and gesture recognition. Utilising domain-specific usability heuristics is vital for addressing these issues in the evaluation process (Figueroa et al., 2019; Othman et al., 2018; Young et al., 2020). Such heuristics can identify relevant usability issues that require immediate attention to ensure an optimal UX. Although specific heuristics may be more complex to understand and apply, they have the potential to uncover specific usability issues related to the application's domain (Inostroza et al., 2016).

HE is a straightforward and cost-effective method for assessing the usability of applications, as noted by Reis et al. (2022), Fuller et al. (2022), and Quiñones and Rusu (2017). This method is particularly advantageous in situations where users are not constantly available for ongoing testing (Oliveira et al. (2017). HE can generate results quickly, often in a fraction of the time required for traditional empirical testing, which is essential in today's fast-paced development environments (Privitera, 2019). Unlike other usability engineering methods, HE employs limited design principles or heuristics, granting usability experts greater control in the software design process (Tang et al., 2006). Furthermore, heuristics are recognised as key attributes of software products (Lodhi, 2010) and are considered effective parameters for assessing usability (Hermawati & Lawson, 2016; Lodhi, 2010; Nik Ahmad et al., 2021).

The use of HE is crucial for validating and inspecting interfaces, especially in the field of VR. It has been effectively used to assess user interfaces, ensuring they meet user needs and enhance overall satisfaction (Jonathan et al., 2022). Adhering to user interface guidelines is essential for usability, as disregarding these guidelines can lead to challenging and complicated user interactions (Rossmy et al., 2022; Solano et al., 2016). In the context of electronic health records, the absence of standardised UI guidelines has led to a fragmented system that negatively impacts efficiency and safety. Therefore, following established guidelines is imperative (Shneiderman, 2011).

HE is adaptable and applicable in various contexts, including video games, where it serves as both an evaluation tool and a design guideline (Ozdowska et al., 2023). These "heuristics" guidelines, resemble rules of thumb rather than rigid usability guidelines (Nielsen, 1994). Typically conducted by usability experts, the informal nature of HE allows

for the implementation of various stages throughout the development cycle (Nielsen, 1992). Research supports the reliability of HE, indicating that it produces consistent results, whether conducted by seasoned experts or novices, thereby underscoring its accessibility and effectiveness in usability evaluations (Pas et al., 2023).

Researchers often utilise predefined heuristics to identify usability requirements specific to their study areas (Lazar et al., 2010; Preece et al., 2015). In educational contexts, for instance, HE acts as a quality assurance mechanism, safeguarding students from flawed processes that could hinder their learning experiences (Botha et al., 2020). Effective user interface design is particularly crucial in VR educational settings; inadequate design can obstruct interaction and diminish learning (Xie, 2023). Consequently, Xie (2023) emphasises the importance of refining user interface guidelines in future research to enhance usability and improve learning efficacy within VR environments.

Numerous studies from the desktop era have established fundamental stages for conducting HE, which remains relevant as the heuristics employed during reviews can be tailored to contemporary needs. For example, Al Isfahani et al. (2023) demonstrated that integrating HE into the Siliwangi University's VClass Application (UNSIL) resulted in significant improvements across three major usability dimensions: effectiveness, efficiency, and satisfaction, including an 86% reduction in time to complete tasks and a 90% decrease in error rates. This highlights the practical benefits of employing HE.

Notably, HE can identify over 75% of usability issues with as few as three to five evaluators, emphasising its efficiency (Abulfaraj & Steele, 2020; Lecaros et al., 2023; Nielsen, 1992). Overall, the number of evaluators significantly impacts the discovery of usability issues, particularly when evaluators possess diverse skill sets (Wong, 2022).

Evaluators' experience substantially influences the effectiveness of HE; more experienced evaluators tend to yield more insightful results, as novice evaluators may overlook critical usability problems (Abulfaraj & Steele, 2020). One study noted that the correlation between usability issues identified by evaluators and those encountered by actual users was moderate (0.5), indicating potential gaps in the evaluators' ability to recognise significant issues faced by users (Khajouei et al., 2018).

During HE review, evaluators systematically compare user task steps against predetermined heuristics (Nielsen & Molich, 1990; Oliveira et al., 2017). This process involves analysing user interactions associated with each task, documenting potential heuristic violations, and providing insights to the product team. This straightforward approach effectively directs a product team's focus towards areas that may require improvement, leading to an enhanced user interface. The immersive nature of VR, for example, necessitates interfaces that are intuitive and responsive to user inputs, particularly in complex applications related to anatomy and chemistry (Dikkatwar et al., 2024). Ultimately, improved user interfaces correlate with increased user satisfaction, which is a key indicator of enhanced UX (Nik Ahmad et al., 2021).

One notable advantage of HE is that it facilitates the early identification of usability issues. Even if certain issues remain unnoticed initially, they can be addressed during subsequent formative evaluations with users' early detection of usability issues; even if they are not identified at this stage, they can be discovered during a formative evaluation with users (Ramadhanti, 2023). By integrating user feedback during formative evaluations, HE can effectively tackle usability concerns that may not be immediately apparent (Folmer & Bosch, 2008).

This method is flexible enough to yield reliable results from both novice and expert evaluators, making it accessible for diverse teams (Paz et al., 2023). Heuristic Evaluation has been utilised in a wide array of applications, including smartphones, web-based platforms, VR applications, and specialised sectors such as entertainment, healthcare, and education. Nielsen's 10 heuristics (Nielsen, 1994a) are the most referenced set, providing categories of usability principles with brief descriptions to guide evaluators in assessing design. The versatility of Nielsen's 10 heuristics has made them a cornerstone in usability evaluations. Nonetheless, their effectiveness can be significantly enhanced when tailored to specific domains, as each field presents unique challenges. For example, a healthcare app might require specific heuristics related to data privacy and security, while a gaming app might prioritise factors like immersion and enjoyment.

Additionally, user expectations vary across domains. A financial app user might prioritise security and clarity, while a social app user might value features like personalisation and community engagement. Technological constraints also play a crucial role, as the available technology and platforms can influence usability considerations. For instance, heuristics for mobile apps might need to consider factors like screen size and touch input.

While creating entirely new heuristics for specific contexts is often necessary, adapting existing ones is frequently more efficient. This can be done by redefining established heuristics to fit applications better. For example, "visibility of system status" might be redefined as "real-time feedback on patient status" within a healthcare app. Additionally, criteria may be integrated into heuristics to address domain-specific concerns. For instance, a "match between the system and the real world" might include factors like

cultural sensitivity for a global app. By carefully adapting general heuristics to meet the distinct needs of various domains, designers and evaluators can ensure that their products adequately meet the unique needs and expectations of their target users.

The justification for employing heuristics in this study is grounded in their established ability to identify a wide range of usability issues in the products (Joyce et al., 2015; Nielsen, 1994b; Quiñones & Rusu, 2019; Rusu et al., 2011; Tang et al., 2006). HE is a popular and cost-effective method due to its effectiveness (Mujuru & Lopez, 2021; Thompson, 2020) and minimal planning requirements (Nielsen, 1994c; Murtza et al., 2017; Quiñones & Rusu, 2017; Schaffer, 2022). However, the effectiveness of HE is highly dependent on the quality and domain-specificity of the heuristics employed (Stadler et al., 2023; Wang et al., 2019). General-purpose heuristics may not adequately capture the unique characteristics of specific domains, such as WVREA, emphasising the need for more tailored heuristic formulations. The use of general heuristics can sometimes lead to misclassification of usability issues, as they may not adequately address the specific needs of contexts. This oversight can fail to identify critical usability problems unique to those environments (Nizamani et al., 2022). For example, several heuristic sets have been developed to evaluate VR applications in general (Rusu et al., 2011; Sutcliffe & Gault, 2004) and specifically for VR-based education (Stanney et al., 2003; Young et al., 2020).

However, these heuristics often overlook the specific needs and functionalities relevant to WVREA. Young et al. (2020) focused solely on designing student-centred lesson plans for wearables, failing to evaluate existing applications. Similarly, Stanney et al. (2003) conducted a Multi-criteria Assessment of Usability for Virtual Environments (MAUVE),

which may not sufficiently address the complexity of educational interactions within a wearable VR context.

Usability considerations in evaluating VR applications extend beyond traditional elements such as learnability and efficiency, encompassing unique characteristics of VR that influence UX, including immersion, presence, and embodiment (Southgate, 2020). Consequently, when developing specific VR applications for educational purposes, it is vital to incorporate additional criteria that align pedagogical approaches. The application of domain-specific heuristics is crucial, as it facilitates a deeper understanding of usability issues, enabling experts to address significant problems that generic heuristics might miss (Nizamani et al., 2022).

In this study, three evaluations were conducted using established methodologies outlined by Quiñones and Rusu (2019) to validate the newly developed heuristics. This empirical approach has proven effective across a variety of domains, including websites, social networks, education, healthcare, entertainment, and gaming (Delgado et al., 2020; Morales et al., 2020; Quiñones & Rusu, 2019; Saavedra et al., 2019). The evaluations involved participation from experts in both academia and industry, thus providing insights into the effectiveness and practical applicability of the WVREA heuristics in enhancing learning experiences through VR technology. The research used three VR science applications based on significant interest revealed in previous studies and being a major area of educational IVR research (Matovu et al., 2023). Moreover, science subjects typically involve active interaction, which is beneficial for exploring lesson content. **Figure 2.2** shows the classification of usability evaluation methods for VEs.

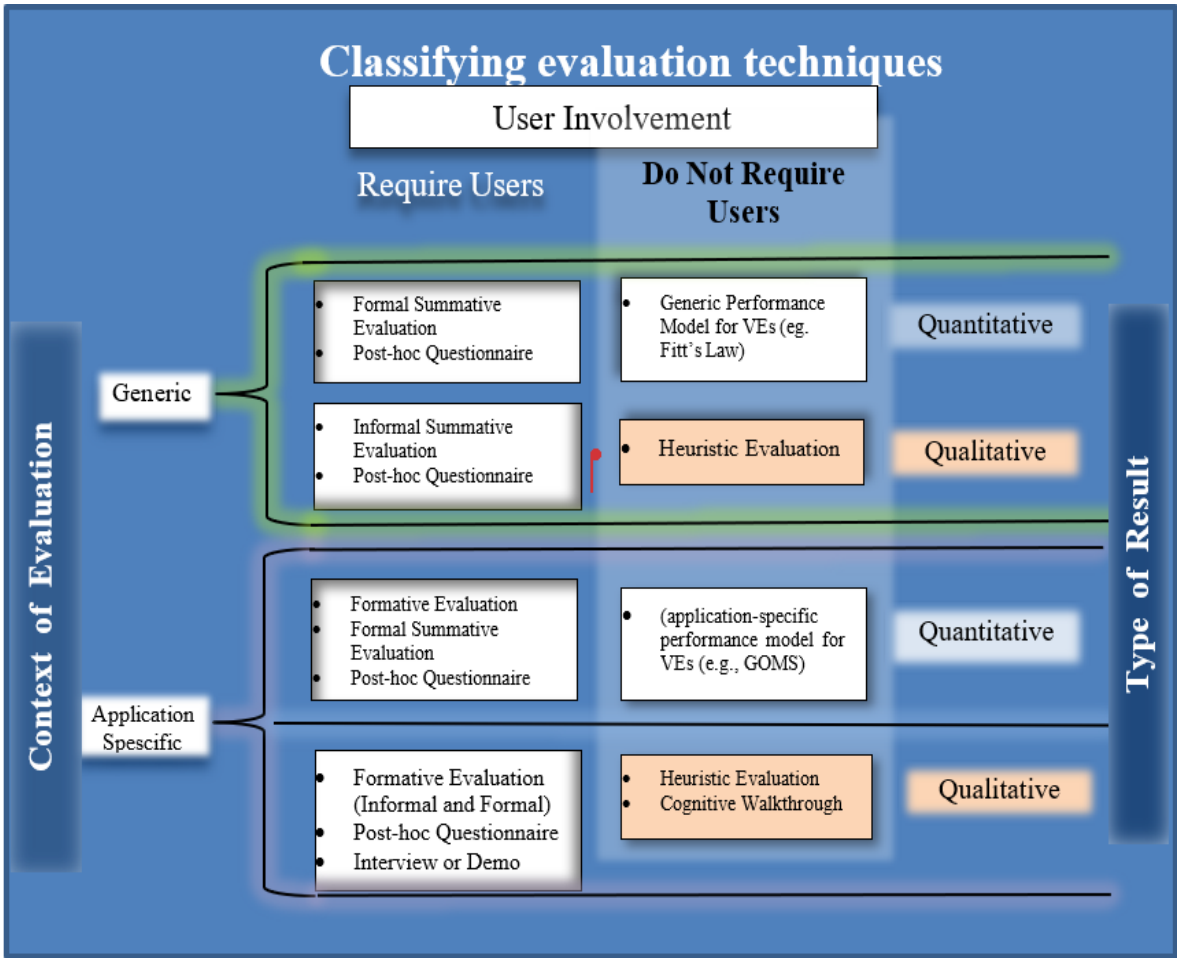


Figure 2.2 A Classification of Usability Evaluation Methods for VEs (Adapted from Bowman et al., 2002)

Based on this framework, there are three characteristics: the involvement of representative users, the context of evaluation, and the types of results produced. The first characteristic distinguishes methods requiring user participation from those that do not. While some methods gather insights directly from users, allowing them to share their design and usage experience, others rely solely on the expertise of usability professionals. The second characteristic pertains to the context in which the evaluation occurs, highlighting whether it takes place in a generic setting or an application-specific evaluation. Evaluation conducted in a generic context tends to yield results that are more broadly applicable to various types of interfaces.

In contrast, application-specific evaluations tend to produce insights best suited for similar applications, limiting the generalisability of their findings. The third characteristic focuses on the nature of the results generated, particularly whether they are primarily qualitative or quantitative. However, these three characteristics are not mutually exclusive; a single evaluation method can produce both qualitative and quantitative data, offering flexibility in the insights provided (Bowman et al., 2002). In this study, the evaluation context is application-specific and does not involve real users, such as school children. Instead, both quantitative and qualitative approaches are applied. Consequently, this study utilised HE with the participation of experts from academia and industry. Additionally, schoolteachers were involved in gaining insight from their expertise in teaching science subjects.

2.4 Theoretical Framework

2.4.1 Norman’s (2013) Theory of Action

The development of new heuristics is based on Norman's Theory of Action, which aims to minimise human errors and accidents in everyday life (Norman, 2013). This aligns with the researcher's goal of creating innovative heuristics. Norman believes that the design or installation of equipment significantly contributes to problems consumer’s encounter. He argues that design teams and installers often need to pay more attention to users' needs, leading to ambiguity and inaccuracies in the technology’s usability. Norman’s Theory of Action, illustrated in Figure 2.2, encompasses "The World", which refers to the physical system relevant to the researcher’s study. The researcher has abstracted this concept into VEs composed of 3D models.

Additionally, the theory includes the user's goals, which have been translated into User Tasks within these VEs. The “gulf of execution" is bridged when users successfully achieve their goals, occurring when their interactions, such as input mechanisms and commands in the VEs, match their thoughts, goals, and intentions (Gabbard et al., 1997). Conversely, the “gulf of evaluation” happens when the output presented exceeds the user’s expectations and understanding. Thus, in this study, the researcher mapped the components of Norman’s (2013) Theory of Action onto VEs, as shown in **Figure 2.3**.

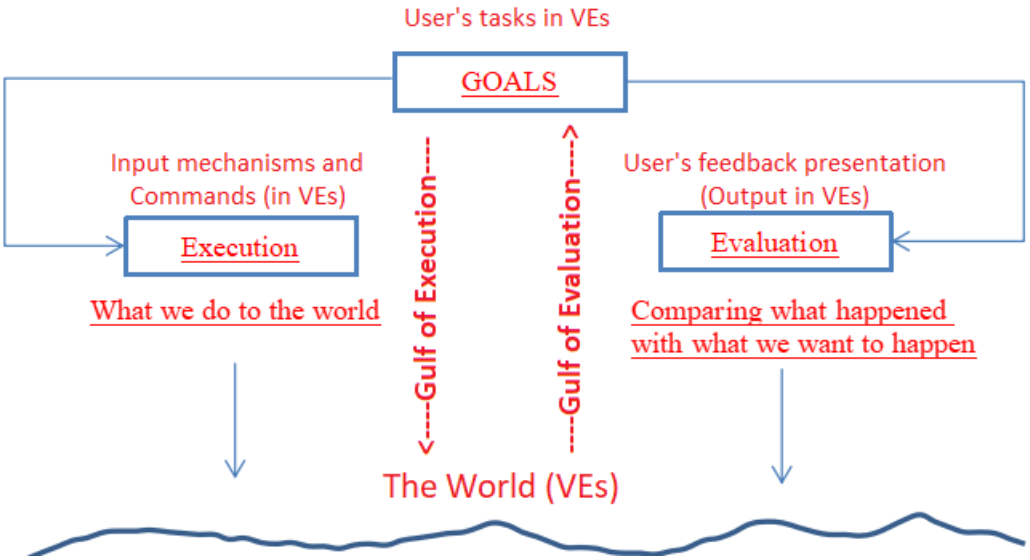


Figure 2.3 Norman’s (2013) Theory of Action (Adopted from Gabbard et al., 1997)

Additionally, the new heuristics designed in this study will ensure that the wearable VR application used in education is accessible and usable for its intended users, ultimately avoiding the misunderstandings or inaccuracies highlighted in Norman’s Theory of Action.

In summary, Norman’s Theory of Action is foundational to this study, as it incorporates all essential components reflected in the newly developed heuristics, including 3D models, input mechanisms and commands, user tasks in VEs, and the presentation of user feedback.

2.4.2 Constructivism Learning Theory and Virtual Reality

Theories of learning play a crucial role in shaping educational practices and significantly impact how knowledge is shared and acquired. As educators strive to accommodate diverse learning styles, it is important to recognise that not all students learn in the same way. Each learner has unique preferences and strengths, which necessitates a variety of instructional strategies to effectively support their individual needs. Constructivist learning theories, which highlight the active role of learners in constructing knowledge through their interactions with the environment, are particularly relevant in this context.

To fully grasp constructivism's implications for education, it is essential to consider the theoretical contributions of influential figures such as Jean Piaget and Lev Vygotsky. Piaget (1976) argued that knowledge develops through various interactions with the world. Learners must engage with subjects in multiple ways—displacing, connecting, combining, participating in, and resembling the objects of study. According to Piaget, true understanding emerges through an active discovery process (Piaget, 1964).

Recent applications of constructivism emphasise the importance of active learning, particularly in how infants learn about their environment through actions such as hitting, pushing, or assembling objects, as discussed by Mueller and Hutchinson (2018). In STEM education, Waldrop (2015) emphasises the significance of active learning in reducing the attrition of young learners in these disciplines. Supporting this notion, Adi Badiozaman et al. (2022) indicated that students not only perceive active learning as effective but also find it intrinsically enjoyable. This enjoyment can be a powerful motivator for educators to implement active learning strategies.

VR technology emerges as a powerful platform facilitating active engagement and enabling students to integrate newly acquired information with their existing knowledge structures, fostering an individualised and enriching discovery experience (Kim et al., 2020). Applications of constructivism in VEs emphasise the need for developers to provide interactive 3D models that effectively support learning (Sutcliffe & Gault, 2004). Particularly, the tenth heuristic proposed by Sutcliffe and Gault stresses the importance of cueing and explaining active objects in VEs to facilitate learning. However, this heuristic seems to contradict Piaget's (1976) assertion that action-based constructivism is vital for fostering creativity and understanding. Moreover, research by Lee and Robling (2010) reinforces the idea that active learning principles significantly enhance user interaction with educational materials. Their findings indicate that such engagement leads to increased mental involvement and improved learning outcomes.

In contrast, Vygotsky (1986) emphasised the significance of social interactions and collaboration in the learning process, positing that educational activities become more impactful when they involve social contexts, leading to the co-construction of knowledge among peers. Constructivist principles are widely applied in inquiry-based science education, where students are encouraged to engage in hands-on laboratory experiences to observe and interpret scientific phenomena (Stoeckel, 2020). Furthermore, pedagogical models such as Problem-Based Learning and Inquiry-Based learning align seamlessly with current educational curricula, reinforcing the importance of constructivism in teaching (Nurulhuda et al., 2023). Constructivism highlights student-centred learning, encouraging active engagement and the development of critical thinking and problem-solving skills (Nurulhuda et al., 2023). Additionally, Stoeckel (2020) also noted that online adaptations of

these methods, including remote and virtual labs, can effectively enhance learning outcomes when designed with intention.

2.4.3 VR Characteristics Support Constructivist Learning Principles.

The advent of technology, especially VR, has created new opportunities for improving constructivist learning environments. VR's unique features align seamlessly with constructivist learning principles (Bani-Salameh et al., 2017; Huang et al., 2010; Katz & Halpern, 2015; Song et al., 2023). It offers interactive experiences that enable students to explore complex concepts hands-on, thereby promoting deeper understanding (Grubaugh et al., 2023; Marougkas et al., 2023). Integrating technology into constructivist settings significantly boosts student engagement and facilitates knowledge construction through interactive tools (Makewa, 2019).

Research shows that VR environments can significantly improve scientific thinking among students. For example, a study found that grade 11 students demonstrated enhanced scores after engaging in a constructivist virtual learning environment focused on solar energy (Lamsombat & Kanjug, 2021). VR encourages exploratory activities and fosters collaborative communication, both key elements of constructivist theory (Wang et al., 2024). By facilitating active exploration and rehearsal of concepts, VR enriches educational experiences (Makewa, 2019).

The effectiveness of VR in education depends not only on the technology itself but also on the pedagogical innovation embedded within VR applications (Southgate, 2020). For example, a case study by Seo et al. (2021) illustrates how constructivist methods applied in VR can support active, experiential learning, particularly in subjects like anatomy. In "Muscle Action VR", participants learned about human muscles by physically moving

within an immersive environment, gaining insights through interactive, dynamic anatomical content.

When developing educational VR applications, it is crucial to reference constructivist learning theories, which emphasise that effective knowledge acquisition involves action, reflection, and construction. VR serves as an ideal medium because it supports these experiential learning processes due to its ability to provide real-time visual, auditory and haptic feedback (Dalgarno & Lee, 2010; Seo et al., 2021; Song et al., 2023). Users can interact with 3D models, navigate through virtual objects, and solve problems in a simulated environment. This interaction enhances student engagement, promotes active constructivist learning, provides authentic learning experiences, allows for empathetic experiences, encourages creativity, and helps students visualise abstract concepts (Hu Au & Lee, 2017).

These characteristics of VR support the constructivist learning principles of Piaget (1976), who stated that learners gain knowledge through active exploration and experimentation. According to Piaget, individuals are constantly engaging with and modifying their environments. For example, infants learn about the world through actions like hitting, pushing, or assembling objects, which may not only lead to knowledge about their surroundings but also lay the groundwork for developing reasoning and cognitive skills.

In today's digital age, where students often struggle to see the relevance of their learning to everyday life, VR can effectively address educational challenges (Hu Au & Lee, 2017). By serving as an immersive, hands-on learning tool supported by a thoughtful pedagogical approach, VR can combat issues such as students' passivity and disengagement. Furthermore, it helps foster essential 21st-century skills, including empathy, systems thinking, creativity, computational literacy, and abstract reasoning. Constructivist learning

is not a passive acceptance of knowledge but involves the learners engaging with the world. The principles of constructivism align perfectly with the characteristics of VR, enabling users to actively interact, manipulate, and navigate their environment for enhanced learning experiences.

2.4.4 **Related Studies Implementing Norman's (2013) Theory of Action**

Norman's (2013) Theory of Action emphasises the importance of understanding user interactions and motivations in technology and design. Various studies have incorporated Norman's concepts into their research, demonstrating the theory's relevance across different contexts. For example, Gabbard et al. (1997) utilised Norman's framework in their research on the taxonomy of usability characteristics in VEs, establishing a foundation for future investigations into new usability evaluation methodologies specific to VE research. Similarly, Borges and Baranauskas (1998) applied Norman's Theory of Action to create an intelligent computer-based learning environment for industrial applications. They emphasised that user interaction with a computer system in task execution aligns with Norman's theory, which outlines a cycle of activities involving action execution and outcome evaluation. Kaur et al. (1999) expanded on this by utilising Norman's theory to develop recommendations for interface design in VE to mitigate common usability issues. Their research refined Norman's general action model by introducing additional stages to characterise user interaction within VEs.

In a different context, Andre et al. (2001) adapted and extended Norman's (1986) action model to establish an effective concept addressing human-machine interaction. They proposed a User Action Framework based on Norman's cycle of interaction, which significantly improved system reliability. They further emphasised that Norman's action

model is versatile and can be applied to various systems, including websites and VEs, as well as everyday devices like elevators, ATMs, bus stop signs and refrigerators.

Cuomo (1994) also leveraged Norman's (1986) user activity model to analyse verbal protocol data, history logs, and videotapes collected using a model-based method for assessing the usability of graphical, direct-manipulation interfaces. In a related study, Rizzo et al. (1997) implemented Norman's model to address design challenges in developing a web service for individuals with disabilities. They encountered issues stemming from the geographically distributed teams involved in the project and the complexities of high-level interaction during the evaluation process. Utilising a cognitive walkthrough based on the revised Norman model facilitated the resolution of two critical design obstacles, ultimately enhancing the development and implementation of their technology.

2.4.5 Related Works on Heuristic Development in Virtual Reality Applications

In 1990, Nielsen and Molich developed a practical set of heuristics for interface evaluation due to its practicality in real-world scenarios. They argue that studying HE methods could significantly improve usability in industrial contexts, prompting their series of experiments on this evaluation technique. Existing usability guidelines tend to be extensive and complex, often causing developers to rely on their intuition rather than formal heuristics, which can be overwhelming. To address this issue, Nielsen and Molich proposed a simplified set of nine basic usability principles, as shown in **Table 2.1**, derived from their extensive experience in usability engineering. These principles effectively address the most common interface issues.

Their experiments involved evaluators analysing user interface designs and reporting usability problems, which were then scored against a predefined list of known issues. Nielsen

and Molich (1990) identified specific usability problems across different systems, such as unclear error messages and navigation issues. Their findings revealed that the percentages of evaluators recognising these problems varied significantly. They emphasise the importance of validating these usability problems through empirical testing, although they acknowledge the limitations of their approach in capturing all potential issues. They argued that usability problems are context-dependent and may not affect every user, necessitating careful consideration of which issues to prioritise during redesigns. Their findings indicated that only half of the usability problems were identified by evaluators, suggesting that HE be supplemented with other methods for more comprehensive results.

Table 2.1 Nielsen and Molich's (1990) Nine usability heuristics

No.	Heuristic
1.	Simple and natural dialogue
2.	Speak the user's language
3.	Minimise user memory load
4.	Be consistent
5.	Provide feedback
6.	Provide clearly marked exits
7.	Provide shortcuts
8.	Good error messages
9.	Prevent errors

In 1994, Nielsen refined the heuristics for web applications based on factor analysis of 249 usability problems to derive a set of heuristics with maximum explanatory power, resulting in 10 revised sets of heuristics, as shown in **Table 2.2** (Joyce & Lilley, 2014; Nielsen, 1994a). New guidelines, such as "Help and documentation," were identified as critical for ensuring users can easily find assistance when needed.

Table 2.2 Nielsen's 10 Usability Heuristics (1994a)

No.	Heuristic
1.	Visibility of the system status
2.	Match between system and the real world
3.	User control and freedom
4.	Consistency and Standards
5.	Error Prevention
6.	Recognition rather than recall
7.	Flexibility and Efficiency of use
8.	Aesthetic and minimalist design
9.	Help users recognise, diagnose, and recover from errors
10.	Help and documentation

These ten heuristics have since been widely adopted by major companies, including Adobe, Apple, and Google, as vital principles in their user interface design processes (Wong, 2022).

In 2004, Sutcliffe and Gault introduced a heuristic for assessing VR, which comprised 12 heuristics addressing usability and presence issues within VEs. This heuristic serves as a valuable tool for evaluating the usability of VE applications in an efficient and meaningful manner. It significantly enhances expert human-computer interaction (HCI) evaluation methods by addressing unique challenges posed by VE, particularly the integration of presence and usability. In contrast, Sutcliffe and Gault's heuristics align with those of Stanney et al. (2003). Sutcliffe and Gault's heuristics are built upon Nielsen's 1994 usability heuristics, expanding them to encompass VR-specific concepts. Their study emphasised evaluating the quality of UX in terms of presence, focusing on how real or natural users found their engagement with the VE. The heuristics emphasised intuitive

interaction and immersion, critical components of effective virtual experiences, as detailed in **Table 2.3**.

Table 2.3 Sutcliffe and Gault's 12 VR heuristics (2004)

No.	Heuristic
1.	Natural engagement
2.	Compatibility with the user's task and domain
3.	Natural expression of action
4.	Close coordination of action and representation
5.	Realistic feedback
6.	Faithful viewpoints
7.	Navigation and orientation support
8.	Clear entry and exit points
9.	Consistent departures
10.	Support for learning
11.	Clear turn-taking
12.	Sense of presence

Their study concluded that heuristics 1 through 7 and 12 should be considered a core set applicable to VEs. Building upon these findings, Hvannberg et al. (2012) introduced the concept of "heuristic patchwork" based on their research into the VR Heuristic proposed by Sutcliffe and Gault (2004) and the extensive reference to these heuristics in existing literature. They evaluated a crisis management training simulator utilising Sutcliffe and Gault's VR heuristics, analysing how the evaluation outcome fitted the heuristic patchwork. Preliminary analysis revealed that while most of the problems fit well into Sutcliffe and Gault's heuristic, some training-related problems did not fit neatly into their framework. It was noted that ten out of twelve heuristics were relevant to the issues encountered. Hvannberg et al. (2012) proposed that the variation in the heuristic patchwork could arise

from different industry sectors, application domains, social organisations, and interaction technology platforms, as well as factors related to the system's genre. Consequently, their heuristic consists of VE, Collaborative Platforms, Serious Games, Learning, Crisis Management, the Transport sector, and Nielsen's heuristic.

Rusu et al. (2011) made significant advancements by proposing usability heuristics tailored for VEs. They introduced a set of 16 new usability heuristics designed specifically for evaluating virtual world (VW) applications, taking inspiration from Nielsen's ten original usability heuristics. These new heuristics aim to assess VR applications from the user's perspective, addressing the specific challenges encountered in immersive environments. The 16 proposed heuristics include: 1) Feedback; 2) Clarity; 3) Simplicity; 4) Consistency; 5) Low Memory Load; 6) Flexibility and Efficiency of Use; 7) Camera Control; 8) Visualization; 9) Avatar's Customization; 10) Orientation and Navigation; 11) World Interaction; 12) World's Rules; 13) Communication Between Avatars; 14. Error Prevention; 15. Recovery from Errors: and 16. Help and Documentation. These heuristics were tested through a case study involving Club Penguin, a virtual world designed for children aged 8 to 14, where they can engage in games and social interactions. During the evaluation, six evaluators identified 52 usability problems, suggesting that Rusu et al.'s heuristics were more effective at detecting usability issues than Nielsen's. This finding indicates that traditional heuristics may be less applicable in the context of virtual worlds. Rusu et al. (2011) acknowledged that these results are preliminary and emphasised the need for further research to refine VW usability heuristics and develop accompanying checklists.

Kuparinen et al. (2013) developed a new set of heuristics for evaluating mobile map applications (MMAs). They argue that usability issues in MMAs are often overlooked due

to limited resources dedicated to usability engineering in development projects. Additionally, the persistence of usability problems in mobile map services can be attributed, in part, to developers' lack of familiarity with usability principles and the necessary resources for effective implementation. They observed that existing usability heuristics are too general for MMAs, highlighting the need for domain-specific heuristics that address unique aspects like visual design and user location. To this end, their study proposes new usability heuristics derived from theoretical concepts in cartography and visual design aimed at enhancing the usability of MMAs. Current general heuristics, such as those developed by Nielsen, fail to incorporate essential cartographic principles, further underscoring the importance of tailored heuristics for mobile map design. The study's initial usability heuristics were developed using a conceptual-theoretical approach, similar to methodologies employed in the creation of other domain-specific heuristics. Each guideline provides specific descriptions and recommendations tailored to mobile map applications, thereby enhancing the ability to identify usability issues more effectively than generic heuristics, ensuring their practical application in the field.

Four usability specialists evaluated the NavFree application using both the proposed heuristics and Nielsen's heuristics to compare their effectiveness. The evaluators were tasked with performing specific map-related tasks, such as finding a location, setting a route, and adjusting map settings. After completing these tasks, the evaluators offered feedback on the applicability and clarity of both sets of heuristics. The proposed MMA heuristics received higher ratings for applicability compared to Nielsen's, indicating their stronger relevance to the domain. This finding reinforces the necessity for domain-specific usability heuristics in the context of mobile map applications.

Inostroza and Rusu (2014) proposed 12 usability heuristics known as Touchscreen-based mobile devices (TMDs) heuristics. These heuristics are specifically designed to improve the relevance and applicability of usability evaluation for touchscreen devices. These heuristics provide a framework for evaluating and improving the usability of TMD interfaces. In this study, they map TMD heuristics against various design principles from different platforms, including iOS, Windows Phone, Android, and Tizen OS. This mapping process helped to identify whether the heuristics cover all necessary dimensions of usability and design. The mapping revealed that the TMD heuristics not only cover existing design patterns but also introduce two new dimensions: UX and cognitive load. These dimensions are crucial for enhancing the usability of TMDs and will be considered in future updates of the heuristics. The methodology used for developing these heuristics involved a structured approach proposed by Rusu et al. (2011), which included several steps to ensure thorough analysis and refinement. As a result, these heuristics serve as valuable guidelines for developers aiming to create more user-friendly interfaces for touchscreen mobile devices.

Van Wyk and De Villiers (2014) developed a Design-Based Research (DBR) to develop VR training programs intended to enhance safety in the South African mining industry, addressing the inadequacies of traditional safety training. The study employed the HE processes as part of its DBR methodology. The evaluation involved six experts, including usability experts, mining training experts, and VR development experts. The heuristics applied in the evaluation focused on several key areas: usability, effectiveness of the training, and user satisfaction. The structured evaluation process involved a series of tasks designed to test the usability, effectiveness, and user satisfaction of the VR training program. While this study does not specify a single general heuristic, it employs a structured

evaluation process that incorporates expert insights and user feedback to enhance the effectiveness of VR training in the mining industry.

Additionally, Van Wyk and De Villiers (2014) collected feedback through interviews with health professionals to understand their perspectives on the VR experience. These data were used to refine the heuristics. Based on the findings, the researchers proposed new heuristics to enhance UX in future VR applications. These new heuristics included: 1) Establishing connections between visual and auditory elements to enhance the quality of the VR experience; 2) linking visual experience to user immersion; 3) determining appropriate comfort levels and conditions for patients; and 4) incorporating training phases. The study emphasises the importance of these heuristics in guiding the development of VR applications tailored for paediatric cancer patients, ensuring the usability issues are addressed effectively to improve patient experiences during treatment. Furthermore, it underscores the importance of tailoring VR applications to fit specific contexts to minimise their effectiveness and user satisfaction.

Building on this foundation, Inostroza et al. (2016) introduced Smartphone Usability Heuristics (SMASH), a set of 12 usability heuristics specifically designed for smartphones. SMASH was created through an interactive process to enhance usability evaluation in mobile applications. SMASH represents an evolved version of the TMD heuristics, which were originally developed for touchscreen-based mobile devices. The transition from TMD to SMASH involved an iterative development process that incorporated expert feedback and a thorough review of usability issues, leading to a more refined set of heuristics tailored specifically for smartphones. This collaborative approach ensures that the heuristics are not

only comprehensive but also reflective of the collective expertise in the field, making the audience feel included and part of the academic community.

SMASH emphasises the unique usability requirements of smartphones, making them highly relevant to contemporary mobile technology. Inostroza et al. (2016) classifies mobile devices based on criteria such as size, input modes, performance, and communication capabilities, defining smartphones as devices with touch-sensitive displays that offer extensive functionalities. This classification helps in understanding the distinct usability challenges that smartphones present compared to other mobile devices. While existing heuristics often build upon Nielsen's principles, they may not fully address the specific challenges associated with smartphone usability. The development of SMASH involved multiple iterative stages, including literature review, guided inspections, and heuristics evaluations to identify usability issues and ultimately refine the heuristics.

Murtza et al. (2017) introduced a novel set of heuristics specifically designed for usability inspections of VR systems through HE. These heuristics are designed to identify usability issues in both existing and developing VR hardware and software. The study surveyed 85 participants, primarily students and industry professionals, to gather insights regarding their VR experience. Participants completed a nine-item online survey that assessed their frequency of VR use and identified specific usability challenges. The findings revealed some critical areas for improvement, such as hardware control design and navigation, which can be addressed without waiting for advancement in technologies. Additionally, this study aimed to provide a resource for user experience researchers (UXRs) to effectively utilise heuristics review in assessing VR products. The heuristics were

developed to serve as guidelines for both informal evaluations and formal heuristic reviews, ultimately enhancing UX in VR applications.

Murtza et al. (2017) proposed nine categories of usability criteria: 1) Synchronous Body Movements; 2) Physical Space Constraints; 3) Immersion; 4) Glitchiness; 5) Minimise switching between actual and virtual world; 6) Cord Design; 7) Headset Comfort; 8) Mental Comfort and 9) User Interface Design. They also recommended that future research include a more diverse user demographic, incorporating casual users and professionals from various industries. Overall, the research underscores the necessity of tailored usability heuristics for VR systems and advocates for their adoption in the design and evaluation process to reduce user frustration and improve overall satisfaction with VR experiences.

Desurvire and Kreminski (2018) introduced a new heuristic called Virtual Reality PLAY (VR PLAY). The VR PLAY guidelines serve as both an evaluative tool for existing VR games and a design resource for creating new VR experiences. The usability of the VR PLAY guidelines was validated through a combination of HE, designer feedback, user study results, and the designer's enhanced understanding of usability principles. These guidelines consist of five categories: Usability, Playability, VR Immersion, Creative VR, and New Player Experience, all aimed at enhancing player experiences in VR games. Within the study, two sets of heuristics were prominently applied to enhance both the design and UX of VR games: The Playability Principles (PLAY) and the Game Approachability Principles (GAP). The GAP heuristics focus on new-player experiences, while the PLAY heuristics cover broader usability and playability issues that are applicable to VR despite not being exclusive to it. However, they note that while these principles offer valuable guidance, they do not fully capture the unique challenges posed by VR. They emphasise that adhering to these

guidelines is “essential but not sufficient" for designers who aim to create captivating VR experiences. The finalised VR PLAY guidelines were published online for designers to access, emphasising principles that significantly impact VR experiences easily.

Figueroa et al. (2019) created a set of usability heuristics specifically tailored for virtual learning environments, referred to as VLE heuristics. To develop this set, they employed the PROMETHEUS methodology, a procedural approach designed for evaluating VR learning environments. However, the effectiveness of the PROMETHEUS methodology relies on a foundation of established heuristics. To validate their findings, Figueroa et al. (2019) performed a HE that incorporated both VLE heuristics and Nielsen’s heuristics (Nielsen, 1994c). Their result revealed that VLE heuristics outperformed Nielsen’s heuristics by identifying a greater number of issues that were more pertinent to the field of virtual learning. Additionally, evaluators using VLE heuristics reported higher satisfaction levels regarding the utility, clarity, ease of use, and perceived need for additional components compared to those who utilised Nielsen’s heuristics (Figueroa et al., 2019).

Yanez-Gomez et al. (2019) introduced the Meta-heuristics Usability Evaluation (MUSE) tool to tackle the challenges associated with evaluating game usability. This innovative tool customises heuristic guidelines based on specific game characteristics and evaluation objectives, aiming to support game developers and academic researchers in creating more tailored HE checklists. The MUSE tool can reconstruct heuristics from existing literature to offer a customised set of heuristic questions based on specific evaluation plans, including goals, game characteristics, and development stages. Preliminary results indicate that MUSE is a potential strategy for identifying usability issues, particularly beneficial when evaluators may need more specialised expertise. Recognising that the

traditional HE extends beyond mere human-computer interaction, MUSE incorporates unique elements such as narrative and immersion. While existing heuristics can assist in evaluating game interfaces, they often inadequately address gameplay-specific challenges, highlighting the necessity for new guidelines.

The study proposes a meta-heuristic approach to usability evaluation, allowing for the selection of the most relevant guidelines from various existing proposals tailored to specific game types. This modular approach enables evaluators to focus on usability aspects while minimising the inclusion of non-applicable heuristics. The selected heuristics encompass 237 items that address different usability aspects across various game genres, drawing from established literature and expert insights. Preliminary evaluations indicate that MUSE effectively provides customised heuristic guidelines, although further testing is needed to validate its performance against established tools like Nielsen's heuristics. The evaluations suggest that MUSE can reduce the evaluator effect, enhancing reliability in usability assessments, but also highlight the need to minimise false positives in future versions. A pilot test comparing MUSE with Nielsen's heuristics revealed that MUSE detected significantly more usability issues in two evaluated games, indicating its potential effectiveness. The evaluator effect was minimised in MUSE, leading to higher agreement levels among evaluators compared to Nielsen's heuristics, enhancing the reliability of usability assessments.

Young et al. (2020) formulated eight heuristics designed to guide educators and VR developers in creating VEs with a primary focus on educational applications, particularly in the domain of geography. The proposed heuristics - Focus, Provocation, Stimulation, Collaboration, Control, Digital Life, Learner Skills, and Multimodal Experience, are all

grounded in relevant learning theories and constructivist pedagogy, which emphasises the significant learning through exploration (Sánchez et al., 2000). The primary goal of their evaluation was to investigate student reactions to the integration of VR technology within classroom settings and to identify the factors that shape their educational experiences. However, these heuristics primarily focus on hedonic aspects, encouraging student engagement with learning materials through experiential application of learning theory and constructivist pedagogy. Nevertheless, they did not involve teachers in assessing lesson planning and learning activities. Consequently, Young et al. recommended that their heuristics be evaluated across different disciplines in future studies to assess their effectiveness.

Botha et al. (2021) derived their own set of heuristics specifically for evaluating the technological and pedagogical knowledge educators apply, in addition to the content knowledge of the materials delivered through the VR experience. These heuristics are built upon those originally proposed by Nielsen (1994c) and cognitive walkthrough techniques, which were used to assess VR application in nursing education. Two expert review boards were established to evaluate the usability of the VE: one comprised of computer science specialists and the other of health science experts. Each board conducted assessments of the VE using HE and cognitive walkthrough methods. The recommendations generated from these expert reviews were implemented to enhance the VE, thereby allowing learners to experience a more accurate virtual scenario that could positively influence their learning outcomes (Botha et al., 2021). Ultimately, the heuristics were designed to assist educators in determining whether VR technology is suitable as a tool to achieve specific learning objectives. The VE has been significantly improved based on the feedback received during the expert evaluations, granting students access to more realistic virtual scenarios that can

enhance their educational experience. The insights and recommendations derived from these evaluations may also guide future advances in the application of VR in health and scientific education.

Iyer et al. (2024) developed a comprehensive set of 144 platform-specific game heuristics known as Smartphone Games Heuristics (SmGH). These heuristics cover various aspects, including technical, non-technical, and gameplay factors, ensuring a holistic evaluation of smartphone games. The heuristics were designed to reflect current trends and player expectations, addressing the limitations of older heuristics that may no longer be relevant. In their study, the authors noted the absence of a standardised procedure for developing heuristics, which can lead to inconsistencies in game evaluations across different platforms. Many existing heuristics in the literature overlook platform-specific considerations, which can result in inaccurate assessments of player experiences. To inform the development of SmGH, Iyer et al. (2024) incorporated insights from player reviews, as these reflections offer an effective tool for understanding player experiences with mobile games (Tong, 2021). Their research revealed that only 7 out of 44 heuristics were common across at least two heuristic sets, indicating limited overlap among existing mobile game heuristics. The introduction of SmGH highlighted the need for a standard set of platform-specific heuristics, which has the potential to significantly enhance both game user research and industry practices.

Notably, usability issues arising from the unique characteristics of VR were often missed by the general heuristics employed in various studies (Abd Hamid et al., 2016; Botha et al., 2021; Castilla et al., 2013; Ferracani et al., 2016; Hvannberg et al., 2012; Langlet et al., 2021; Slone, 2009; Stadler et al., 2023; Wang et al., 2019). General heuristics often

overlook hedonic aspects, such as immersion, a sense of presence, embodiment, and flow. As technology evolves, there is a pressing need for domain-specific heuristics, as traditional heuristics are increasingly deemed inadequate for VR interfaces.

The literature on wearable virtual reality, especially in educational applications, often lacks a strong foundation in learning theories, as many studies prioritise usability without establishing a robust theoretical framework. By incorporating specific features relevant to these applications, established heuristics can significantly enhance their effectiveness in addressing challenges within the educational environment. As the field continues to evolve, it is essential to promote dialogue, share best practices, and develop guidelines that emphasise inclusive learning environments tailored to meet the diverse needs of students (AlGerafi et al., 2023).

Although there have been some heuristics designed for VEs, such as those by Murtza et al. (2017) and Sutcliffe and Gault's (2004) twelve VR heuristics, they do not adequately encompass the learning context required in educational settings, which emphasise the significance of learning theories. Learning theories establish a foundation for understanding various educational methods and their function in the learning process. Grounding educational tools and activities in sound learning theories is considered fundamental (Hamilton, 2021; Harasim, 2017) as these theories outline how students acquire, process, and retain information (Pritchard, 2017; Schunk, 2012). In the context of educational immersive virtual reality (IVR), learning theories are critical in providing a pedagogical framework for designing effective interventions (Hamilton, 2021).

Young et al. (2020) highlighted that such guidelines could be invaluable for instructors and software designers in the development, implementation, and assessment of

VR lesson plans. These guidelines would support effective user-centred design (UCD) techniques, ultimately enriching learner experiences with VR technology and Immersive VEs. Although some heuristics have been proposed in the VR literature (e.g., Sutcliffe & Gault, 2004), they tend only to address the learning context in broad terms. This lack of specificity may lead to unrealistic learning objectives.

It is important to note that, as of now, there has yet to be any research dedicated to developing a unique VR-based wearable educational application that specifically addresses the pedagogical aspects outlined in The Malaysia Education Blueprint (2013-2025). Consequently, researchers are building upon previous work by developing WVREAs heuristics through three stages: Expert survey, Heuristics Evaluation and User testing. The objective of these refined heuristics is to bridge the existing gap and assist educators in identifying optimal VR applications while guiding VR developers in creating suitable applications that meet educational requirements.

2.4.6 Related Works on Heuristic Evaluation in Virtual Reality Applications

In 1990, Nielsen and Molich introduced HE as a method for assessing user interfaces. This technique involves experts examining products or applications based on established usability principles. It is typically conducted by a team of three to five experts who identify usability issues by comparing tasks against predefined guidelines. The process is both simple and effective, allowing for early detection of usability problems and improvements in interfaces and user satisfaction before formal user testing occurs.

Heuristics have been primarily utilised for evaluating VR environments, as demonstrated in the works of Tham et al. (2018), Fernandes et al. (2019), Figueroa et al. (2019), and Hara et al. (2021), or as design guidelines as noted by Gammanpila et al. (2019).

The concept of HE was first introduced by Nielsen and Molich in 1990 as a method for assessing user interfaces across various domains. Nielsen and Molich highlighted that automatic evaluations are rarely practical and observed that empirical evaluations are often overlooked in real-world settings due to constraints such as time and motivation. Consequently, they advocated for improving user interface usability as a strategic necessity, especially in industrial contexts where it is likely to yield practical benefits. Their research, documented in the paper "Heuristic Evaluation User Interfaces", demonstrated that heuristics evaluation principles provide a framework for practical decision-making rather than rigid rules for assessing interface suitability.

Nielsen's (1994a) heuristic is used not only as an assessment tool for evaluating application usability but also as a foundational element in developing methodological processes such as the PROMETHEUS framework. Gabbard et al. (1999) proposed an iterative human-centred design approach that includes HE of immersive VEs.

Tehrani et al. (2014) applied Nielsen's ten heuristics to assess Virtual Muzium Negara prototyping. The study highlighted limitations related to the quality of images used in the application. The researchers did not utilise professional photography, resulting in subpar panoramic images. This issue indicates a gap in the visual presentation that could affect user engagement.

Altarteer et al. (2017) borrowed from Nielsen and Molich's (1990) heuristic alongside Sutcliffe and Gault's (2004) field-related heuristics to evaluate their semi-immersive VR interface application aimed at enhancing UX. Before conducting user trials, HCI experts performed HE to identify potential usability issues. The results of the heuristic

session highlighted important elements and design features within the system in terms of the system's functionality, visualisation, and interaction quality.

Oliveira et al. (2017) proposed to evaluate the usability of low-cost immersive virtual reality environments through HE methods, specifically focusing on two games developed for Android using Google Cardboard. According to Oliveira et al., traditional usability assessment methods, like HE, face limitations in the VR context, necessitating the development of new tools tailored for 3D environments. They noted that existing heuristics must be updated and fully applicable to the unique challenges presented by modern VR applications. Usability inspection techniques must adapt to the unique design considerations of digital games, which differ significantly from traditional software. Therefore, their research identified two heuristics for VR environments, including Sutcliffe and Gault (2004) and Rusu et al. (2011), that aimed to enhance the evaluation of user interactions in VR settings.

The earlier development of specific heuristics revealed a notable absence of heuristics specifically designed for WVREAs. This gap highlights the necessity for tailored heuristics that effectively address the concepts of immersion and presence. This study aimed to quantify usability issues and validate the effectiveness of the HE in immersive VR environments. In the HE proposed by Sutcliffe and Gault, evaluators identified 27 usability problems in the game Supernatural: The Origin, highlighting issues related to navigation and user control. The evaluation revealed that many problems stemmed from the game’s linear narrative, limiting user freedom in the VE. In the HE proposed by Rusu et al., Evaluators reported 60 usability issues, primarily related to feedback and clarity of information in the game Lamper VR: Firefly Rescue. The evaluation underscored the need for intuitive controls

and clear communication of system states to enhance UX. The research confirmed the efficacy of HE in the context of current VR applications. While the heuristics provided valuable insights, some were considered outdated or contextually irrelevant, suggesting a need for ongoing adaptation and refinement in usability assessment methods.

Paes and Irizarry (2018) conducted evaluations of VR games using Nielsen and Molich (1990) heuristics and user testing, revealing that issues related to multiple head-mounted displays (HMDs) and natural language interactions were inadequately addressed by the general heuristics. Some participants experienced significant motion sickness, affecting their ability to effectively engage with the system. In Paes & Irizarry's (2018) study, five of the ten heuristics proposed by Nielsen & Molich (1990) were particularly pertinent for evaluating immersive virtual reality platforms for building design due to their focus on user interface display features:1) Consistency and Standards; 2) Visibility of System Status; 3) Match Between System and the Real World; 4) User Control and Freedom; 5) Aesthetic and Minimalist Design. These heuristics helped identify minor usability issues in the VE interface, revealing that participants were highly engaged in exploring the virtual space.

Nielsen's ten heuristics have been applied in evaluating the Fountain of The Lions Software Application, which is an interactive 3D virtual reality cultural heritage museum display, as detailed by Tromp et al. (2018). In their assessment, they also employed two additional usability evaluation methods: the development of personas and a cognitive walkthrough conducted by three expert usability participants. Users reported difficulties with navigation in the main view screen, which required two hands to operate independently. This

issue suggests a need for a more intuitive design that accommodates one-handed use, which is not explicitly covered by general heuristics like user control and freedom.

In a related study, Matlock et al. (2018) examined their M-Commerce application in response to Google findings, which revealed that 54 per cent of travellers abandon hotel mobile apps due to usability limitations. Their evaluation utilised Nielsen's general usability heuristics alongside industry guidelines from Google, Android, and Apple. The research resulted in the identification of 13 heuristics, including "Status", "Matching-Real-World", "Control", "Error-Prevention", "Recognition", "Flexibility and-Efficient Use", "Design", "Diagnose-and-Recover", "Help", "Performance", "Information–and-Visual Hierarchy", "Natural-Interaction", "Dynamic Engagement. These heuristics serve as guidelines for developers to enhance the usability of their applications, ensuring that users can navigate and complete tasks efficiently. This study emphasises the need for specific heuristics to enhance UX and reduce abandonment rates.

Wang et al. (2019) conducted a study to identify usability issues in VR applications, with a particular focus on Firefox, using Nielsen’s 10 heuristics. Their findings revealed several inefficiencies in user interaction stemming from the specific input methods used in VR. Users expressed a desire for additional features, such as keyboard support and voice-to-text capabilities, to improve their overall experience. Moreover, users highlighted the need for a consistent design that aligns with their expectations, pointing out difficulties in navigation control. They also reported challenges with camera control and the fidelity of viewpoint transitions, indicating a need for improvements in motion tracking and rendering to reduce discomfort. These findings illustrate the complex nature of usability challenges

within VR, demonstrating that a comprehensive approach is necessary to effectively meet user needs.

Interestingly, the study discovered that not all usability issues could be classified using Nielsen's heuristics, indicating that traditional heuristics often fall short in the context of VR applications. The researchers found that only 77% of usability issues could be mapped to Nielsen's heuristics. The researchers highlighted the importance of addressing unique usability challenges inherent in VR, such as input efficiency and navigation. The study emphasises the need for the development of tailored heuristics specifically designed for function-oriented VR applications.

In their study, Hara et al. (2021) developed Communica-Enf 3D, a serious game designed to teach students how to use verbal and nonverbal communication effectively with virtual patients, as well as to apply clinical reasoning and decision-making skills. Additionally, the game aims to help students recognise and professionally manage conflict. To enhance communication abilities, Hara et al. (2021) conducted a HE of the Communica-Enf 3D, utilising the HE for Digital Educational Games (HEDEG), which allows for assessment by non-expert evaluators. In addition, it used Nielsen's (1994) to evaluate the Comunica-Enf serious games ensure "play motivation, pedagogical quality, and technical effectiveness of this digital educational technology (Hara et al., 2021). During the evaluation, several usability issues were identified, including difficulties with recognition and diagnosis. Some players experience challenges in recognising, diagnosing, and recovering from mistakes made while interacting with the avatar patient. This indicates a gap in the game's feedback mechanisms, which could hinder learning outcomes. While the heuristics evaluation provided valuable insights, it may not have captured all usability issues,

particularly those related to the emotional and interactive aspects of the game. The evaluation primarily focused on the interface and educational elements, which might overlook the overall UX.

Abd Majid et al. (2021) explored the feasibility and effectiveness of using VR as a distraction intervention for paediatric cancer patients undergoing chemotherapy. The study utilised a HE technique to assess the usability of VR games specifically designed for these patients. They classified usability issues using the MAUVE usability criteria derived from Stanney et al. (2003). These heuristics focused on several key areas, such as Object Manipulation, Visual and Audio Output, Comfort, Engagement and Immersion. The HE processes involve multiple stages. Experts identified and categorised usability problems within the VR interface, while Health professionals observed patients interacting with the VR system to gather insights on usability.

In another study, Alwafi et al. (2022) developed VR smartphone applications for foreign language learning using only three Nielsen heuristics (1994a) due to time constraints. These heuristics focused on 1) User control and freedom, 2) Consistency and standards, and 3) Aesthetic and minimalist design. These three heuristics were selected for testing due to their relevance to the proof-of-concept version of the application, and they played a significant role in guiding the design and usability improvements made during the study. Their findings revealed that 30 per cent of users experienced difficulties finding existing points, while 20 per cent were confused by certain icons. However, due to time restrictions and the constraints posed by COVID-19 social distancing measures, the application could not be fully evaluated for its impact on English language learning, and usability testing was restricted to three heuristics with only ten participants.

Alwafi et al. (2022) recommended including a greater number of participants to provide more comprehensive insights into the application's usability and effectiveness. This would help in understanding diverse UX and improving the application based on broader feedback. Alwafi et al. highlighted that future studies should include assessments of actual learning outcomes to determine the effectiveness of the VR application in improving English language skills. This could involve pre- and post-tests to measure progress in speaking, vocabulary retention, and overall language proficiency.

Another study by Videva et al. (2019) integrated selected heuristics from Sutcliffe and Gault's with those from Rusu et al. (2011) and the Lugano Milano Evaluation Method (MiLE+) by Triacca et al. (2005). Their study linked a smartphone with head-mounted devices to provide users with an immersive experience. The findings revealed that the platform's content is inadequate, and no audio guidance, text, or labelling is provided. As a result, the content dimension receives the lowest score from the inspection tests, with an overall performance of poor to average (4.68). Videva et al. (2019) emphasised that content quality is crucial even in an immersive environment, impacting other aspects significantly. For example, navigation received criticism for failing to indicate how to reach target locations. Users suggested that additional text labels on menus or other textual signals could facilitate navigation and clarify the information presented.

Participants in Videva et al. (2019) indicated that both platforms require a clear understanding of the avatar's position, more in-depth content, faithful perspectives that are insufficient, and a balanced information load in the interface design. They identified these as usability issues. In terms of UX issues, the researcher discovered that the platform's content distribution and design should be improved since the platform's clear goal was

lacking, resulting in inefficiency during task completion. During user testing, challenges included ineffective content distribution, dull visuals, and poor engagement with objects, which resulted in less natural perception.

Based on their analysis, Videva et al. (2019) proposed usability and UXprinciples for immersive tourism experiences in online VR, including 1) having a clear map of the avatar/user's position at any point easily accessible on the desktop; 2) being able to instantly access from one point to another directly from the menu; 3) having clear indications of what can be found in any different scene through text labels or images; 4) having clear indications of interactive objects with the help of arrows, buttons, signs, and colour; 5) having the forward and backward navigation feature always easily accessible on the screen; 6) being able to get additional in-depth information on specific points of interest; 7) having a balanced distribution of information without overloading with heterogenous tools like text and audio.

Gammanpila et al. (2019) developed a virtual learning environment (VLE) to assess awareness and preferences for using VR as an educational method in Sri Lanka. This VLE featured a historically designed scenery that allowed learners to navigate and interact with a virtual tutor freely. The goal was to create an immersive and satisfying UX, enabling smooth navigation through the landscape. To enhance UX, the design of this VLE incorporated Nielsen's usability heuristics (Nielsen, 1994a), adjusted specifically for the user. In VR, the user interface acts as the primary visual representation for the user.

Consequently, principles from Nielsen's heuristics guided the VR user interface, considering factors such as the user's comfort zone. For example, elements that are too close to the viewer can cause discomfort, leading to crossed eyes, while elements positioned further away may appear blurred. To improve the UX, interactive components and guidance

information were strategically placed within the optimal line of sight for users; most "call to action" items were positioned in the eye comfort zone, while other essential interactive elements were placed within the neck of the comfort zone (Gammanpila et al., 2019).

Fernandes and Werner (2019) conducted a study that utilised heuristics as an evaluation method to investigate the teaching of abstract concepts in software engineering through a VR application called OO Game VR. The usability of this application was assessed using a HE based on the VR heuristics proposed by Sutcliffe and Gault (2004). Their findings revealed that heuristics #10, which pertains to learning support, accounted for 17% of the usability issues identified, highlighting the necessity for heuristics that facilitate user understanding of how to manipulate and interact within VEs. Additionally, they found that 50% of the challenges encountered were related to learning support, indicating its importance within the usability framework. Meanwhile, Kharoub et al. (2019) evaluated a novel 3D user interface for computer science training, but their analysis overlooked immersion experiences or aspects related to learning achievement, concentrating only on user satisfaction with the interface.

Moreover, following Nielsen's (1994a) heuristics, the interface was designed to ensure that users could perform actions without making errors, emphasising "User Control and Freedom" and Recognition over Recall." This allows users to undo or redo actions if they make a mistake easily. However, despite stating that they utilised and adapted Nielsen's usability heuristics for VR, they did not provide detailed information on how these heuristics had been implemented.

Sutcliffe and Gault (2004) applied twelve heuristics to evaluate the usability of VR e-Bahari, a semi-immersive VR application developed by Dantes et al. (2020). This

evaluation aimed to identify areas for improvement, particularly considering factors that could lead to symptoms of cyber-sickness. The study revealed that VR e-Bahari successfully represented an underwater environment with a comprehensive array of 3D objects, including coral reefs, fish, underwater effects, and lighting. However, Dantes et al. (2020) noted that the user interface felt less natural, needing more sound effects and narrative content, as well as navigation buttons. Consequently, the study recommended enhancing the VR environment's boundaries, adding more navigation buttons, providing additional information for each object, and increasing the visibility of air bubbles and impact effects. Furthermore, tests on head movement revealed that fast up, down, and rotational movements could induce cyber-sickness symptoms. However, users reported feeling more comfortable using the ANTVR kit than they would with Google Cardboard.

Moore et al. (2020) investigated the use of VR learning environments as a complement to traditional Advance Life Support (ALS) training. They focused on identifying specific user needs while developing their application, ALS-Sim VR. To evaluate usability, the researchers conducted semi-structured interviews and supplemented these findings with a HE based on twelve criteria from Sutcliffe and Gault' (2004). These heuristics included natural engagement, compatibility with the user's tasks and domain, natural expression of action, close coordination of actions and representation, realistic feedback, faithful viewpoints, navigation and orientation support, clear entry and exit points, consistent departure, support for learning, clear turn-taking, and a sense of presence". The combined results from interviews and the heuristics evaluations highlighted five critical areas of design considerations for developing similar VR applications: affordances, agency, diverse input modalities, mental models, and advanced roles (Moore et al., 2020). Additionally, the clinical settings involved in the study expressed a desire for an educational

package that allows them to engage in high-fidelity, realistic, and engaging simulations within a clinical context. Specifically, Sutcliffe and Gault's (2004) tenth heuristic, which pertains to learning support, needs to be detailed and thorough to facilitate active learning – this involves users participating in activities that are directly related to acquiring knowledge.

Hara et al. (2024) developed a serious game called "Comunica-Enf", aimed at enhancing nursing students' communication skills with patients and families through immersive virtual reality technology. The game underwent validation using the HE for Digital Educational Games (HEDEG) instrument, which assessed its appearance and usability – critical factors for determining its effectiveness in an educational setting. The evaluation involved 13 nurse teachers and 30 nursing students whose diverse perspectives contributed to a comprehensive understanding of usability issues. While the game was validated, the process of achieving the desired usability standard involved addressing various usability issues identified during the evaluation. The scoring system used in HEDEG highlighted potential problems, which required the team to prioritise and resolve them to ensure the game met the 75% usability standard. The serious game "Comunica-Enf" was successfully validated as it met the criteria of having no more than 25% of type 3 and 4 errors during the evaluation process. This indicates that the game was effective in its design and usability, as it achieved the necessary standards of the research team.

Adjorlu and Serafin (2024) developed an immersive VR application designed to provide exposure therapy aimed at children suffering from social anxiety. To create this application, they followed design guidelines established by Brinkman et al. (2010), emphasising the importance of creating user interfaces (UIs) that enable therapists to control the VR environment effectively. The application allows therapists to modify virtual scenes

to gradually expose children to social singing situations, which is intended to help reduce their anxiety. They conducted a HE based on Nielsen's principles (1994b), focusing on critical aspects such as visibility of system status, user control and freedom, error prevention, and efficiency of use. Following this evaluation, they held a focus group interview with four clinicians experienced in working with children with social anxiety to gather qualitative feedback on both the desktop and VR versions of the application. Participants reported difficulties in reading button labels and expressed a desire for better indicators of progress within the application, indicating challenges related to the visibility of system status.

Additionally, some clinicians noted that their inexperience with the VR system could lead to errors during prolonged interactions, potentially impacting the usability evaluation. The evaluation revealed that while the traditional desktop interface was easier to navigate, the immersive VR interface had the potential to enhance engagement and foster trust between the child and therapist. Based on the clinicians' feedback, the authors identified three main functional requirements for the next iteration of the application, which include improved clarity of the user interface, better progress indicators, and more natural interaction mechanisms. This feedback indicates the authors' commitment to improve both usability and effectiveness in subsequent versions of the application.

While HE has been adapted for both general applications and specific VR contexts, these general heuristics may struggle to identify features unique to three-dimensional (3D) spatially immersive environments, as evidenced by the work of researchers such as Stanney et al. (2003), Zhang and Simeone (2021), Stadler et al. (2023), Paes and Irizarry (2018), Botha et al. (2021), and Abd Hamid et al. (2016).

Many usability issues were discovered in past studies (Alwafi et al., 2022; Dantes et al., 2020; Fernandes & Werner, 2019; Figueroa et al., 2019; Kabassi et al., 2019; Moore et al., 2020; Sajjadi et al., 2020; Wang et al., 2019), that used general heuristics such as Nielsen's general heuristics and Sutcliffe and Gault (2004), to evaluate the effectiveness of VR applications. Sutcliffe & Gault's (2004) heuristics, which are tailored for VR and learning context, did not adequately address all elements of learning context in the tenth heuristic concerning support for learning, resulting in unachievable learning objectives.

While research has yielded various heuristics for VR applications, few have been tailored explicitly for educational wearable VR. As technology rapidly evolves, the heuristics developed years ago may contain outdated perspectives. Numerous studies have identified usability issues within VR applications that have utilised general heuristics such as Nielsen's (1994a) and Sutcliffe's and Gault's (2004) frameworks. These heuristics often fail to comprehensively address the educational context, particularly concerning learning.

CHAPTER 3

WEARABLE VIRTUAL REALITY EDUCATIONAL APPLICATION USABILITY HEURISTICS (WVREAUH)

3.1 Overview

Wearable Virtual Reality Applications (WVREAs) require specific heuristics to effectively identify usability and user experience (UX) issues, which are crucial for their future development. Therefore, a formal methodology should be applied to develop these heuristics to ensure their effectiveness. The researcher utilised the methodology developed by Quiñones and Rusu (2019) for this purpose.

This methodology has been validated through multiple iterations, involving expert feedback and various case studies (Quiñones et al., 2018), which is why the researcher selected it. Furthermore, the researcher found that this methodology provides a detailed explanation of how to apply each stage, how to do the iterations and when to conclude the process. Notably, this methodology has successfully facilitated the development of several new sets of heuristics for various specific application domains, including education, healthcare, entertainment, and gaming (Saavedra et al., 2019; Morales et al., 2020; Delgado et al., 2020).

Although various methodologies have been used to create new heuristics. (Figueroa et al., 2019; Quiñones et al., 2018; Quiñones & Rusu, 2019; Rusu et al., 2011b), many studies fail to provide detailed documentation on the application of these approaches or the process followed to develop the heuristics, as seen in the studies by Murtza et al. (2017), Rusu et al. (2011b) and Hermawati and Lawson (2015). Quiñones and Rusu (2017) argue that adhering to a formal process is essential for developing an effective and efficient set of heuristics. A

formal process involves activities like formulating, specifying, validating, and refining heuristics tailored to a specific domain while considering considerations usability and UX. The researcher presented the details of the development of heuristics in section 3.3, and the results are presented in chapter 4.

3.2 Heuristic Development Method

In developing the WVREA heuristics, the researcher applied the methodology developed by Quiñones and Rusu (2019), which consists of eight stages, as illustrated in **Figure 3.1**.

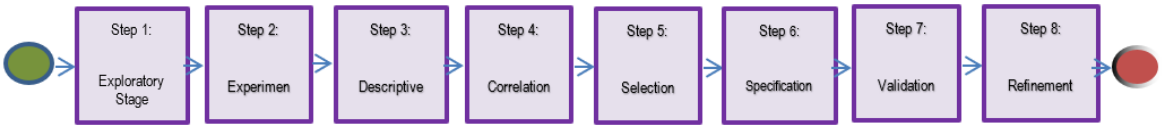


Figure 3.1 Stages of the methodology developed by Quiñones and Rusu (2019)
Adapted from Quiñones and Rusu (2019)

These stages include Exploratory, Experimental, Descriptive, Correlational, Selection, Specification, Validation and Refinement. While these stages are presented sequentially, as shown in **Figure 3.1**, these stages can be performed iteratively to refine unsuitable heuristics identified throughout the evaluation process. Some stages may be optional and not performed for specific reasons. Some stages may be revisited or paused based on feedback and suggestions from experts. This flexibility allows for the refinement of the heuristics to ensure their effectiveness.

3.2.1 Exploratory Stage

In the exploratory stage, the researcher conducted a thorough literature review to identify the domain that requires a new set of specific heuristics and to assess the

shortcomings of existing heuristics in evaluating this identified domain. The findings from this review will address Research Question 1 (RQ1). To carry out this step, the researcher selected several electronic databases: SCOPUS, IEEE Xplore, ACM Digital Library, ERIC, and Web of Science. These databases were chosen for their high quality, extensive coverage of relevant research in fields such as information systems, education, technology, engineering, and computer science, as well as their regular publication of articles related to VR and usability evaluation. This combination of resources ensured comprehensive, high-quality, and accessible data sources for addressing the RQ1.

Subsequently, the researcher collected relevant information regarding WVREAs, focusing on their definitions and features, usability, and UX attributes, as well as examining relevant studies on heuristic development. Furthermore, to understand the impact of the proposed heuristics on a broader scale, the researcher embarked on a comparison of features between less immersive VR educational applications (typically designed for desktops or mobile devices) and WVREAs.

3.2.2 Experimental Stage

The researcher performed a comprehensive literature review during the previous stage (Exploratory stage) and revealed no existing research specifically focused on developing usability / UX heuristics for WVREAs. Therefore, the researcher omitted the experimental stage and proceeded to propose a new set of usability / UX heuristics for WVREAs.

3.2.3 Descriptive Stage

The descriptive stage helped identify key areas that the new heuristics needed to address in terms of usability and UX aspects of WVREAs. It was a multi-stage process that

involved selecting, organising, and prioritising the domain-specific information, existing heuristics, and checklists in the literature. The researcher selected and prioritised the information collected from the exploratory stage. The necessary information was categorised based on its relevance to WVREA, including definition, purpose, context of use, area of use, research justification, main features of WVREA, usability and UX attributes and existing sets of heuristics or other relevant elements. The researcher focused on the significance of this information for evaluating the usability of WVREA heuristics by following the two-step selection process recommended by Quiñones et al. (2018).

- Data Selection and Analysis

This stage concentrated on selecting and analysing data pertinent to evaluating the usability and UX of WVREAs. Each piece of information was assigned an importance score based on its relevance, with scores of 3 indicating highly important, 2 for somewhat important, and 1 for not important to the domain of WVREA usability. Following this scoring process, only the information deemed important – those with scores of 2 or 3 - was further analysed and categorised.

- Comparative Analysis and Heuristic Prioritisation

A comparative analysis of existing usability heuristics was conducted based on the identified criteria to determine whether established heuristics adequately address all the usability attributes specific to VR educational applications. This analysis served two main purposes. First, it aimed to prioritise existing heuristics. Heuristics that consistently appeared across various sets and addressed core usability concerns for WVREA received a high prioritisation score of 3. This approach ensured that the new framework incorporated well-established and relevant evaluation criteria. Second, the analysis sought to identify gaps and

inform the development of new heuristics. Heuristics that were not present in existing sets or could not be fully adapted for specific domains were recognised as potential knowledge gaps and assigned a score of 1, marking them for further development and refinement. This process aimed to ensure that the new framework effectively addresses the unique usability needs of VR educational applications.

3.2.4 Correlational Stage

The Correlational Stage analysis focused on matching the relevant features of WVREA with the usability or UX attributes and the high-priority heuristics identified in Stage 3. This analysis aimed to uncover gaps in existing heuristics that do not address these domain-specific features. By comparing heuristic priorities and WVREA features, the researcher achieved two key results:

1. Well-matched heuristics: Several existing heuristics with high-priority scores were found to correspond to key WVREA features. This correspondence indicates their strong applicability for evaluating WVREA usability.

2. Gaps in Heuristics: The analysis also identified specific WVREA features that lacked corresponding high-priority heuristics. These gaps highlight areas where new heuristics might be crucial for effectively evaluating WVREA usability.

The findings from this stage will inform the development of new, WVREA-specific heuristics in the next stage.

3.2.5 Selection Stage

In the selection stage, the researcher decides whether to keep, adapt, create, or eliminate the selected heuristics. “Keep” refers to those heuristics that effectively and

accurately evaluate the application's aspects and usability attributes. "Adapt" means modifying existing heuristics to better align with the domain attributes. "Delete" involves removing heuristics that are deemed unrelated to the domain. Lastly, the researcher will develop new heuristics for features that do not match any existing guidelines, ensuring comprehensive usability evaluations.

3.2.6 Specification Stage

During the specification stage, the focus was on formal documentation of newly developed usability heuristics for WVREA. The researcher adopted the guidelines established by Quiñones et al. (2018) to ensure comprehensive documentation of each heuristic, which includes six essential elements:

i. A unique identifier.

ii. A concise name and clear definition of its purpose

iii. A detailed explanation linking the heuristic to relevant usability principles, potential usability issues it addresses, and existing heuristics.

iv. Specific examples that highlight both violations and successful implementations within VR educational applications.

v. A clear explanation of the benefits gained by following the heuristic during design

vi. Potential problems that could arise from misunderstanding or misinterpreting the heuristic.

By adhering to this structured approach, the researcher ensures that the newly developed heuristics are clearly defined, informative, and easily applicable for evaluating

the usability of wearable VR educational applications. These proposed heuristics will undergo a series of validation procedures in the following stage.

The proposed heuristics will undergo expert judgment and two heuristic evaluations (HEs). This process will allow the researcher to gather valuable data on expert perceptions and assess their effectiveness.

3.2.7 Validation Stage

3.2.7.1 First experiment procedure: Expert judgement procedure

The first experiment aims to gather expert opinions and insights regarding WVREA heuristics. The researcher can determine if the new heuristics need to be refined based on the experts' feedback. This experiment was conducted to ensure that the WVREA heuristics effectively identify usability issues, thereby avoiding gaps potentially caused by lacking appropriate heuristics or those not clearly defined (Quiñones & Rusu, 2019).

Validation method: Expert survey. Acquiring experts' perceptions of the proposed heuristics.

Participants recruitment: Two distinct groups of experts participated: (1) Researchers (Academics) (n=15) with an extensive experience (10-15 years) in Human-Computer Interaction (HCI) and VR technology, and (2) Industry Practitioners (n=10). A thorough recruitment process ensured the participation of qualified individuals.

Informed consent: Before the evaluation, the researcher asked all participants to complete an informed consent form and provided them with written information about their rights and the procedures for managing their data. As the experiments involved human

participants, the researcher strictly adhered to university research ethics guidelines throughout the entire research process (IRB approval HREC(NM)/2023(1)/31).

Expert validation: The evaluation was conducted via an online Google Form, selected for its convenience and efficiency. The form consisted of two sections. The first section assessed each heuristic across four dimensions using a 5-point Likert scale (1 = Strongly Disagree, 5 = Strongly Agree). These dimensions evaluated the heuristic's Utility (D1), Clarity (D2), Ease of Use (D3), and the Necessity of an additional checklist (D4). The second section provided an overall evaluation of the heuristics, using a similar 5-point Likert scale, and addressed factors such as Easiness, Intention and Completeness. This thorough evaluation process ensured a comprehensive assessment of all aspects of the heuristics.

Subsequently, the researcher analysed the results of the first experiment, leading to the validation of the first 14 WVREA heuristics. The feedback from the initial experiment informed the second experimental procedure, in which the proposed usability heuristics underwent further validation by sixteen experts from various backgrounds: academicians, UX researchers, VR developers, Research and Product Development Executives and VR consultants.

3.2.7.2 Second experiment procedure: Heuristics Evaluation procedure (with the Experts)

This validation procedure aims to answer Research Question 3 (RQ3). This procedure assesses the effectiveness of WVREA heuristics in identifying usability issues within three selected VR educational applications: Titans of Space PLUS, The Body VR, and The Big Table, as illustrated in **Figure 3.2**, **Figure 3.3**, and **Figure 3.4**.

Validation method: Heuristic Evaluation (HE).

Participants recruitment: A total of sixteen participants were recruited for the HE via email invitation, encompassing a diverse range of expertise, including HCI lecturers (n=3) specializing in VR education (4-15 years of experience), VR lecturers (more than 10 years of experience)(n=2), VR developers with 1-5 years of experience (n=7), Research and Product Development Executive (n=1) (1-3 years of experience), UX researchers (1-3 years of experience) (n=1) and VR consultant (more than ten years of experience) (n=1). However, due to motion sickness, one participant withdrew, resulting in a final group of fifteen evaluators.

Informed consent form: All participants provided informed consent prior to the evaluation, ensuring they understood their rights and how their data would be handled.

Evaluation Tools:

i. Informed consent form

ii. Demographic questionnaire

iii. Oculus Rift, sensors, high-end laptop, and controllers

iv. WVREA heuristics as outlined in **Table 4.7**

v. Tasks performed by the experts as presented in **Table 3.1**, **Table 3.2** and **Table 3.3** below:-

Table 3.1 The Titans of Space PLUS VR educational application tasks

No.	Task
1.	Select the English Language.
2.	Choose sitting or standing in the setting.
3.	Choose sensitiveness to motion.
4.	Grab the Earth.
5.	Spin the Earth to the left and the right.
6.	Activate the tour guide by pressing the orange button on your left.
7.	Press the purple button on your left to aim, launch, and then coast.
8.	Go back to the previous and next tour.
9.	Press the green button on your left to find the diameter of all the planets.
10.	Where is the position of the Venus?
11.	Find the diameter of a mercury.
12.	Turn off the music.
13.	Find additional facts about the Earth.
14.	Press the silver button and move towards the earth.
15.	Quit the apps.

Table 3.2 The Big Table VR educational application tasks

No.	Task
1.	Press the start button.
2.	Pull down the lever to activate.
3.	Point and pull the trigger to pick up the cube
4.	Pull the trigger to teleport.
5.	Grab the access cube.
6.	Select the ice cube and place it on the analyser.
7.	Go to the sixth station.
8.	Choose graphite, place it on the analyser and pull the lever down.
9.	Go to the fourth station.

Table 3.2 continued

10.	Choose any of the items (ice cube, soda can, steel spoon, and gold bar) to see which one is a great conductor and which is a poor conductor. Place it on the analyser.
11.	Quit the apps.

Table 3.3 The Body VR educational application tasks

No.	Task
1.	Choose the third menu and press the start button.
2.	Look back at the red blood cell shown to you and grab it.
3.	Adjust the narration volume to 85%.
4.	Adjust the music volume to 70%.
5.	Set the language to English.
6.	Go to the third menu.
7.	Go to the previous scene.
8.	Go to the next scene.
9.	Pause the lesson.
10.	Quit from the lesson.

vi. Wearable Virtual Reality Educational Applications (WVREAs): (i) Titans of Space PLUS VR educational application, (ii) The Big Table VR educational application, and (iii) The Body VR educational application as illustrated in Figure 3.2, Figure 3.3, and Figure 3.4.



Figure 3.2 Titans of Space PLUS VR educational application

The Titans of Space PLUS VR educational application features a spaceship specifically designed to take participants on a tour of a holographic miniature Solar System. This spaceship is equipped with various buttons to assist in navigating and accessing information about the planets.



Figure 3.3 The Big Table VR educational application

The Big Table VR educational application is a dynamic and quick virtual laboratory that invites participants to interact with a variety of advanced machinery and charming robotic creations. The participants will also learn about the periodic table, subatomic particles, and elemental properties.



Figure 3.4 The Body VR educational application

The Body VR application offers an immersive educational experience that transports participants inside the human body. Participants witnessed how blood cells function in delivering oxygen throughout the body. They could also explore one of the billions of living cells and discover how organelles collaborate to combat harmful viruses.

HE Evaluation: Participants were given a minimum of 15 minutes to familiarise themselves with each VR application before starting the formal evaluation. The time allocated for the tasks was limited between 30-45 minutes per expert to minimise the effects of prolonged VR use. During the exploration, the experts were required to complete the tasks (which were read aloud by the researcher) outlined in **Table 3.1**, **Table 3.2**, and **Table 3.2**

As participants identified issues, they read them aloud, and the researcher documented these issues. Since the experts were using wearables, the researcher took on the role of note-taker, as it was not practical for participants to write down the issues themselves.

After the experiments, the participants were asked to review the list of usability issues. They were then asked to assess the severity of each issue. Participants mapped each issue to the corresponding WVREA heuristics and assigned a severity rating on a scale of 0

to 4, as established by Nielsen (1994d). This scale ranged from “Not a usability issue” (0) to “Catastrophe issue” (4), enabling a detailed assessment of the seriousness of identified problems.

Furthermore, participants were allowed to navigate the environment freely for five to ten minutes. After the exploration, they were given the option to conduct another evaluation using a different VR app. If they choose to proceed, the researcher selects another science VR application. However, if time constraints, fatigue, dizziness, or motion sickness from prolonged headset use occurred, they could conclude their evaluations after assessing one or two applications.

If all identified usability issues can be mapped to the WVREA’s heuristics and no expert feedback suggests the need for refinement, the refinement stage would be omitted, and no further iterations would be necessary. Conversely, if any usability issues cannot be mapped to the WVREA’s heuristics, the researcher would refine them based on the expert feedback received.

3.2.7.3 Third experiment procedures: Heuristics Evaluation procedure (with the schoolteachers)

The results of this stage will address Research Question 3 (RQ3), as the researcher assessed the effectiveness of the WVREA’s heuristics through a second round of evaluation, this time including science schoolteachers. These educators were recruited for their subject matter expertise relevant to the science content presented in the VR applications. Evaluating heuristics with schoolteacher representatives is one of the most effective methods for identifying usability issues and, importantly, for capturing schoolteachers’ perceptions regarding the features considered relevant in the educational application domain.

The primary goal of this evaluation phase is to identify potential usability issues based on their subject knowledge and address other usability concerns related to the applications. Their feedback may result in further refinements to the heuristics, improving the evaluation process and ensuring it is more closely aligned with real-world usability needs.

Participants recruitment: Sixteen experienced science schoolteachers were recruited through snowball sampling, of all whom volunteered to participate in the face-to-face HE sessions. However, similar to the expert evaluation, one participant withdrew due to motion sickness, leaving a final group of fifteen schoolteachers.

Informed consent form: Prior to the testing, the researcher requested that schoolteachers complete the informed consent form, which provided information about their rights and data treatment procedures.

Evaluation Tools:

i. Informed consent form

ii. Demographic questionnaire

iii. Oculus Rift, sensors, high-end laptop and controllers

iv. WVREA heuristics as outlined in Table 4.7

v. Tasks performed by the schoolteachers as presented in Table 3.1

vi. Wearable Virtual Reality Educational Application (WVREA): (i) Titans of Space PLUS VR educational application.

User validation: The user validation process involved the researcher briefing participants on the HE procedures and the WVREA heuristics, obtaining informed consent, and providing training on using the VR controller. The participants took between 20 and 30 minutes to familiarise themselves with the application before attempting to complete the tasks. The participants were asked to complete all tasks and instructed to think aloud as they completed them. Similar to the other evaluation, the participants would read aloud the identified issues, which the researcher would document. The researcher functioned as a note-taker as the participants used wearables, which is not practical for writing the identified issues. This approach allowed the researcher to gain valuable insights into the UX and identify potential areas for improvement within the WVREA heuristics.

During the user validation, participants focused solely on the Titans of Space PLUS VR educational application. They were provided with a pre-defined list of representative tasks detailed in Table 3.1, which they were instructed to complete. Similar to the expert HE, users employed a severity rating scale (0-4, established by Nielsen, 1994d) to assess the encountered usability issues. The ratings are categorised as follows: 0 (not a usability issue), 1 (cosmetic issues), 2 (minor issues), 3 (major issues), and 4 (catastrophic issues).

Furthermore, the participants were given the option to conduct another evaluation using a different VR app. If they choose to proceed, the researcher would select another science VR application: The Big Table and The Body VR, as illustrated in Figure 3.3 and Figure 3.4. However, if time constraints arise or an expert experiences fatigue, dizziness, or motion sickness from prolonged headset use, they may conclude their evaluations after assessing one or two applications. If all identified usability issues can be mapped to the WVREA's heuristics, and there are no comments suggesting the need for refinement, the

refinement stage can be omitted, resulting in no further iterations. Conversely, if any usability issues cannot be mapped to the WVREA's heuristics, the researcher will refine them based on the user's feedback received.

3.2.8 Refinement Stage

In the refinement stage (Stage 8), the researcher refines the proposed set of heuristics based on the results obtained from the validation stage. This process clearly defines the heuristics to be finalised, including details on heuristics that were refined and/or eliminated.. If the heuristics need refinement, the researcher will document these refinements, which may comprise changes to the definitions of some heuristics, the addition of more details to the specifications (such as expanding items in the template), eliminating existing heuristics, or creating new ones based on feedback and suggestions received from an expert during the validation stage.

The rationale for these changes and the methods used to implement them, will also be outlined. In addition, the researcher will identify which stages may need to be repeated to improve the set of heuristics. It is possible to follow the eight-stage methodology without iterations if there are no comments or suggestions from the experts (Quiñones and Rusu, 2019). Suppose the heuristics are well-designed, and all identified usability issues can be adequately mapped to the WVREA heuristics. In that case, the researcher may conclude the process without further refinement.

CHAPTER 4

FINDINGS

4.1 Results and Discussion

4.1.1 Stage 1: Exploratory stage

The findings from the first stage, the Exploratory stage, are presented in **Table 4.1**.

Table 4.1 Exploratory Stage

1. Identifying domain: Wearable Virtual Reality Educational Application (WVREA)		
2. The shortcomings of current heuristics for evaluating WVREA are as follows. This finding addresses Research Question 1 (RQ1).		
Authors	**Heuristics applied**	**Shortcomings**
Moore et al. (2020).	Sutcliffe and Gault (2004) • Natural engagement • Compatibility with the user's task and domain • Natural expression of action • Close coordination of action and representation • Realistic feedback • Faithful viewpoints • Navigation and orientation support • Clear entry and exit points • Consistent departures • Support for learning • Clear turn-taking • Sense of presence	The heuristic evaluations highlighted only five critical design considerations for developing similar VR applications: affordances, agency, diverse input modalities, mental models, and advanced roles.

Table 4.1 continued

Young et al. (2020)	Eight heuristics for student-centred VR lesson plans: Focus • Provocation • Stimulation • Collaboration • Control • Digital Life • Learner Skills • Multimodal Experience	Developed heuristics for assessing insights into students' attitudes and behaviour towards VR in the classroom. Focused on specific VR use cases and student populations. Did not measure learning outcomes.
Botha et al. (2021)	Nielsen and Molich (1990) • Simple and natural dialogue • Speak the user's language • Minimize user memory load • Be consistent • Provide feedback • Provide clearly marked exits • Provide shortcuts • Good error messages • Prevent errors	Some of the issues arise which is related to education during the validation could not be detected by general heuristics used, such as follows: • The oxygen mask went through the patient's nose. • The Arterial Blood Gasses results were not correct, and there was no indication whether the results were taken with room air or during oxygen therapy. • The patient's face needed a blue discolouration (cyanosis) to indicate that there was a lack of oxygen.

Table 4.1 continued

		• The patient saturation did not react accordingly. The saturation should increase by a small enough amount to prompt the students to contact the physician.
		• The VE needed a real flow meter. • The patient required an authentic chest rise.
3. Details about the application		
Category	**Description**	**References**
Definition	Wearable VR combines wearable technology and virtual reality to create a unique educational environment. It delivers educational content aligned with active learning principles to enhance the learning experience.	Ogwuegbu et al., 2023; Li et al., 2022; Neuwirth et al., 2021; Rupp et al., 2019; Lamb et al., 2018; Sankaranarayanan et al., 2018; Johnston et al., 2018; Allcoat & von Mühlenen, 2018; Maresky et al., 2019; Liou & Chang, 2018.
Purpose	WVREAs serve a variety of educational goals, including:	
	Spatial knowledge representation: Generating simulated 3D environments for exploration and fostering spatial understanding	Flood, 2024; Norwood et al., 2023; Kim et al., 2023; Maresky et al., 2019; Villena Taranilla et al., 2022; Hanson et al., 2019; Klippel et al., 2019
	Experiential learning: Emphasizing hands-on learning	Bernardo & Duarte, 2023; Di Natale et al., 2020; Junge et al., 2023; Adi Badiozaman et al.,

Table 4.1 continued

	through direct experiences and active engagement	2022; Cecotti, 2024; Byukusenge et al., 2023;Kadri et al., 2024; Newbutt et al., 2017;Gelsomini et al., 2016; Parmar et al., 2023; Yu & Xu, 2022; Makransky et al., 2019; Nuguri et al., 2021; Hsu et. al., 2022; Li et al., 2022; AlGerafi et al., 2023; Neuwirth et al., 2021; Rupp et al., 2019; Lamb et al., 2018; Sankaranarayanan et al., 2018; Cho & Lim, 2017; Johnston et al., 2018; Grotzer et al., 2017; Allcoat & von Mühlenen, 2018; Maresky et al., 2019; Liou & Chang, 2018; Ahmed et al., 2023; Wu et al., 2020; Parong & Mayer, 2018;Concannon et al., 2019; Detyna & Kadiri, 2020.
	Bringing abstract concepts to life: Providing an immersive way to explore and understand abstract concepts	Kim et al., 2023; Byukusenge et al., 2023; Parmar et al., 2023; Li et al., 2023; Maria Becker et al., 2023.
	Motivation: Enhancing student motivation through a highly interactive and immersive learning environment	Parmar et al., 2023; Byukusenge et al., 2023; Maria Becker et al., 2023; Di Natale et al., 2020; Makransky et al., 2019; Dirin & Laine, 2023; Newbutt et al., 2017;

Table 4.1 continued

		Gelsomini et al., 2016; Lee et al., 2017; Parong & Mayer, 2018.
	Collaboration: Facilitating collaborative problem-solving scenarios where learners work together	Pellas, Dengel, et al., 2020; Diederich et al., 2021; De Back et al., 2023; Makransky et al., 2019.
	Accessibility: Providing inclusive learning experiences catering to diverse learning styles and preferences, overcoming geographical barriers, and adapting to individual learning paces	Cecotti et al., 2024; Romero & Cecotti, 2024; Paxinou et al., 2022; Dunnagan et al., 2020; Kamińska et al., 2019; Neuwirth et al., 2021; Chen et al., 2017; Siddhpura et al., 2020; Qu et al., 2021; Grassini et al., 2020; Neuwirth et al., 2021; Smutny et al., 2019; Wolfartsberger, 2019.
Context of use	WVREAs can be utilised in various settings, including:	
	Classroom setting: To enhance students' learning experiences. It provides a more interactive and immersive learning experience than traditional teaching methods and can be used to teach a wide range of subjects and concepts.	Bogusevschi et al., 2020; Sherman & Craig, 2018.
	Field of trips and outdoor learning: These applications can provide students with an interactive and engaging way to learn about the environment and nature around them	Qu et al., 2021; Ahir et al., 2020; Hills & Thomas, 2020; Quay et al., 2020; Jitmahantakul & Chenrai, 2019

Table 4.1 continued

	Professional training: Professional training purposes or to provide virtual simulations for dangerous job training	Grassini et al., 2020; Sherman & Craig, 2018; Ahir et al., 2020.
	Remote learning: These applications are useful in a remote learning environment, where students may not have access to traditional classroom settings. They can provide students with an interactive and engaging way to learn, regardless of their physical location.	Soliman et al., 2021; Neuwirth et al., 2021; Nesenbergs et al., 2020.
Disadvantages	Physical discomfort: Headaches, eye strain, and neck pain can impact UX.	Belsam Attallah & Ilagure, 2018; Garzotto et al., 2017; Pellas, Dengel, et al., 2020.
	Motion sickness: Some users may experience nausea when using VR, especially if unfamiliar with VEs.	Garzotto et al., 2017; Pellas, Dengel, et al., 2020; Tychsen & Foeller, 2020; Newbutt et al., 2017.
General Key Features	These features contribute to WVREAs' overall immersive and engaging learning experience.	
	High Representational Fidelity: Delivers an immersive and realistic learning experience with high-quality representations.	Qorbani et al., 2021; Pellas, Dengel, et al., 2020; Smutny et al., 2019; Lee & Wong, 2014; Dalgarno et al., 2002; Choi & Baek, 2011, Dalgarno & Lee, 2010; Christopoulos et al., 2020, Saeed Alqahtani et al., 2017, Wolfartsberger, 2019,

Table 4.1 continued

		Pellas & Kazanidis, 2014, Moore et al., 2020, Al-Azawi et al., 2019, Concannon et al., 2019, Hite et al., 2019; Makransky et al., 2017; Vats & Joshi, 2024; Neuwirth et al., 2021; Kadri et al., 2024.
	Immersive Learning Environment: This provides a more engaging educational experience, fully immersing users in a virtual world.	Vats & Joshi, 2024; Qorbani et al., 2021; Smutny et al., 2019; Lee & Wong, 2014; Choi & Baek, 2011; Dalgarno & Lee, 2010; Scavarelli et al., 2021; Saeed Alqahtani et al., 2017; Wolfartsberger, 2019; Dalgarno et al., 2002; A. Wang et al., 2022;Pellas, Dengel, et al., 2020; Segura et al., 2020; Fernandes & Werner, 2019; Al-Azawi et al., 2019; Concannon et. al., 2019; Makransky et al., 2017; Maheshwari & Maheshwari, 2020; Freina & Canessa, 2015.
	Easy-to-use interface: User-friendly interface with intuitive design for accessibility.	Qorbani et al., 2021; Wolfartsberger, 2019; Moore et al., 2020; Segura et al., 2020; Fernandes & Werner, 2019; Al-Azawi et al., 2019; Concannon et al., 2019; Nuguri et al., 2021.

Table 4.1 continued

	Presence: Evokes a strong sense of presence or "being there" within the VE.	Maria Becker et al., 2023; Lee & Wong, 2014; Hite et al., 2019; Gerini et al., 2023.
	Engagement: Captivates and involves users in a highly immersive and interactive learning experience.	Vats & Joshi, 2024; Dalgarno & Lee, 2010; Dalgarno et al., 2002; Pellas, Dengel, et al., 2020; Fernandes & Werner, 2019; Makransky et al., 2017; Sun et al., 2021; Kadri et al., 2024
Specific Key Features	In addition to general features, WVREAs can incorporate features to enhance specific learning goals.	
	Engages multiple senses (visual, auditory, tactile) to enhance learning and retention.	Vats & Joshi, 2024; Qorbani et al., 2021; Saeed Alqahtani et al., 2017; A. Wang et al., 2022; Choi & Baek, 2011; Cui et al., 2006; Sandrone & Carlson, 2021; Sanfilippo et al., 2022; Wu et al., 2020; Neuwirth et al., 2021; Kadri et al., 2024,
	Interactivity: Dynamic and engaging features enable users to participate in learning actively.	McFadden & Li, 2019; Almusawi et al., 2021;Qorbani et al., 2021; Smutny et al., 2019; Lee & Wong, 2014; Dalgarno et al., 2002; Choi & Baek, 2011; Dalgarno & Lee, 2010; Scavarelli et al., 2021; Christopoulos et al., 2020; Saeed Alqahtani et al., 2017; Wolfartsberger, 2019; Wang et

Table 4.1 continued

		al., 2022; Moore et al., 2020;Pellas, Dengel, et al., 2020; Segura et al., 2020; Fernandes & Werner, 2019; Al-Azawi et al., 2019; Concannon et al., 2019; Makransky et al., 2017; Maheshwari & Maheshwari, 2020; Southgate, 2020; Hamilton et al., 2021
	Collaboration: Facilitates seamless communication between students and teachers through 3D virtual environments and avatars.	Almusawi et al., 2021; Dalgarno & Lee, 2010; Scavarelli et al., 2021; Saeed Alqahtani et al., 2017; Wolfartsberger, 2019; Pellas & Kazanidis, 2014; A. Wang et al., 2022; Moore et al., 2020; Pellas, Kazanidis, et al., 2020; Segura et al., 2020; Fernandes & Werner, 2019; Al-Azawi et al., 2019; Concannon et al., 2019; Maheshwari & Maheshwari, 2020; Southgate, 2020.
	Real-time Feedback: Sensors analyse user actions, providing immediate feedback on performance and skills, personalising the learning journey.	Smutny et al., 2019; Dalgarno et al., 2002; Choi & Baek, 2011; Dalgarno & Lee, 2010; Scavarelli et al., 2021; Christopoulos et al., 2020; Moore et al., 2020; Pellas, Dengel, et al., 2020; Segura et al., 2020; Fernandes & Werner,

Table 4.1 continued

		2019; Al-Azawi et al., 2019; Concannon et al., 2019; Hite et al., 2019.
	Pedagogy & Cognition: Immerses users in realistic environments for experiential learning through simulations, role-playing scenarios, critical thinking challenges, and problem-based learning activities	Maria Becker et al., 2023; Vats & Joshi, 2024; Chen & Huang, 2023; Christopoulos et al. 2020; Qorbani et al., 2021; Soliman et al., 2021; Neuwirth et al., 2021; Smutny et al., 2019; Dalgarno et al., 2002; Wolfartsberger, 2019; Choi & Baek, 2011; Saeed Alqahtani et al., 2017; A. Wang et al., 2022; Moore et al., 2020; Pellas, Dengel, et al., 2020; Segura et al., 2020; Fernandes & Werner, 2019; Al-Azawi et al., 2019; Concannon et al., 2019; Hite et al., 2019; Choi & Baek, 2011; Hodgson et al., 2019; Mikropoulos & Natsis, 2011;Eser et al., 2020; Sanfilippo et al., 2022; Wu et al., 2020.
	Curriculum-aligned Content: Designed to align with established curriculum to Ensure the VR experience directly contributes to learning outcomes.	Qorbani et al., 2021; Southgate, 2020; MacDowell et al., 2022; Sandrone & Carlson, 2021; Neuwirth et al., 2021; Kadri et al., 2024.
	Personalisation: Tailors learning experiences to individual needs by	

Table 4.1 continued

	leveraging user data to adapt content and challenges.	Qorbani et al., 2021; Smutny et al., 2019; Dalgarno et al., 2002; Scavarelli et al., 2021; Pellas & Kazanidis, 2014; Christopoulos et al., 2020; Saeed Alqahtani et al., 2017; Dalgarno & Lee, 2010;
	Learning Measurement: Integrates measurement tools to track and evaluate learner progress and performance with real-time feedback.	A. Wang et al., 2022; Moore et al., 2020; Pellas, Dengel, et al., 2020; Segura et al., 2020; Fernandes & Werner, 2019; Al-Azawi et al., 2019; Concannon et al., 2019; Maheshwari & Maheshwari, 2020.
	Gamification: Integrates game-like elements (e.g., points, badges) to increase engagement and motivation.	Bosmos et al., 2023; Scavarelli et al., 2021; Pellas & Kazanidis, 2014; Segura et al., 2020.
	Accessibility: This provides an accessible platform for learners who may have difficulty with traditional methods due to learning disabilities or other factors.	Scavarelli et al., 2021; Neuwirth et al., 2021; Soliman et al., 2021; Moore et al., 2020; Maheshwari & Maheshwari, 2020; Fealy et al., 2019; Bower et al., 2020; Carreon et al., 2023.
Type	Immersive Virtual Reality technology	
Application	Science Education	
Target audience	VR developers, schoolteachers, and students	

Table 4.1 continued

4. Comparison of immersive VR Education Apps with Wearable VR Educational Applications			
Features	**Less immersive VR Education apps**	**Wearable VR Educational Application**	**Impact on New Heuristics**
Platform	Desktop computer or mobile device, without additional headset (HMD, Wearable) (Zhao et al., 2020).	Wearable VR headset (Almusawi et al., 2021; Miguel-Alonso et al., 2023; Gabbard et al., 1997; Newbutt et al., 2017; Chen, 2016; Gelsomini et al., 2016; Garzotto et al., 2017; Sun et al., 2021).	Heuristics might need to address limitations specific to the VR headset platform, such as processing power or controller design.
Immersion	Negligible (Pedram et al., 2021; Banerjee et al., 2023).	High; Users fully immerse themselves in a virtual world (Qorbani et al., 2021; Smutny et al., 2019; Lee & Wong, 2014; Choi & Baek, 2011;Dalgarno & Lee, 2010; Scavarelli et al., 2021; Saeed Alqahtani et al., 2017; Wolfartsberger, 2019; Dalgarno et al., 2002; Wang et al., 2022; Pellas, Dengel, et al., 2020; Segura et al., 2020; Fernandes & Werner, 2019; Al-Azawi et al., 2019; Concannon et al., 2019; Makransky et al., 2017; Maheshwari & Maheshwari, 2020; Wu et al., 2020).	Focus on preventing cybersickness, ensuring a clear sense of presence, and optimising UX within a fully immersive environment.

Table 4.1 continued

Mobility	Technology dependent (Criollo et al., 2021; Pimmer et al., 2016)	Highly portable and usable in various settings (DuTell et al., 2022)	Heuristics should address potential safety concerns with physical movement, consider natural user interface design for interaction within the VR space, and account for potential disorientation during movement.
Interaction Style	Limited to navigation (mouse, keyboard, touch) (Paes et al., 2021; Banerjee et al., 2023)	Natural gestures, VR hand controllers (Banerjee et al., 2023; Qorbani et al., 2021; Smutny et al., 2019; Lee & Wong, 2014; Dalgarno et al., 2002; Choi & Baek, 2011; Dalgarno & Lee, 2010; Scavarelli et al., 2021; Christopoulos et al., 2020; Saeed Alqahtani et al., 2017; Wolfartsberger, 2019; Wang et al., 2022; Moore et al., 2020; Pellas, Dengel, et al., 2020; Segura et al., 2020 Fernandes & Werner, 2019; Al-Azawi et al., 2019;	Heuristics might need to focus on user comfort and ease of use with VR controllers, natural user interface design for hand and body movements, and the effectiveness of voice commands within the environment.

Table 4.1 continued

		Concannon et al., 2019; Makransky et al., 2017; Maheshwari & Maheshwari, 2020; Han, 2020; Makransky et al., 2019)	
Visualisation	2D (Monoscopic perspective) (Paes et al., 2021; Rusu et al., 2011)	3D scene (Han, 2020; Banerjee et al., 2023)	Heuristics might address potential limitations in visual fidelity due to hardware constraints and ensure clear and focused visuals to avoid user strain.
Online Collaboration	Limited opportunities (Banerjee et al., 2023)	Supports various forms of collaboration (Banerjee et al., 2023)	Heuristics might consider leveraging the immersive nature of WVREAs to enhance user motivation and maintain engagement throughout the learning experience.
Motivation	Lower inherent motivation (Liu et al., 2023)	Increased motivation through immersion (Han, 2020; Makransky et al., 2019)	Heuristics might consider leveraging WVREAs' immersive nature to enhance user motivation and maintain engagement throughout the learning experience.
Hardware Requirement	A wider range of devices (tablets, PCs, smartphones) (Criollo-C et al., 2021)	Specialised VR headsets are required (Almusawi et al., 2021; Miguel-Alonso et	Heuristics could address potential limitations caused by the VR headset's processing power or battery life.

Table 4.1 continued

		al., 2023; Gabbard et al., 1997; Newbutt et al., 2017; Chen, 2016; Gelsomini et al., 2016; Garzotto et al., 2017; Sun et al., 2021)	
Cost	Typically, lower cost	Typically, higher cost (VR headset)	While the cost would not directly impact heuristics, understanding the cost implications might influence design choices that prioritise usability without exceeding budget constraints.

Table 4.1 continued

5. Usability and UX attributes	
Authors	**Usability attributes**
a. Nielsen (2012)	• Learnability • Efficiency • Memorability • Errors • Satisfaction
b. International Organization for Standardisation (2011)	• Effectiveness • Efficiency • Learnability • Operability • User error protection • Freedom from risk, and • Context completeness.
Authors	**UX attributes**
a. Tcha-Tokey et al. (2018)	• Presence • Engagement • Immersion • Flow • Usability • Skill • Emotion • experience consequence • judgment • technology adoption

Table 4.1 continued

6. Existing sets of heuristics			
Virtual World Heuristics (Rusu et al., 2011a)	**VR apps Heuristics** (Sutcliffe & Gault, 2004)	**VE Characteristic** (Gabbard et al., 1997)	**User Interface Design Heuristics** (Nielsen, 1994a)
R1: Feedback: A VW interface should keep the user informed about his avatar's state and the relevant facts and events that affect him.	**SG1: Natural engagement**: Interaction should, as closely as possible, approach the user's expectation of interaction in the real world.	**GBSysInfo2:** Pay close attention to the visual, aural, and haptic organisation of presentation (e.g., eliminate unnecessary information, minimise overall and local density, group-related information, and emphasise information related to user tasks)	**N1: Visibility of system status:** The design should always keep users informed about what is going on, through appropriate feedback within a reasonable amount of time.
R2: Clarity: A VW should offer an easy-to-understand user control panel, using clear graphic elements, text, and language, grouping elements by	**SG2: Compatibility with the user's task and domain.** The VE and behaviour of objects should correspond as closely as possible to the user's	**GBSysInfo3:** Strive to maintain interface consistency across applications.	**N2: Match between system and the real world**: The design should speak the users' language. Use words, phrases, and concepts familiar to the

Table 4.1 continued

their purposes and offering easy access to the main functionality.	expectation of real-world objects; their behaviour; and affordances for task action.		user, rather than internal jargon. Follow real-world conventions, making information appear in a natural and logical order.
R3: Simplicity: A VW should provide easy and intuitive interaction with the environment's virtual objects. Only relevant information should be given, to avoid the control panel's overload.	**SG3: Natural expression of action**. The representation of the self/presence in the VE should allow the user to act and explore in a natural manner and not restrict normal physical actions.	**GBSysInfo4:** Language and labelling for commands should clearly and concisely reflect meaning.	**N3: User control and freedom:** Users often perform actions by mistake. They need a clearly marked "emergency exit" to leave the unwanted action without having to go through an extended process.
R4: Consistency: A VW should be consistent in using language and concepts. Avatar's actions and their effects on the VW's environment should be coherent	**SG4:** Close coordination of action and representation. The representation of the self/presence and behaviour manifest in the VE should be faithful to the user's actions. Response time between user	**GBSysInfo5:** System messages should be worded in a clear, constructive manner to encourage user engagement (as opposed to user alienation)	**N4: Consistency and standards:** Users should not have to wonder whether different words, situations, or actions mean the same thing. Follow platform and industry conventions.

Table 4.1 continued

and consistent. User – avatar, as.well as avatar – VW's objects, should be consistent	movement and update of the VE display should be less than 200 ms to avoid motion sickness problems.		
R5: Low memory load: A VW should maintain main objects, options, elements, and actions always available or easy to get to. It should provide ways to mark and remember places already visited and/or of user's interest.	**SG5: Realistic feedback:** The effect of the user's actions on virtual world objects should be immediately visible and conform to the laws of physics and the user's perceptual expectations.	**GBSysInfo6:** For large environments, include a navigational grid and/or a navigational map.	**N5: Error Prevention**: Good error messages are important, but the best designs carefully prevent problems from occurring in the first place. either eliminate error-prone conditions or check for them and present users with a confirmation option before they commit to the action.
R6: Flexibility and efficiency of use: A VW should provide customisable shortcuts, abbreviations, accessibility keys or command lines. The user	**SG6: Camera control and visualization** - The system should allow the user to determine the level and quality of textures, visual effects, or	**GBSysInfo7:** When implementing maps, adhere to map design principles (Darken and Sibert, 1995)	**N6: Recognition rather than recall:** Minimize the user's memory load by making elements, actions, and options visible. The user should not have to remember information from one part of the interface to

Table 4.1 continued

interface/control panel should be customisable.	objects with a purely aesthetic proposal. The system should also allow the user to control the camera or angle from where it is viewed.		another. Information required to use the design (e.g. field labels or menu items) should be visible or easily retrievable when needed.
R7: Camera control: A VW should give user control over the camera, allowing a customizable user's view.	judged in a trade-off with naturalness (see heuristics 1 and 2).	**GBSysInfo8:** Present domain-specific data in a clear, unobtrusive manner such that the information is tightly coupled to the environment and vice-versa.	**N7: Flexibility and efficiency of Use:** Shortcuts — hidden from novice users — may speed up the interaction for the expert user so that the design can cater to both inexperienced and experienced users. Allow users to tailor frequent actions.
R8: Visualization: A VW should give user control over the objects and visual effects that he/she will get visible.	**SG8: Clear entry and exit points.** The means of entering and exiting from a virtual world should be clearly communicated.	**GBSysInfo9:** Strive for unique, powerful presentation of application-specific data, providing insight not possible	**N8: Aesthetic and minimalist design:** Interfaces should not contain information that is irrelevant or rarely needed. Every extra unit of information

Table 4.1 continued

		through other presentation means.	in an interface competes with the relevant units of information and diminishes their relative visibility
R9: Avatar's customization: A VW should allow full avatars' customization.	**SG9: Consistent departures**. When design compromises are used, they should be consistent and clearly marked	**GBAgents1**: Include agents that are relevant to user tasks and Goals	**N9: Help users, recognise, diagnose, and recover from Errors:** Error messages should be expressed in plain language (no error codes), precisely indicate the problem, and constructively suggest a solution.
R10: Orientation and navigation: A VW should provide full (customizable) information on avatar's position, paths to a desired destination, and passageways	**SG10: Support for learning.** Active objects should be cued and if necessary, explain themselves to promote learning of VEs.	**GBAgents2**: Real-world, high-fidelity physical and behavioural agent representation may be useful for training and simulation VEs	**N10: Help and Documentation:** It's best if the system doesn't need any additional explanation. However, it may be necessary to provide documentation to

Table 4.1 continued

from one position to another (according to VW's rules).			help users understand how to complete their tasks.
R11: World interaction: A VW should clearly indicate the objects that user may interact with, as well as the actions that user may perform over the objects.	**SG11: Clear turn-taking**. Where system initiative is used it should be clearly signalled and conventions established for turn-taking.	**GBAgents3**: Allow agent behaviour to dynamically adapt, depending upon context, user activity, etc.	
R12: World's rules: A VW should clearly indicate its own rules and the rules that govern avatars, especially the actions that are impossible in the real (user's) world but are possible in the VW (and vice versa).	**SG12: Sense of presence.** The user's perception of engagement and being in a 'real' world should be as natural as possible.	**GBAgents4**: Represent interactions among agents and users (rules of engagement) in a semantically consistent, easily visualisable manner	
R13: Communication between avatars: A VW should allow easy		**GBAgents5**: Organize multiple agents according to user tasks and goals.	

Table 4.1 continued

communication among users, through their avatars			
R14: Error prevention: A VW should prevent users from performing actions that could lead to errors, and should avoid confusion that could lead to mistakes, during user–control panel interaction, as well as during (user's) avatar – VW interaction.		**GBSetting2:** Exploit real-world experience, by mapping desired functionality to everyday items (e.g., clock to convey time)/ components of the environment may suggest activity as well, via real-world metaphor of functionality.	
R15: Recovering from errors: A VW should provide user appropriate mechanisms to recover from errors and exit ways from unwanted situations. It should include clear messages, hopefully indicating causes and solutions for errors.		**GBSetting3:** Use relevant settings that suggest user activity and tasks.	

Table 4.1 continued

R16: Help and documentation: A VW should provide an easy to find, easy to understand, and complete online documentation, accessible from both inside and outside of the world itself.		**GBSetting4**: Employ rendering techniques that support detailed presentation of setting without introducing.	
		GBNav2: Layout, or floor plan, of a VE should be consistent-Facilitate user acquisition of survey knowledge (e.g., maintain a consistent spatial layout)	
		GBNav3: Organizational principles- when designing landscaping and terrain layout, consider organizational principles.	

Table 4.1 continued

		GBNa4: When appropriate, include spatial labels, landmarks, and a horizon.	
		GBNav5: Provide information so that users can always answer the questions: Where am I now? What is my current attitude and orientation? Where do I want to go? How do I travel there?	
		GBNav6: Avoid mode-based navigation-user cannot perform any other tasks but locomotion. **GBUsers1: Take into account user experience:** (i.e.: support both expert and novice users)	

Table 4.1 continued

		GBUsers2: Domain Knowledge-Support users with varying degrees of domain knowledge (Expert/Novice users) **GBUsers3: Orientation, spatial visualization, and spatial memory-** users with low spatial abilities generally have longer task performance times with more errors on the first trial. Many of these users find themselves lost within the system. - developing better design metaphors and provide additional information such as context, landmarks, and maps.	

Table 4.1 continued

		GBInput2: Eliminate extraneous degrees of freedom by implementing only those dimensions which users perceive as being related to given tasks. **GBInput8:** Decrease user cognitive load by avoiding devices such as joysticks and wands which, in effect, place themselves between users and environments **GBUserRep2**: Ensure that users' avatars provide a familiar, accurate, and relevant frame of reference.	

Table 4.1 continued

		GBUserRep3: Provide egocentric point of view(s) when users need to experience a strong sense of self-presence. **GBUserRep4:** Provide exocentric view(s) when relative positioning and motion between the user and objects are important. **GBUserRep5:** User embodiments should be as efficient as possible. (e.g., useful, and relevant content, detail, and sensory representation) **GBUserRep6:** Allow users to control presentation of both	

Table 4.1 continued

		themselves and others. (e.g., support graceful degradation) **GBUserRep7:** Allow users to alter point of view, or viewpoint (i.e., support the ability to view scenes and objects from many different angles **GBSetting1:** Use setting to increase user presence/a relevant setting may increase user presence and immersion. **GBHaptic2:** Use other sensory information to reinforce or enhance haptic tasks **GBHaptic14:** Be cautious in presenting, and semantically	

Table 4.1 continued

		inding a large number of haptic intensities levels. **GBHaptic20**: When possible, provide kinaesthetic or tactile feedback for manipulation-based tasks. **GBTask2**: When designing collaborative VEs, support social interaction among users. **GBTask3**: In collaborative VEs, support cooperative task performance (e.g., facilitate social organization, construction, and execution of plans, (e.g., group communication, role-play, informal interaction) **GBTask6**: Design interaction mechanisms and methods to	

Table 4.1 continued

		support user performance of serial tasks and tasks sequences. **GBTask7: Stackable**- Provide stepwise, subtask refinement, including the ability to undo. **GBSelect2**: When selecting distant objects via direct manipulation, exaggerate object size, appearance, interobject distances, etc. **GBSelect3:** Facilitate selection of multiple objects **GBSelect5:** Use non-direct manipulation means (such as query-based selection) when selection criteria are temporal, descriptive, or relational.	

Table 4.1 continued

		GBSelect6: Supply users with appropriate selection feedback (e.g., highlighting, outlining, acoustic or verbal confirmation) **GBSelect11:** Targeting of three dimensional objects should be based upon relative motion. **GBSelect12:** Use ray casting when objects to be selected are very small or co-located among many others. **GBManip1**: Provide accurate depiction of location and orientation of surfaces. **GBManip2**: Minimize display lag. **GBManip3**: Support multimodal interaction.	

Table 4.1 continued

		GBManip4: Provide spatially relevant and revealing user point of view.	
		GBManip5: Avoid non-intuitive, unnatural, or poorly mapped gesturing. **GBManip6**: When using pinch gloves, keep in mind user experience when determining the number of modes or pinching combinations. **GBManip7**: Support two-handed interaction (especially for manipulation-based tasks) **GBManip8**: For two-handed manipulation tasks, assign dominant hand to fine-grained	

Table 4.1 continued

	manipulation relative to the non-dominant hand.
	GBManip9: When rotating objects through large angles via natural wrist rotation, employ a clutching or ratcheting mechanism. **GBManip10**: Allow users to alter basic object attributes (e.g., color, shape, labels) **GBManip11**: When possible, combine query formation with selection methods. **GBManip12**: Support interface query for users to determine what actions are available for objects.

4.1.2 Stage 2: Experimental Stage.

Given the novelty of VR education and its unique usability requirements, the researcher focused on developing a new set of usability heuristics. A comprehensive literature review revealed a gap in existing research on usability heuristics for VR education.

4.1.3 Stage 3: Descriptive stage

In this stage, each criterion was prioritised using a three-level scale: 3 for highly important, 2 for somewhat important, and 1 for not important based on the scale developed by Quiñones and Rusu (2019). The categorised data, presented in **Table 4.2**, follow this scale for evaluating WVREA. This table provides valuable insights into the key aspects that should be considered when assessing the usability of VR educational applications.

Table 4.2 Descriptive Stage Analysis

Category	Value (Importance)	Explanation/justification
Definition	2	Describes the core functionality of WVREAs: integrating wearable technology and VR to facilitate knowledge and skill transfer between virtual and real-world environments. Additionally, it emphasises applying educational principles like active learning to enhance the learning experience.
Context of use	2	Identifies potential use cases for WVREAs, including classroom settings, field trips, professional training, and remote learning.
Area of use	3	It highlights the diverse applicability of WVREAs across various domains, including education, military, medicine, rehabilitation, and entertainment.
Research justification	3	Emphasises the need for specific WVREA usability evaluation guidelines due to the limitations of existing general and specific

Table 4.2 continued

		heuristics relevant to the domain due to the unique features of WVREAs.
The main features of WVREA	3	Categorises features into general and specific categories for further analysis.
Usability and UX attributes	3	Identifies relevant frameworks for evaluating usability and UX
Existing sets of heuristics or other relevant elements	3	Lists previously identified sets of heuristics that will serve as a foundation for developing new WVREA-specific heuristics: (1) Rusu et al. (2011a) - 16 usability heuristics for virtual worlds. (2) Sutcliffe & Gault (2004) - 12 heuristics for VR applications. (3) Gabbard et al. (1997) - Taxonomy of Usability of Characteristics in Virtual Environments. (4) Nielsen (1994a) - 10 usability heuristics for user interface design.

Before prioritising the existing heuristics for WVREA, the researcher conducted a comparative analysis, as recommended by Quiñones and Rusu (2019). This analysis aimed to identify overlaps and similarities among the criteria evaluated by each heuristic set. The researcher carefully examined each set to determine how they addressed common usability concerns, whether they used the same or similar wording for evaluation criteria and any potential gaps where existing heuristics might not fully address WVREA-specific usability challenges. The detailed results of this comparative analysis are presented in **Table 4.3**, which compares the criteria evaluated by each heuristic set.

Table 4.3 Comparative Analysis of existing heuristics

Value	Virtual World Heuristics (Rusu et al., 2011)	VR apps Heuristics (Sutcliffe & Gault, 2004)	VE Characteristic (Gabbard et al., 1997)	User Interface Design Heuristics (Nielsen, 1994a)
3	**R1: Feedback**: A VW interface should keep the user informed about his avatar's state and the relevant facts and events that affect him.	**SG5: Realistic feedback:** The effect of the user's actions on virtual world objects should be immediately visible and conform to the laws of physics and the user's perceptual expectations. **SG1: Natural engagement**: Interaction should, as closely as possible, approach the user's expectation of interaction in the real world.	**GBSelect6:** Supply users with appropriate selection feedback (e.g., highlighting, outlining, acoustic or verbal confirmation)	**N1: Visibility of system status** The design should always keep users informed about what is going on through appropriate feedback within a reasonable amount of time.
	R2: Clarity: A VW should offer an easy-to-understand user control panel, using	**SG2: Compatibility with the user's task and domain.** The VE and behaviour of objects should correspond as closely as possible to the user's	**GBSysInfo4:** Language and labelling for commands should clearly and concisely reflect meaning.	**N2: Match between system and the real world** The design should speak the users' language. Use words, phrases, and concepts familiar

Table 4.3 continued

3	clear graphic elements, text, and language, grouping elements by their purposes, and offering easy access to the main functionality.	expectation of real-world objects, their behaviour, and affordances for task action.	**GBSysInfo5:** System messages should be worded in a clear, constructive manner to encourage user engagement (as opposed to user alienation) **GBAgents3**: Allow agent behaviour to dynamically adapt, depending upon context, user activity, etc. **GBAgents4**: Represent interactions among agents and users (rules of engagement) in a semantically consistent, easily visualisable manner **GBAgents5**: Organize multiple agents according to user tasks and goals.	to the user, rather than internal jargon. Follow real-world conventions, making information appears in a natural and logical order.

Table 4.3 continued

			GBSetting2: Exploit real-world experience by mapping desired functionality to everyday items (e.g., clock to convey time)/ components of the environment may suggest activity as well, via real-world metaphor of functionality. **GBSetting3:** Use relevant settings that suggest user activity and tasks. **GBSetting4**: Employ rendering techniques that support detailed presentation of setting without introducing.	
3	**R3: Simplicity**: A VW should provide easy and intuitive interaction with the	-	**GBAgents1**: Include agents that are relevant to user tasks and Goals	**N8: Aesthetic and minimalist design**

Table 4.3 continued

	environment's virtual objects. Only relevant information should be given, to avoid the control panel's overload.		**GBSysInfo2:** Pay close attention to the visual, aural, and haptic organisation of presentation (e.g., eliminate unnecessary information, minimise overall and local density, group related information, and emphasise information related to user tasks)	Interfaces should not contain information that is irrelevant or rarely needed. Every extra unit of information in an interface competes with the relevant units of information and diminishes their relative visibility.
3	**R4: Consistency:** A VW should be consistent in using language and concepts. Avatar's actions and their effects on the VW's environment should be coherent and consistent. User – avatar, as well as avatar – VW's objects, should be consistent.	**SG9: Consistent departures**. When design compromises are used, they should be consistent and clearly marked	**GBNav2: Layout, or floor plan, of a VE should be consistent-** Facilitate user acquisition of survey knowledge (e.g., maintain a consistent spatial layout)	**N4: Consistency and standards** Users should not have to wonder whether different words, situations, or actions mean the same thing. Follow platform and industry conventions.

Table 4.3 continued

			GBSysInfo3: Strive to maintain interface consistency across applications.	
3	**R5: Low memory load:** A VW should maintain main objects, options, elements, and actions always available or easy to get to. It should provide ways to mark and remember places already visited and/or of user's interest.	-	**GBUsers3: Orientation, spatial visualisation, and spatial memory-** users with low spatial abilities generally have longer task performance times with more errors on the first trial. Many of these users find themselves lost within the system. - developing better design metaphors and provide additional information such as context, landmarks, and maps. **GBInput8:** Decrease user cognitive load by avoiding	**N6: Recognition rather than recall** Minimise the user's memory load by making elements, actions, and options visible. The user should not have to remember information from one part of the interface to another. Information required to use the design (e.g. field labels or menu items) should be visible or easily retrievable when needed.

Table 4.3 continued

			devices such as joysticks and wands which, in effect, place themselves between users and environments	
3	**R6: Flexibility and efficiency of use**: A VW should provide customisable shortcuts, abbreviations, accessibility keys or command lines. The user interface/control panel should be customisable.	-	**GBSetting4:** Employ rendering techniques that support detailed presentation of setting without introducing lag.	**N7: Flexibility and efficiency of Use** Shortcuts — hidden from novice users — may speed up the interaction for the expert user so that the design can cater to both inexperienced and experienced users. Allow users to tailor frequent actions.
3		**SG3: Natural expression of action**. The representation of the self/presence in the VE should	**GBUserRep5**: User embodiments should be as efficient as possible (e.g.,	

Table 4.3 continued

		allow the user to act and explore in a natural manner and not restrict normal physical actions.	useful, and relevant content, detail, and sensory representation).	
3	**R7: Camera control:** A VW should give user control over the camera, allowing a customisable user's view.	**SG6: Camera control and visualisation** - The system should allow the user to determine the level and quality of textures, visual effects, or objects with a purely aesthetic proposal. The system should also allow the user to control the camera or angle from where it is viewed.	**GBUserRep7:** Allow users to alter point of view, or viewpoint (i.e., support the ability to view scenes and objects from many different angles	**N3: User control and freedom** Users often perform actions by mistake. They need a clearly marked "emergency exit" to leave the unwanted action without having to go through an extended process.
3	**R8: Visualization**: A VW should give user control over the objects and visual effects that he/she will get visible.	-	**GBSetting1:** Use setting to increase user presence/a relevant setting may increase user presence and immersion. **GBHaptic2:** Use other sensory	**N3: User control and freedom** Users often perform actions by mistake. They need a clearly marked "emergency exit" to leave the unwanted

Table 4.3 continued

	-		information to reinforce or enhance haptic tasks **GBHaptic14:** Be cautious in presenting, and semantically binding a large number of haptic intensities levels. **GBHaptic20**: When possible, provide kinaesthetic or tactile feedback for manipulation-based tasks. **GBSysInfo8:** Present domain-specific data in a clear, unobtrusive manner such that the information is tightly coupled to the environment and vice-versa. **GBSysInfo9:** Strive for unique, powerful presentation of	action without having to go through an extended process. -

Table 4.3 continued

			application-specific data, providing insight not possible through other presentation means.	
	R9: Avatar's customisation: A VW should allow full avatars' customisation.	**SG4:** Close coordination of action and representation. The representation of the self/presence and behaviour manifest in the VE should be faithful to the user's actions. Response time between user movement and update of the VE display should be less than 200 ms to avoid motion sickness problems. **SG12: Sense of presence.** The user's perception of engagement and being in a	**GBUserRep2**: Ensure that users' avatars provide a familiar, accurate, and relevant frame of reference. **GBUserRep3**: Provide egocentric point of view(s) when users need to experience a strong sense of self-presence. **GBUserRep4:** Provide exocentric view(s) when relative positioning and motion between the user and objects are important.	**N3: User control and freedom** Users often perform actions by mistake. They need a clearly marked "emergency exit" to leave the unwanted action without having to go through an extended process.

Table 4.3 continued

		'real' world should be as natural as possible.	**GBUserRep5:** User embodiments should be as efficient as possible. (e.g., useful, and relevant content, detail, and sensory representation) **GBUserRep6:** Allow users to control presentation of both themselves and others. (e.g., support graceful degradation) **GBInput2:** Eliminate extraneous degrees of freedom by implementing only those dimensions which users perceive as being related to given tasks. **GBAgents2**: Real-world, high-fidelity physical and behavioural	

Table 4.3 continued

			agent representation may be useful for training and simulation VEs	
3	**R10: Orientation and navigation:** A VW should provide full (customisable) information on avatar's position, paths to a desired destination, and passageways from one position to another (according to VW's rules).	**SG7: Navigation and orientation support.** The users should always be able to find where they are in the VE and return to known, preset positions. Unnatural actions such as fly-through surfaces may help but these have to be judged in a trade-off with naturalness (see heuristics 1 and 2).	**GBNav3: Organizational principles-** when designing landscaping and terrain layout, consider organisational principles. **GBNav4**: When appropriate, include spatial labels, landmarks, and a horizon. **GBNav5:** Provide information so that users can always answer the questions: Where am I now? What is my current attitude and orientation?	**N3: User control and freedom** Users often perform actions by mistake. They need a clearly marked "emergency exit" to leave the unwanted action without having to go through an extended process.

Table 4.3 continued

			Where do I want to go? How do I travel there? **Provide** information so that users can always answer the questions: Where am I now? What is my current attitude and orientation? Where do I want to go? How do I travel there? **GBSysInfo6:** For large environments, include a navigational grid and/or a navigational map. **GBSysInfo7:** When implementing maps, adhere to map to [Darken and Sibert, 1995] design principles.	

Table 4.3 continued

3	**R14: Error prevention**: A VW should prevent users from performing actions that could lead to errors, and should avoid confusion that could lead to mistakes, during user–control panel interaction, as well as during (user's) avatar – VW interaction.	**SG11: Clear turn-taking**. Where system initiative is used it should be clearly signalled and conventions established for turn-taking. **SG8: Clear entry and exit points.** The means of entering and exiting from a virtual world should be clearly communicated.	GBNav6: **Avoid mode-based navigation**-user cannot perform any other tasks but locomotion.	**N5: Error Prevention** Good error messages are important, but the best designs carefully prevent problems from occurring in the first place. Either eliminate error-prone conditions or check for them and present users with a confirmation option before they commit to the action.
3	**R15: Recovering from errors**: A VW should provide user appropriate mechanisms to recover from errors and exit ways from unwanted situations. It should include		**GBTask7: Stackable**- Provide stepwise, subtask refinement, including the ability to undo. **GBTask6**: Design interaction mechanisms and methods to	**N9: Help users recognise, diagnose, and recover from** **Errors** Error messages should be expressed in plain language

Table 4.3 continued

	clear messages, hopefully indicating causes and solutions for errors.	-	support user performance of serial tasks and tasks sequences.	(no error codes), precisely indicate the problem, and constructively suggest a solution.
3	**R16: Help and documentation**: A VW should provide an easy to find, easy to understand, and complete online documentation, accessible from both inside and outside of the world itself.	-	-	**N10: Help and Documentation** It is best if the system does not need any additional explanation. However, it may be necessary to provide documentation to help users understand how to complete their tasks.
2	**R11: World interaction:** A VW should clearly indicate the objects that user may interact with, as well as the	**SG10: Support for learning.** Active objects should be cued and if necessary, explain themselves to promote learning of VEs.	-	-

Table 4.3 continued

3	actions that user may perform over the objects. **R12: World's rules**: A VW should clearly indicate its own rules and the rules that govern avatars, especially the actions that are impossible in the real (user's) world but are possible in the VW (and vice versa).	-	-	-
1	**R13: Communication between avatars**: A VW should allow easy communication among users, through their avatars	-	-	-
1		-	**GBUsers1: Take into account user experience.** (i.e., support both expert and novice users)	-

Table 4.3 continued

			GBUsers2: Domain Knowledge-Support users with varying degrees of domain knowledge (Expert/Novice users) **GBSelect2**: When selecting distant objects via direct manipulation, exaggerate object size, appearance, interobject distances, etc. **GBSelect3:** Facilitate selection of multiple objects **GBSelect5:** Use non-direct manipulation means (such as query-based selection) when selection criteria are temporal, descriptive, or relational.	-

Table 4.3 continued

			GBSelect11: Targeting of three dimensional objects should be based upon relative motion. **GBSelect12:** Use ray casting when objects to be selected are very small or co-located among many others. **GBManip1**: Provide accurate depiction of location and orientation of surfaces. **GBManip2**: Minimize display lag. **GBManip3**: Support multimodal interaction. **GBManip4**: Provide spatially relevant and revealing user point of view.	

Table 4.3 continued

			GBManip5: Avoid non-intuitive, unnatural, or poorly mapped gesturing.	
			GBManip6: When using pinch gloves, keep in mind user experience when determining the number of modes or pinching combinations. **GBManip7**: Support two-handed interaction (especially for manipulation-based tasks) **GBManip8**: For two-handed manipulation tasks, assign dominant hand to fine-grained manipulation relative to the non-dominant hand. **GBManip9**: When rotating objects through large angles via natural wrist rotation, employ a	

Table 4.3 continued

			clutching or ratcheting mechanism. **GBManip10**: Allow users to alter basic object attributes (e.g., colour, shape, labels) **GBManip11**: When possible, combine query formation with selection methods. **GBManip12**: Support interface query for users to determine what actions are available for objects. **GBTask2**: When designing collaborative VEs, support social interaction among users.	
			GBTask3: In collaborative VEs, support cooperative task performance (e.g., facilitate	

Table 4.3 continued

			social organisation, construction, and execution of plans (e.g., group communication, role-play, informal interaction)	

Building on the identified criteria in **Table 4.3**, this comparative analysis informed the prioritisation of heuristics for WVREA evaluation. Heuristics that appeared in multiple sets and addressed core usability concerns, such as "Recovering from Errors", were assigned high importance. Heuristics relevant to WVREAs but with less frequently represented received a moderate score. Meanwhile, domain-specific heuristics or those requiring adaptation for WVREAs were assigned a lower score but will be reviewed further for potential inclusion.

4.1.4 Stage 4: Correlational stage

Table 4.4 serves as a valuable resource, providing a comprehensive breakdown of matched features, attributes, and existing heuristics alongside the identified gaps in heuristic coverage.

Table 4.4 Correlational stage

Features	Attributes	Heuristics
High representational fidelity: This includes the sharpness of images, the realism of textures, the accuracy of lighting and shadows, and the smoothness of motion. These elements contribute to immersive VE.	1. Satisfaction (Nielsen, 2012) 2. Tcha-Tokey et al. (2018) i. Presence ii. Immersion	**GBAgents2**: Real-world, high-fidelity physical and behavioural agent representation may be useful for training and simulation VEs.
Engages various sensory experience: WVREAs can engage multiple senses, including visual, auditory, and tactile. This can enhance learning and retention by creating a more engaging and interactive experience.	1. Learnability (ISO, 2011) 2. Satisfaction (Nielsen, 2012) 3. Engagement (Tcha-Tokey et al., 2018)	-

Table 4.4 continued

Interactivity: Users can interact with the VE using natural gestures and movements. This allows for a more intuitive and immersive learning experience.	1. Learnability **(**ISO, 2011; Nielsen, 2012) 2. (Tcha-Tokey et al., 2018) i. Engagement ii. Flow iii. Skills iv. Emotion v. Experience Consequences vi. Judgement	**GBSelect2**: When selecting distant objects via direct manipulation, exaggerate object size, appearance, inter-object distances, etc. **GBSelect3:** Facilitate selection of multiple objects **GBSelect5:** Use non-direct manipulation means (such as query-based selection) when selection criteria are temporal, descriptive, or relational. **GBSelect11:** Targeting of three dimensional objects should be based upon relative motion. **GBSelect12:** Use ray casting when objects to be selected are very small or co-located among many others. **GBManip1**: Provide accurate depiction of location and orientation of surfaces. **GBManip2**: Minimize display lag. **GBManip3**: Support multimodal interaction.

Table 4.4 continued

Pedagogy & Cognition: The application should be designed based on sound pedagogical principles and support a variety of instructional strategies, such as simulations, role-playing, critical thinking skills development, and problem-based learning. **Engagement:** Research suggests that WVREAs can promote user engagement (Kadri et al., 2024; Vats & Joshi, 2024; Adi Badiozaman et al., 2022) **Gamification:** Incorporating gamification elements can increase user engagement and motivation (Scavarelli et al., 2021; Pellas & Kazanidis, 2014; Segura et al., 2020; Kadri et al., 2024).		**GBManip4**: Provide spatially relevant and revealing user point of view. **GBManip5**: Avoid non-intuitive, unnatural, or poorly mapped gesturing. **GBManip6**: When using pinch gloves, keep in mind user experience when determining the number of modes or pinching combinations. **GBManip7:** Support two-handed interaction (especially for manipulation-based tasks) **GBManip8**: For two-handed manipulation tasks, assign dominant hand to fine-grained. manipulation relative to the non-dominant hand. **GBManip9**: When rotating objects through large angles via natural wrist rotation, employ some form of clutching or ratcheting mechanism. **GBManip10**: Allow users to alter basic object attributes (e.g., colour, shape, labels)

Table 4.4 continued

		GBManip11: When possible, combine query formation with selection methods. **GBManip12**: Support interface query for users to determine what actions are available for objects.
Sense of Presence: A strong presence in the virtual environment can enhance learning by making it feel more real and engaging. **Immersive Learning Environment:** WVREAs create an immersive learning environment that can allow students to explore and interact with concepts in a more realistic way.	1. The Usability Attributes (ISO, 2011) i. Efficiency ii. Operability iii. User error protection 2. Satisfaction (Nielsen, 2012) 3. Tcha-Tokey et al. (2018) i. Presence ii. Immersion iii. Experience consequence.	**R9:** Avatar's customisation: A VW should allow full avatars' customisation, **SG4:** Close coordination of action and representation. The representation of the self/presence and behaviour manifest in the VE should be faithful to the user's actions. Response time between user movement and the update of the VE display should be less than 200 ms to avoid motion sickness problems. **SG12:** Sense of presence. The user's perception of engagement and being in a 'real' world should be as natural as possible.

Table 4.4 continued

		GBUserRep2: Ensure that users' avatars provide a familiar, accurate, and relevant frame of reference GBUserRep3: Provide egocentric point of view(s) when users need to experience a strong sense of self-presence. **GBUserRep4**: Provide exocentric view(s) when relative positioning and motion between user and objects are important. **GBUserRep5**: User embodiments should be as efficient as possible (e.g., useful, and relevant content, detail, and sensory representation) **GBUserRep6:** Allow users to control the presentation of both themselves and others (e.g., support graceful degradation) **GBInput2**: Eliminate extraneous degrees of freedom by implementing only those dimensions which users perceive as being related to given tasks.

Table 4.4 continued

Collaborative Learning: Collaborative features like 3D virtual environments and avatars can facilitate communication and interaction between students and teachers via text, voice, and camera.	1. Learnability (ISO., 2011; Nielsen, 2012) 2. Nielsen (2012) i. Efficiency ii. Errors iii. Satisfaction 3. Tcha-Tokey et al. (2018) i. Presence ii. Engagement iii. Immersion iv. Flow v. Usability vi. Skill vii. Emotion viii. Experience consequences ix. Judgement x. Technology adoption	**GBTask2**: When designing collaborative VEs, support social interaction among users. **GBTask3**: In collaborative VEs, support cooperative task. Performance (e.g., facilitate social organisation, construction, and execution of plans (e.g., group communication, role-play, informal interaction)

Table 4.4 continued

Real-time feedback: The application should provide immediate and continuous feedback to users as they interact with it. This helps them learn from their mistakes and improve their performance.	1. ISO (2011) i. Learnability ii. Context Completeness 2. Errors (Nielsen, 2012) 3. Tcha-Tokey et al. (2018) i. Flow ii. Emotion iii. Experience consequence. iv. Judgement	**R1: Feedback**: A VW interface should keep user informed on both avatar's state, and the relevant facts and events that affect him. **SG5: Realistic feedback**: The effect of the user's actions on virtual world objects should be immediately visible and conform to the laws of physics and the user's perceptual expectations. **GBSelect6**: Supply users with appropriate selection feedback (e.g., highlighting, outlining, acoustic or verbal confirmation) **N1: Visibility of system status.** The design should always keep users informed about what is going on through appropriate feedback within a reasonable amount of time.

Table 4.4 continued

Easy-to-use interface: A user-friendly interface ensures accessibility and a positive learning experience for all ages and backgrounds. **(**Qorbani et al., 2021; Wolfartsberger, 2019; Moore et al., 2020; Segura et al., 2020; Fernandes & Werner, 2019; Al-Azawi et al., 2019; Concannon et al., 2019).	1. Nielsen (2012) i. Learnability ii. Efficiency iii. Memorability iv. Errors v. Satisfaction 2. Tcha-Tokey et al. (2018) i. Presence ii. Immersion iii. Flow iv. Emotion v. Experience Consequence vi. Judgement	**R2: Clarity:** A VW should offer an easy-to-understand user control panel, using clear graphic elements, text, and language, grouping elements by their purposes, and offering easy access to the main functionality. **SG2: Compatibility with the user's task and domain**. The VE and behaviour of objects should correspond as closely as possible to the user's expectation of real-world objects; their behaviour; and affordances for task action. **GBSysInfo4:** Language and labelling for commands should clearly and concisely reflect meaning. **GBSysInfo5:** System messages should be worded in a clear, constructive manner to encourage user engagement (as opposed to user alienation)

Table 4.4 continued

		GBAgents3: Allow agent behaviour to dynamically adapt, depending upon the context, user activity, etc. **GBAgents4**: Represent interactions among agents and users (rules of engagement) in a semantically consistent, easily visualisable manner. **GBAgents5**: Organize multiple agents according to user tasks and goals **GBSetting2**: Exploit real-world experience, by mapping desired functionality to everyday items (e.g., clock to convey time)/ components of the environment may suggest activity as well, via real-world metaphor of functionality. **GBSetting3**: Use relevant settings that suggest user activity and tasks

Table 4.4 continued

		GBSetting4: Employ rendering techniques that support detailed presentation of setting without introducing lag. **N2: Match between system and the real world** The design should speak the users' language. Use words, phrases, and concepts familiar to the user, rather than internal jargon. Follow real-world conventions, making information appear in a natural and logical order.
Personalisation: VR allows for tailoring learning experiences to individual needs, making them more effective than traditional one-size-fits-all approaches	1. Nielsen (2012) i. Learnability ii. Efficiency iii. Satisfaction 2. Tcha-Tokey et al. (2018) i. Emotion ii. Judgment	**GBUsers1: Take into account user experience.** (i.e. support both expert and novice users)

Table 4.4 continued

Curriculum-aligned content: The VR experience should be designed to support and enhance the educational objectives outlined in the curriculum. **(**Qorbani et al., 2021)	1. Nielsen (2012) i. Learnability ii. Satisfaction 2. Tcha-Tokey et al. (2018) i. Skills ii. Judgment	-
Learning Measurement: Learning measurement tools allow tracking learners' progress and performance, enabling real-time feedback and identification of areas for improvement (Qorbani et al., 2021; Christopoulos et al., 2020; Pellas & Kazanidis, 2014; Pellas, Dengel, et al., 2020).	1. ISO (2011**)** i. Effectiveness ii. Efficiency iii. Learnability 2. Tcha-Tokey et al. (2018) i. Skills ii. Emotion iii. Judgement	-
Accessibility: The application should be accessible and usable for learners of different abilities and backgrounds (Moore et al., 2020; Maheshwari & Maheshwari, 2020; Fonseca et	1. Context Completeness (ISO, 2011) 2. Tcha-Tokey et al. (2018) i. Flow ii. Emotion	**GBUsers2: Domain Knowledge-** Support users with varying degrees of domain knowledge (Expert/Novice users)

Table 4.4 continued

al., 2018; Scavarelli et al., 2021., 2018; Fealy et al., 2019; Detyna & Kadiri, 2020)	iii. Experience Consequence iv. Judgement	

4.1.5 Stage 5: Selection stage

Table 4.5 presents the comprehensive results of this selection process, including the designations assigned to each heuristic.

Table 4.5 Heuristics classification after the selection stage

Existing ID	Heuristics	Action	WVREA Features Covered	New ID
GBAgent2	Real-world, high-fidelity physical and behavioural agent representation may be useful for the training and simulation of VEs.	Adapt	High fidelity or stylised representational	**WVREA 1**
GBAgents3	Allow agent behaviour to dynamically adapt, depending upon the context, user activity, etc.	Adapt (into GBAgent2)		
GBAgents4	Represent interactions among agents and users (rules of engagement) in a semantically consistent, easily visualisable manner.			
GBAgents5	Organise multiple agents according to user tasks and goals.			
GBSetting4	Employ rendering techniques that support detailed presentation of setting without introducing.			

Table 4.5 continued

-	Engages multiple visual, auditory, and tactile senses to enhance learning and retention.		Create	Multi-sensory Learning	WVREA 2
R1	Feedback		Keep	Real-time feedback	WVREA 3
SG5	Realistic feedback		Adapt (into R1)		
GBSelect6	Supply users with appropriate selection feedback				
N1	Visibility of system status				
GBSelect2 GBSelect5 GBSelect12 GBSelect3 GBSelect11	Object Selection	Non-isomorphic	**Adapt (as WVREA 4)** Nonisomorphic (Non-Realistic magic technique)	Interactivity Pedagogy & Cognition Engagement Gamification	**WVREA 4**
		Isomorphic	**Adapt (as WVREA 5)** Isomorphic (Realistic)		**WVREA 5**

Table 4.5 continued

GBManip1 GBManip12 GBManip2 GBManip3 GBManip4 GBManip5	Object Manipulation	Nonisomorphic	**Adapt (as WVREA 6)** Nonisomorphic (Non-Realistic magic technique)	Interactivity Pedagogy & Cognition Engagement Gamification	**WVREA 6**
GBManip6 GBManip7 GBManip8 GBManip9 GBManip10		Isomorphic	**Adapt (as WVREA 7)** Isomorphic (Realistic)		**WVREA 7**
R9	Avatar's customisation		**Keep**	Sense of Presence Immersive Learning Environment.	**WVREA 8**
SG4	Close coordination of action and representation.		**Adapt (into R9)**		
SG12	Sense of presence.				
GBVisual1**2**	Representative user tasks may implicitly suggest the mix of immersion, self-presence, and object presence required.				
GBUserRep2	Ensure that users' avatars provide a familiar, accurate, and relevant frame of reference.				

Table 4.5 continued

GBUserRep3	Provide an egocentric point of view(s) when users must experience a strong self-presence.		**Adapt (into R9)**		
GBUserRep4	Provide exocentric view(s) when relative positioning and motion between user and objects are important.				
GBUserRep5	User embodiments should be as efficient as possible (e.g., useful and relevant content, detail, and sensory representation)				
GBUserRep6	Allow users to control the presentation of both themselves and others (e.g., support graceful degradation)				
GBInput2	Eliminate extraneous degrees of freedom by implementing only those dimensions which users perceive as being related to given tasks.				
GBTask2 **GBTask3**	Collaborative learning	When designing collaborative VEs, support social interaction among users. In collaborative VEs, support cooperative task performance (e.g., facilitate social organisation, construction, and execution of plans (e.g., group communication, role-play, informal interaction)	**Adapt (as WVREA 9)**	**Collaborative Learning**	**WVREA 9**

Table 4.5 continued

R2	Clarity	**Keep**		
SG2	Compatibility with the user's task and domain.			
GBSysInfo4	Language and labelling for commands should clearly and concisely reflect meaning.			
GBSysInfo5	System messages should be worded in a clear, constructive manner to encourage user engagement (as opposed to user alienation)			
GBSetting2	Exploit real-world experience, by mapping desired functionality to everyday items (e.g., clock to convey time)/ components of the environment may suggest activity as well, via real-world metaphor of functionality.	**Adapt (into R2)**	**Easy-to-use interface**	**WVREA 10**
GBSetting3	Use relevant settings that suggest user activity and tasks.			
N2	Match between system and the real world			
GBUser1	Consider user experience. (i.e., support both expert and novice users)	**Adapt (as WVREA 11)**	**Personalisation**.	**WVREA 11**

Table 4.5 continued

-	Ensure that the virtual reality experience is purposefully designed to support and enhance the educational objectives outlined in the curriculum.	**Create WVREA 12**	**Curriculum-aligned content.**	**WVREA 12**
-	Provides measurement tools that track learners' progress and performance, allowing for real-time feedback and identification of areas for improvement	**Create WVREA 13**	**Learning Measurement**	**WVREA 13**
-	The application should be accessible and easy for learners of different abilities and backgrounds.	**Create WVREA 14**	**Accessibility**	**WVREA 14**

4.1.6 Stage 6: Specification stage

Stage 6, known as the Specification stage, focused on formally documenting the final set of usability heuristics for WVREAs. This stage emphasised the importance of maintaining a concise and manageable set of heuristics, recognising that overly extensive lists can impede practical application (Quiñones et al., 2018). Based on the heuristic selection process outlined in Stage 5, a final set of heuristics was established.

Table 4.6 summarises these key heuristics, including:

Table 4.6 Details sets of heuristics (WVREA)

ID	WVREA 1
Name	**Aligned Representation for Virtual Agents in VR Education.**
Definition	The physical and behavioural characteristics of agents in VR education apps should be designed to effectively support learning objectives. This can encompass high-fidelity representations for realistic scenarios or engaging, stylised approaches for specific audiences.
Explanation	VR educational experiences can leverage a range of visual styles for the agents (characters/Avatar) that learners interact with. While high-fidelity representations can be ideal for situations requiring a deep understanding of real-world mechanics or procedures, stylised approaches can be equally effective, particularly for: 1. Younger audiences: Appealing visuals and a less intimidating environment can spark curiosity and make complex topics more approachable. 2. Introducing new concepts: Stylization can simplify details and focus learners' attention on key aspects of the topic..
Example(s)	High-fidelity representation: Creating virtual avatars that closely resemble real-world scientists or science teachers. These avatars can have detailed facial features, realistic clothing and accessories that reflect their field of expertise, and lifelike movements that enhance the feeling of interacting with a real person. For instance, a VR experience on the human body might feature a high-fidelity avatar of a doctor explaining the anatomy in detail. Stylised representation: Developing engaging, cartoon-like avatars of scientists or science teachers. This style can be particularly effective for younger audiences. The characters can have exaggerated features for better recognition and wear

Table 4.6 continued

	clothing that emphasises their scientific background. For example, a VR app on the solar system might introduce learners to a friendly, stylised astronomer character who guides them through the planets.
Benefit(s)	Tailoring the level of realism to the learning objectives creates a more engaging and effective educational experience. Regardless of style, a consistent visual approach fosters a cohesive learning environment that draws learners in.
Checklist	**Align Representation with Learning Goals:** 1. Consider the target audience and the specific learning objectives. 2. High fidelity may be ideal for some situations, while a stylised approach might be better for others. **Maintain Consistency:** 1. Maintain a consistent visual style throughout the VR experience, whether realistic or stylised, to ensure a cohesive learning environment. 2. Characters, environments, and interactions should all adhere to the chosen style. **Consider Emotional Connection:** 1. Design characters (even stylised ones) to evoke emotions and build a connection with learners, enhancing their engagement with the learning experience.
ID	**WVREA 2**
Name	**Engages various sensory experience**
Definition	Engages multiple visual, auditory, and tactile senses to enhance learning and retention.

Table 4.6 continued

Explanation	It creates an immersive learning environment that stimulates multiple senses to enhance the learning experience, such as visual and auditory experience, haptic feedback, spatial awareness, Gesture motion, and olfactory stimulation.
Example(s)	The application can provide 3D visuals, ambient sounds, character voices, vibrations, pressure, texture variations, and sensors to track user movements and gestures and incorporate smells into the virtual environment.
Benefit(s)	The application creates a more immersive learning environment, enhances memory and information retention, fosters deeper connections with the educational content, increases motivation, and promotes experiential learning, hands-on learning, and critical thinking skills.
Checklist	**Visuals:** 1. Are the visuals high-resolution and realistic? 2. Is the virtual environment visually appealing and immersive? **Auditory Experience:** 1. Are sound effects used to enhance the virtual environment and interactions? 2. Is there clear and synchronised narration or explanations for educational content? **Haptic Feedback:** 1. Does the application provide haptic feedback through the wearable device? 2. Does the feedback feel realistic and accurately convey the intended sensations? 3. Is haptic feedback appropriately synchronised with the visual and auditory elements? **Gesture and Motion Tracking:**

Table 4.6 continued

	1. Does the wearable device accurately track the user's movements and gestures? 2. Is the tracking responsive and seamless, providing a natural and intuitive experience? **Olfactory Stimulation:** 1. If applicable, does the application incorporate scents or smells to enhance the virtual environment? 2. Are the scents appropriately synchronised with the educational content and virtual scenarios? 3. Is using olfactory stimulation safe and considerate of user preferences and sensitivities?
ID	**WVREA 3**
Name	**Realistic Feedback**
Definition	It refers to providing users with responses and interactions that resemble those encountered in the real world. It involves creating a sense of presence and authenticity by simulating the consequences of users' actions and enabling them to receive feedback that mirrors real-world scenarios.
Explanation	The application must provide users with information about their actions, both during and after their input. This ensures that users have enough depth and position cues while manipulating 3D objects. They receive feedback that simulates how things behave or respond in the real world.
Example(s)	Subtle lighting effects, realistic shadow, or different degrees of transparency.
Benefit(s)	Realistic feedback could create an immersive learning experience through experiential learning, error correction, retention, and transferable skills, which are all important components of a successful learning experience.

Table 4.6 continued

Checklist	**Sensory Integration:** 1. Do the visual, auditory, and haptic feedback elements work together to create a coherent, immersive experience? **2.** Is there consistency between the sensory feedback and the actions performed by the user? **Accurate Physics Simulation:** 1. Do objects behave realistically when users interact with them (e.g., proper weight, collision detection, and response? **Real-Time Responsiveness:** 1. Does the application provide immediate feedback in response to user actions? 2. Is the feedback synchronised with the user's interactions, ensuring a seamless and natural experience? 3. Are there minimal delays or latency between user input and the corresponding feedback? **Contextual Relevance:** 1. Does the feedback provided align with the specific educational context and objectives? 2. Are the responses and interactions relevant to the subject matter being taught?
ID	**WVREA 4**
Name	**Object selection:** Nonisomorphic (Non-Realistic magic technique)
Definition	It refers to the process of choosing or interacting with virtual objects in an unnatural way that deviates significantly from strict realism within the VR environment.

Table 4.6 continued

Explanation	Nonisomorphic object selection technique refers to unconventional and imaginative ways of selecting objects that deviate from traditional real-world interaction.
Example(s)	Enlarging the user's virtual arm, increasing the size of the selection tool, Virtual pointing by using ray casting, Grabbing, Grasping and Clutching by using Go-go, Virtual Pads, Friction Surface, PRISM, Adaptive pointing, Aperture selection (uses a cone as a selection tool and allows users to adjust its apex angle manually)
Benefit(s)	It allows the user to select objects beyond their area of reach precisely and requires relatively less physical movement.
Checklist	1. Are the selected objects easily accessible and interactable in virtual reality? 2. Is there any instruction or tutorial on interacting with and manipulating the object effectively? 3. Are the instructions or tutorials clear? 4. Is the object selection aligned with established pedagogical principles and instructional strategies?
ID	**WVREA 5**
Name	**Object Selection: isomorphic** (Realistic magic technique)
Definition	The selection of an object in a way that mirrors real-world behaviour.
Explanation	Object selection is acquiring or identifying a particular object or subset of objects from the entire set of objects available naturally.
Example(s)	Picking or grabbing up one or more objects with a virtual hand (3D cursor: sphere, cube, and hand avatar, pointing to one or more objects by using Bubble-cursor, Silk Cursor, Ray Casting (a ray or a cone), Direct image plane, Eye-gazed selection, Viewfinder, etc.

Table 4.6 continued

Benefit(s)	The selection technique allows the learner to select naturally, visualise, explore, and understand the object more effectively.
Checklist	1. Is the object selection seamless and natural for the user? 2. Are there any visual or auditory feedback mechanisms? 3. Is the feedback unambiguous? 4. Is there any support for alternative input methods, such as voice commands or adaptive controllers, to enable users with disabilities to interact effectively with the virtual reality environment? 5. Is there any error handling mechanism to handle situations where object recognition or selection fails?
ID	**WVREA 6**
Name	**Object Manipulation: Nonisomorphic**
Definition	This technique enables users to manipulate objects in ways distinct from the physical world while ensuring usability and performance.
Explanation	This departure from strict realism introduces virtual tools with extraordinary capabilities, including, and more, offering users a sense of 'magical' interaction."
Example(s)	disassembling and reassembling, resizing, stretching or morphing using laser beams, rubber arms, voodoo dolls, Go-Go
Benefit(s)	A flexible virtual environment enables creative exploration and experimentation, providing unique learning opportunities.
Checklist	1. Are the controls and gestures intuitive and easy to understand? 2. Does the application provide users with feedback when manipulating objects non-isomorphically?

Table 4.6 continued

ID	WVREA 7
Name	**Object Manipulation: Isomorphic**
Definition	It is an authentic interaction that enables users to interact with the objects in a manner that closely resembles real-world interactions.
Explanation	An interaction technique precisely designed for 3D environments results in a virtual reality experience that can be perceived as an enhanced version of reality.
Example(s)	Deformation, Reaching, grabbing, grasping, moving, clutching, and orienting objects by single virtual hand, Rigid-Body Fingers-based grasping technique, Soft-Body Finger, God Fingers.
Benefit(s)	It will allow users to examine and learn the object or the VE, which may improve user performance and improve learning with a sense of presence and immersion, leading to user enjoyment more accurately.
Checklist	1. Can the user perform a variety of manipulations, such as rotation, translation, scaling, and assembly? 2. Are there any restrictions on object manipulation, such as limits on rotation angle or collision avoidance? 3. Are there multiple ways for users to manipulate objects, catering to different preferences and accessibility needs?

Table 4.6 continued

ID	**WVREA 8**
Name	**Avatar's customisation**
Definition	It refers to users' ability to personalise and modify the appearance and features of their virtual representation, often known as an avatar. It enables individuals to establish a unique and personalised virtual identity that represents them in the virtual world.
Explanation	It enables individuals to establish a unique and personalised virtual identity that represents them in the virtual world.
Example(s)	Customising voice characteristics, body shape and proportions, facial features, clothing, accessories, personal style, and avatar movements such as walking, running, sitting, and gesturing. In addition, users can switch between first and third-person viewpoints, and this can help some people experience less cybersickness, a condition that has symptoms like motion sickness (headache, nausea, dizziness, and clamminess) (Rebenitsch & Owen, 2016)
Benefit(s)	It enables users to develop a virtual representation corresponding to their preferences, identities, and preferred levels of self-expression, increasing their engagement and sense of presence in the virtual environment.
Checklist	1. Does the application provide various customisation options to accommodate various customer preferences? 2. Are the tools for avatar customisation user-friendly? 3. Does the VR application provide real-time feedback for users as they customise their avatars?
ID	**WVREA 9**
Name	Collaborative learning
Definition	It refers to a method of education in which several people engage and learn together in a shared virtual environment.

Table 4.6 continued

Explanation	Collaborative learning in VE includes features that allow learners to engage, share ideas, and work together towards a common objective.
Example(s)	Collaborative learning elements include instructor facilitation tools, team-based challenges or games, shared whiteboards or canvas, and multi-user environments.
Benefit(s)	Students engage in discussions, problem-solving, and hands-on activities to gain a deeper understanding and retention of knowledge.
Checklist	1. Does the VE allow multiple users to join the same virtual reality session and interact with each other in real time through seamless communication, such as voice chat, gestures, or text-based communication, to facilitate collaboration among learners? 2. Does the virtual environment accommodate multiple users simultaneously so that they can move, interact with objects, and engage in activities together? 3. Does the VE implement effective communication tools, such as voice chat, text chat, or hand gestures, that enable users to interact and exchange ideas to facilitate seamless communication and collaboration? 4. Does the VE support collaborative activities and tools such as shared whiteboards, project-based tasks, problem-solving activities, or group discussions promoting teamwork and active user engagement? 5. Does the VE support features that allow for shared object manipulation, such as joint object handling or synchronised interactions, to support collaborative learning experiences?

Table 4.6 continued

ID	WVREA 10
Name	**Clarity**
Definition	Clarity means that language, system messages, and commands should be labelled and concisely. The intended functionality, activity and tasks should be set appropriately.
Explanation	The labelling for the commands, language used, and system messages should be simple and easy for users to understand. Real-world examples relate the desired features to everyday objects. The user's activity and tasks are based on relevant settings, making the system practical.
Example(s)	Clear and concise language and labelling for commands, system messages are constructively, and real-world experiences are mapping desired functionality to everyday items. Relevant settings suggest user activity and tasks, and the system is compatible with the real world.
Benefit(s)	It improves user experience, enables faster task completion, facilitates real-world transferability, reduces errors, and increases accessibility.
Checklist	1. Is the VR application's language for commands and instructions clear and concise? 2. Are the labels for buttons, menus, and interactive elements descriptive and easily understandable? 3. Are the system's messages and feedback helpful in resolving issues or errors? 4. Is the language used encouraging and providing positive reinforcement that can motivate learners and enhance their learning experience? 5. Do the objects and activities within the virtual environment use familiar settings that mirror real-world experiences

Table 4.6 continued

	and make the learning content relatable?
ID	**WVREA 11**
Name	**Design for User Experience (UX)**
Definition	VR educational applications should be designed with the user experience (UX) in mind, catering to learners of varying proficiency levels.
Explanation	A well-designed VR educational experience considers the needs of users at different skill sets. This means providing features and functionalities that: 1. Support exploration and discovery: Allow learners to explore the VR environment at their own pace and discover new information independently. 2. Offer scaffolded learning: Provide structured guidance and support for beginners, gradually increasing complexity as skills develop. 3. Enable mastery: Offer opportunities for advanced learners to challenge themselves and delve deeper into specific topics.
Example(s)	1. Tailored Learning Paths: The VR application could offer two main learning paths: a beginner track with pre-defined lessons and activities that introduce core concepts in a step-by-step manner, and an advanced track that allows users to skip introductory material and focus on specific topics or delve deeper into complex areas.

Table 4.6 continued

	2. Progressive Scaffolding: For novice users, the VR experience might provide guided tours with clear instructions and highlighted points of interest. As users progress through the lessons or activities, the level of scaffolding can gradually decrease, encouraging independent exploration and discovery.
Benefit(s)	1. Tailored learning: By catering to individual needs, VR education can become more engaging and effective. 2. Increased accessibility: A well-designed UX can make VR education more accessible to a wider range of learners, regardless of their prior knowledge or experience. 3. Improved learning outcomes: By personalising the learning experience, VR apps can optimiwe knowledge retention and skill development.
Checklist	1. Multiple Learning Paths: Does the VR application offer different learning paths or difficulty levels that users can choose from based on their proficiency? 2. Progressive Scaffolding: Does the application provide instructional scaffolding, such as tutorials, hints, or guided activities, to support novice users? 3. Mastery Opportunities: Does the VR experience offer challenges, complex tasks, or opportunities for independent exploration for advanced learners? 4. Personalization Options: Can users customise their VR experience by adjusting settings like speed, difficulty, or the level of guidance provided?

Table 4.6 continued

ID	WVREA 12
Name	**Curriculum aligned content**
Definition	It refers to educational material or content, experiences, and activities directly corresponding to a specific school curriculum's learning objectives, topics, and standards.
Explanation	It ensures that the virtual reality experiences supplied by the app are directly related to the academic content the students are meant to learn.
Example(s)	Students can virtually examine, visualise and understand microscopic organisms, witness biological processes in action, or even simulate ecological experiments.
Benefit(s)	1. Alignment with educational goals ensures that the VR application addresses the specific learning outcomes, skills, and knowledge that students are expected to acquire. Educators can design assessments and track learning outcomes within the VE environment, providing valuable insights into individual student achievements and identifying areas that require further attention. 2. It may be smoothly integrated into educators' lesson planning and instructional strategies. 3. This can help the students to understand complex principles and encourage problem-solving skills.
Checklist	1. Do the VR application’s content and activities align with the curriculum's learning objectives? 2. Do the VR experiences and interactions support acquiring knowledge and skills outlined in the curriculum?

Table 4.6 continued

ID	WVREA 13
Name	**Learning measurement**
Definition	It refers to assessing, evaluating, and quantifying the VR application's learning outcomes, engagement levels, and effectiveness in facilitating learning experiences.
Explanation	The VR apps provide tools for assessing the knowledge and skills acquired by learners, measuring their engagement in the VR environment, and facilitating effective learning.
Example(s)	It includes quizzes, assessments, simulations, or performance-based tasks that provide data on learners' achievements, strengths, and areas for improvement.
Benefit(s)	1. It enables educators to assess and evaluate students' learning outcomes based on their performance, knowledge acquisition, and skills within the VR environment. 2. Learning measurement tools provide real-time feedback, engaging learning, self-reflection, motivation, skill development, and reinforcement to help students understand their strengths and areas for improvement, adjust, and learn more effectively.
Checklist	1. Does the VR application integrate learning measurement to evaluate learners' progress and understanding of the curriculum-aligned content? 2. Does the VR application include formative and summative learning measurement components that provide feedback and track learners' performance?

Table 4.6 continued

ID	**WVREA 14**
Name	**Accessibility**
Definition	It refers to the design and implementation of features that enable learners with diverse abilities and needs to access and engage with the application's content and functionalities.
Explanation	The application provides an educational experience that is inclusive and usable for people with disabilities or other limitations.
Example(s)	For visual accessibility, the VR application provides alternative text or audio descriptions for visual content, offers high contrast options, or implements customisable font sizes.
Benefit(s)	This application can create an inclusive learning environment where users with diverse abilities can fully participate and benefit from the educational content and experience.
Checklist	1. Does the VR application provide adjustable font sizes and high contrast options? 2. Does the VR application use colour combinations that are accessible for users with colour blindness? 3. Does the VR application include captions or subtitles for all audio content within the VR experience? 4. Does the VR application provide volume controls and the option to adjust audio settings? 5. Are the instructions clear and step-by-step?

Table 4.6 provides a detailed breakdown of each heuristic to ensure its effective application within the WVREA evaluation context. This breakdown includes clear definitions and explanations of each heuristic's purpose and its specific relevance to WVREA usability. It also presents illustrative examples demonstrating how to apply each heuristic to identify potential usability issues and discusses the benefits of adhering to each heuristic during the evaluation process. It includes a practical checklist, where relevant, to assist evaluators during assessments. By offering this comprehensive documentation, the table enhances the clarity, usability, and effectiveness of the newly developed WVREA heuristics, making them more accessible for practical use in future evaluations.

Table 4.7 addresses Research Question 2 (RQ2).

Table 4.7 Set of usability heuristics for WVREA

ID	Name
WVREA 1	Aligned Representation for Virtual Agents in VR Education.
WVREA 2	Engages various sensory experience
WVREA 3	Realistic Feedback
WVREA 4	Object Selection: Non-isomorphic (Non-Realistic magic technique)
WVREA 5	Object Selection: Isomorphic (Realistic)
WVREA 6	Object Manipulation: Non-isomorphic (Non-Realistic magic technique)
WVREA 7	Object Manipulation: Isomorphic (Realistic)
WVREA 8	Avatar's customisation
WVREA 9	Collaboration
WVREA 10	Clarity
WVREA 11	Design for User Experience (UX)
WVREA 12	Curriculum aligned content
WVREA 13	Learning measurement
WVREA 14	Accessibility

4.1.7 Stage 7: Validation stage

4.1.7.1 First Experiment: Expert Judgement Survey

In the first experiment, twenty-five experts assessed the usability of the newly developed WVREA heuristics. The survey focused on four key dimensions: Utility (usefulness), Clarity (understandability), Ease of Use (application during evaluation), and the Necessity of additional Checklist. The overall findings, as detailed in **Table 4.8**, were positive.

Table 4.8 Average scores of evaluators' perception of WVREA

Heuristics	D1 (Utility)	D2 (Clarity)	D3 (Ease of use)	D4 (Need for Additional Checklist)	Mean (Each WVREA)
WVREA1	4.0	3.92	3.76	3.72	**3.9**
WVREA2	4.24	4.16	4.0	3.52	**4.0**
WVREA3	4.24	4.16	3.96	3.6	**4.0**
WVREA4	4.0	4.0	3.88	3.84	**4.0**
WVREA5	4.2	4.08	3.88	3.6	**3.9**
WVREA6	4.12	4.0	3.92	3.8	**4.0**
WVREA7	4.16	4.12	3.8	3.6	**3.9**
WVREA8	3.64	3.84	3.92	3.56	**3.7**
WVREA9	4.36	4.16	4.0	3.48	**4.0**
WVREA10	4.12	4.2	4.04	3.28	**3.9**
WVREA11	4.24	3.96	3.88	3.8	**4.0**
WVREA12	3.92	4.16	3.96	3.76	**4.0**
WVREA13	4.08	4.28	3.88	3.56	**4.0**
WVREA14	4.28	4.12	3.96	3.44	**4.0**
Mean of Each Dimension	**4.1**	**4.1**	**3.9**	**3.6**	**3.9**

The heuristics received high scores across multiple evaluation dimensions, with both Utility (D1) and Clarity (D2) exceeding an average of 4.1. Ease of Use (D3) also scored favourably at 3.9, approaching a 4. Additionally, the perceived need for an additional checklist dimension (D4) was comparatively lower, with and average score of 3.6.

Descriptive Statistics

	Mean	Std. Deviation	N
Mean_Utility	4.1143	.38410	25
Mean_Clarity	4.0829	.34112	25
Mean_EaseOfUse	3.9171	.53000	25
Mean_NeedAdditionalChecklist	3.6114	.76545	25

Figure 4.1 Mean perception of overall WVREA usability heuristics

The expert validation survey assessed the average usability scores and explored the relationships between expert perceptions using correlation coefficients. The findings are visualised in **Figure 4.1** and further analysed in the following subsections.

4.1.7.1.1 High Ratings for Utility and Clarity

The participants provided highly positive feedback on the newly developed heuristics, particularly their utility. With an average rating of 4.1 out of 5 on the utility dimension (**Figure 4.1**), the heuristics were considered very useful. Similarly, the clarity dimesion received an equally strong average score of 4.1 out of 5. This indicates that the heuristics were easily understood and clear to most participants. The ratings were consistent, with the majority of the agreeing on the clarity and usefulness, as evidenced by the ratings clustering around the average.

4.1.7.1.2 Positive Feedback on Ease of Use, Mixed Views on Checklists

The ease-of-use dimension received an average rating of 3.9 out of 5, suggesting that participants generally found the heuristics is easy to apply. However, there were some variations in opinion, with some finding them easier to use than others. The need for an additional checklist received an average rating of 3.6 out of 5. This suggests a moderate need for checklists to complement the existing heuristics. However, the ratings showed significant variability. Some participants felt strongly about the need for additional checklists, while others found them unnecessary.

Correlations

		Mean_Utility	Mean_Clarity	Mean_EaseOfUse	Mean_NeedAdditionalChecklist
Mean_Utility	Pearson Correlation	1	.809**	.602**	-.420*
	Sig. (2-tailed)		<.001	.001	.036
	N	25	25	25	25
Mean_Clarity	Pearson Correlation	.809**	1	.636**	-.231
	Sig. (2-tailed)	<.001		<.001	.266
	N	25	25	25	25
Mean_EaseOfUse	Pearson Correlation	.602**	.636**	1	-.066
	Sig. (2-tailed)	.001	<.001		.754
	N	25	25	25	25
Mean_NeedAdditionalChecklist	Pearson Correlation	-.420*	-.231	-.066	1
	Sig. (2-tailed)	.036	.266	.754	
	N	25	25	25	25

**. Correlation is significant at the 0.01 level (2-tailed).

*. Correlation is significant at the 0.05 level (2-tailed).

Figure 4.2 Correlation Coefficients for average perception scores among WVREA heuristics

4.1.7.1.3 Correlations Reveal Interesting Relationships

Figure 4.2 explores the correlations between user perceptions of the different dimensions. The analysis revealed several interesting relationships:

1. Strong Positive Correlations: A significant positive correlation exists between utility and clarity (correlation coefficient of .809) and ease of use (correlation coefficient of .602). This indicates that participants who found the heuristics more useful also perceived them as clearer and easier to use.
2. Weak Negative Correlation: A weak negative correlation exists between utility and needing an additional checklist (correlation coefficient of -.420). This suggests that participants who found the heuristics highly useful were less likely to feel the need for additional checklists.
3. Positive Correlation for Clarity and Ease of Use: A significant positive correlation exists between clarity and ease of use (correlation coefficient of .636). This indicates that participants who found the heuristics clearer also perceived them as easier to use.
4. No Significant Correlations: There were no significant correlations between clarity and the need for an additional checklist (correlation coefficient of -.231) or between ease of use and the need for an additional checklist (correlation coefficient of -.066). This suggests no clear connection between user perceptions of clarity or ease of use and the need for checklists.

These findings offer valuable insights into UX with the newly developed WVREA heuristics. The strong positive correlations between utility, clarity, and ease of use suggest a cohesive design that effectively balances usability with achieving the intended goals. The mixed views on checklists warrant further investigation into user preferences and potential design improvements.

4.1.7.1.4 Overall UX with the Evaluation Process

Descriptive Statistics

	N	Mean	Std. Deviation
Easiness: How easy it was to perform the expert evaluation, based on this set of usability/UX heuristics?	25	4.08	.400
Intention: Would you use the same set of usability/UX heuristics when evaluating similar software product in the future?	25	3.96	.455
Completeness: Do you think the set of usability/UX heuristics covers all usability aspects for this type of software product?	25	4.16	.374
Valid N (listwise)	25		

Figure 4.3 Average perception of overall WVREA usability heuristics

Figure 4.3 illustrates the overall UX of the WVREA usability heuristics. It focuses on three aspects:

1. Ease of Evaluation: The experts rated the ease of performing the expert evaluation process highly, with a mean score of 4.08, indicating that they found it user-friendly. The low standard deviation of 0.4 suggests that the responses from the experts were consistently similar, supporting the assessment of ease in the evaluation process.
2. Intention for Future Use: The experts demonstrated a strong intention to apply the same set of heuristics to evaluate similar applications in the future. The mean score for this intention was 3.96, with a low standard deviation of 0.455, suggesting that the experts' ratings were largely consistent. This consistency indicates a significant potential for the broader adoption of these heuristics when assessing similar software products in the future.

3. Heuristic Completeness: The experts highly perceived the heuristics' completeness in addressing all usability aspects of WVREA. With a mean score of 4.16 and a low standard deviation of 0.375, the consistency of the ratings indicates a strong consensus among the experts. This high average suggests that most experts agree on the comprehensiveness of the heuristics.

4.1.7.2. Second Experiment: Validation through heuristic evaluation (with the experts)

For the second experiment, the experts conducted a series of heuristic evaluations on WVREA based on the newly developed heuristics and identified issues while using three selected WVREA: Titans of Space PLUS, The Big Table and The Body VR. A summary of the number of problems identified by the experts is presented in **Table 4.9**.

Table 4.9 Summary of Heuristic Evaluation Results

The Severity of Usability Problems	Number of Problems Identified
Titans of Space plus WVREA	
4 = Usability Catastrophe	13
3 = Major Usability Problem	13
2 = Minor Usability Problem	14
1 = Cosmetic Problem Only	3
Total problems identified	43
The Big Table	
4 = Usability Catastrophe	13
3 = Major Usability Problem	14
2 = Minor Usability Problem	7
1 = Cosmetic Problem Only	1
The problems identified	35
The Body VR	
4 = Usability Catastrophe	7

Table 4.9 continued

3 = Major Usability Problem	13
2 = Minor Usability Problem	7
1 = Cosmetic Problem Only	0
The problems identified	27

Evaluators identified forty-three problems for Titans of Space Plus. Thirteen of these issues were rated 4 (Usability catastrophe), indicating a critical need for resolution before the product could be considered for release. Additionally, thirteen problems received a rating of 3, signifying major usability issues requiring significant attention. Most of the identified usability issues fall into the category of minor usability problems (14). However, only three usability problems are classified as cosmetic issues.

The Big Table VR app had thirty-five usability problems identified. Thirteen issues required crucial fixes before the product could be released (rated 4), fourteen were rated major usability problems (3), seven were rated 2, indicating minor usability problems, and one issue was considered solely a cosmetic problem.

Twenty-seven usability issues were identified in The Body VR app. Seven were classified as usability catastrophes, thirteen were categorised as major usability problems, and seven were labelled as minor usability issues. Notably, no usability problems were classified as cosmetic issues.

Findings from the evaluation of the three VR apps indicate that all the issues identified by both the academician and the experts could be mapped using WVREA heuristics, as shown in **Table 4.10**, **Table 4.11**, and **Table 4.12**.

Table 4.10 Usability issues in Titans of Space PLUS apps with severity ratings and its corresponding WVREA heuristics

Evaluators	Usability Issues	Severity Ratings	WVREA
E1	There is no clear instruction on how to teleport	4	4
	The app did not warn/tell user something is wrong when user made mistake	3	4
	No instruction on how to operate the spaceship.	3	4
E2	Meaningless icon	4	10
	Selection too difficult	4	4
	Manipulation too difficult	4	4
	Unstructured interface	4	10
E3	Choosing the color not proper	4	10
	No clear instruction	4	10
	No collaboration (only one way communication)	4	9
	Designing the environment needs improvement	4	1
E4	No assessment to test the user knowledge understands	3	13
	Exit button should be display at the menu but only visible in setting	3	10
	Controller navigation button at home is not label properly. User will confuse.	2	10
	The app is non-collaborative due to the user has no interaction with other user	4	9
E6	No Metaverse ability/interaction - latest trend in VR	3	9
	No quizes/assessment for users	3	13
	User Interface - aesthetic value, less trendy	1	10
	User Interface- icon not organised	2	10
	Flow of information - needs guidance	3	10
E7	Content interface (guideline during the program e.g exit button, back button)	2	10

Table 4.10 continued

E8	Program flow and interactive functions well coordinate, but need more simplified function (such as backtract, exit)	2	10
E9	No exit button	2	10
	No instruction given to the user	2	4
	No flow	2	4
E10	No exit button	3	10
	Exit button should be display at the menu but only visible in setting	3	10
	Ready button and next button has the same function	3	10
	icon meaningless	4	10
E11	icon meaningless	2	10
E12	No exit button	4	10
	No clear instruction on how to manipulate the object	4	4
	Meaningless icon	4	10
	No assessment to test the user knowledge understands	4	13
13	A navigation button should be on the controller	2	10
	more interactable option	2	4
E14	Need a simple tag on every button of plane	1	10
E15	The finger animation did not show that the finger is positioned ontop of the button for "oculus"	3	14
	The legibility of the words at the controller was a bit blurry, especially for the word 'Oculus' since it was written in purple font colour	2	3
E16	icon meaningless	3	10
	No assessment to test the user knowledge understands	2	13
	no previous or exit button	3	10
	quit button is not at the right interface	1	10
	No collaboration (only one way communication)	2	9

Table 4.11 Usability issues in The Big Table apps with severity ratings and its corresponding WVREA heuristics

Evaluators	Usability Issues	Severity Ratings	WVREA
E3	Find difficult to teleport	4	4
	Usability problem	4	10
	Instruction for the first time user not clear	4	10
E4	No guideline to perform the task	4	10
	Not user friendly	2	10
	No exit button	3	10
	controller navigation is not properly labelled	3	10
	non-collaborative	4	9
E7	No Flow - unable to see the big picture	3	10
	usability of content function (didn't have proper instruction)	3	10
E8	Unorganise program flow	3	10
	Preferable simplified the development and interative features	3	11
E10	No exit button	4	10
	There is no instruction on how to perform the experiment	4	10
	The arrangement of the models is unstructured	2	10
	hard to understand the task	3	11
E11	No clear instruction	2	10
	Button is not really functioning	3	4
E12	hard to understand the task	3	11
	Instruction for the first time user not clear	3	10
	No exit button	3	10
E14	The caption is too high	2	10
E15	There were robots that shouldn’t be picked up and placed at the burner, but I did it anyway because there wasn't any constraint to the robot itself	1	4
E16	No instruction in order to perform the task	3	10
	No Quit button	2	10
	No assssment	2	13
	Not user friendly	2	10

Table 4.12 Usability issues in The Body VR apps with severity ratings and its corresponding WVREA heuristics

Evaluators	Usability Issues	Severity Ratings	WVREA
E4	No exit button to quit the app	3	10
	The option to select the level is too confusing. No proper instruction for user	4	10
	not user friendly due to the location of the button/option is not suitable	2	10
	No assessment to test user knowledge understanding	4	13
	The controller's button not fully utilize. Only 1 button can be used	3	4
	non-collaborative	4	9
E5	Users will lose focus if they must glance up and down to view the name or shape of each designated item or object.	3	10
	A minimap could help users comprehend where they are in the blood artery.	2	10
	Labelling some of the essential things or objects that are floating or moving may assist users in better understanding.	3	10
	Missing pause or play back button from a certain topic	2	10
E8	Very less interactive and control of program environment	3	2
	Positioning of interactive instruction at user's eye level area	3	10
	Reduce serious elements to ensure user's enjoy the content	2	10
E10	No next or previous button	3	10
	Can't teleport	4	4
	No assessment to test user knowledge understanding	3	13
E11	less interactive	3	2
	No clear instruction	3	10
	the menu button is too low - located at the bottom	2	10
E12	No next button	3	10
	No exit button	4	10
	No assessment to test user knowledge understanding	4	13
	less interaction with the object	3	2

Table 4.12 continued

E15	The displayed information was a bit lower than usual gaze position, causing me to bend down a bit	2	10
	The options for Main menu reorientation, etc. was too low and was too close together, causing me to have to be in an awkward position (neck pain)	3	10
E16	Not interactive	4	2
	menu or button are not at the right position	3	10
	No assessment to test user knowledge understanding	3	13
	not user friendly due to the location of the button/option is not suitable		10

4.1.7.3 Third experiment: Validation through Heuristics Evaluation (with schoolteachers)

The reason for selecting science schoolteachers was their prior knowledge of the science content and the types of usability defects that might arise during the learning activities. Most of the usability issues identified in this evaluation were already identified during heuristic evaluation, such as the absence of a quit button, lack of instruction provided to the user, and menu setting issues.

Table 4.13 Summary of Heuristic Evaluation Results

The Severity of Usability Problems	**Number of Problems Identified**
Titans of Space PLUS	
4 = Usability Catastrophe	8
3 = Major Usability Problem	5
2 = Minor Usability Problem	4
1 = Cosmetic Problem Only	4
Total problems identified	21

For Titans of Space Plus, the schoolteachers identified twenty-one problems. Eight were rated as 4 (usability catastrophe), indicating a critical need for resolution before the product could be considered for release. Additionally, five problems received a rating of 3, signifying major usability issues requiring significant attention. Four of the identified usability issues fall into the category of minor usability problems. However, only four usability problems are classified as cosmetic issues. All the identified issues were successfully mapped using the WVREA heuristics.

Table 4.14 Summary of usability issues with the severity ratings and corresponding heuristics

Users	Usability Issues	Severity Ratings	WVREA
User1	need more information if the students need more info	2	11
	motion sickness	2	11
	lot of unnecessary information that might affect the learning objectives	3	12
	no assessment given in the app	3	13
	no BM version	4	11
User2	Hard to adjust the volume button - not accurate	2	10
User3	No issues	-	-
User4	no problem	-	-
User5	audio in Bahasa Melayu	4	11
	The select button (up and down arrow) should be visible in the VR interface	4	10
User6	No quizes or assessments to assess student's understanding	4	13
	the language should be simple and easy to understand	4	11
	the content should aligned with the syllabus	4	12
User7	No Quit button	1	10
User8	No issues	-	-

Table 4.14 continued

User9	More clues/instruction given (arrow, speech bubbles, etc.)	1	10
	The menu on the controller should be accessible/seen easily	1	10
User10	Hard to grab the object	1	11
User11	The menu button on the controller hard to find	4	10
User12	No Exit button	2	10
User13	Hard to find the quit button	4	10
	Should align with the curriculum content	3	12
User14	The VR app is not aligned with the school curriculum content	3	12
User15	Must have minimap for guidelines	3	10

All the usability issues identified during the evaluation were successfully mapped with the newly developed heuristics, as illustrated in **Table 4.14**. Notably, issues related to content alignment with the syllabus or curriculum (19%) and the need for assessment (10%) were successfully mapped to the new heuristics created by the researcher in this study, specifically WVREA12 and 13. These issues were also identified during expert validation. This highlights the significance of specific-domain heuristics as essential guidelines for developing effective WVREA in the future. The findings from this evaluation complemented those conducted in phase two and the expert judgment evaluation from phase one. Schoolteachers, equipped with content knowledge and pedagogical skills, provided valuable insights that could be incorporated into the design of VR education apps. Their feedback highlighted desirable features of effective VR apps, such as language appropriateness, content alignment with the curriculum, and essential learning measurements that could be integrated into VR educational apps. Significantly, the aim of heuristic evaluation extends

beyond merely assessing usability; it also encompasses the overall UX, including users' emotions, beliefs, preferences, comfort, behaviours, and accomplishments throughout the entire interaction process, as outlined in International Organization for Standardization (2018).

Figure 4.4 illustrates the similarities and differences found in the HE conducted by experts and schoolteachers. This comparison highlights the significance of incorporationg user perspectives to enhance the effectiveness of the WVREA heuristic.

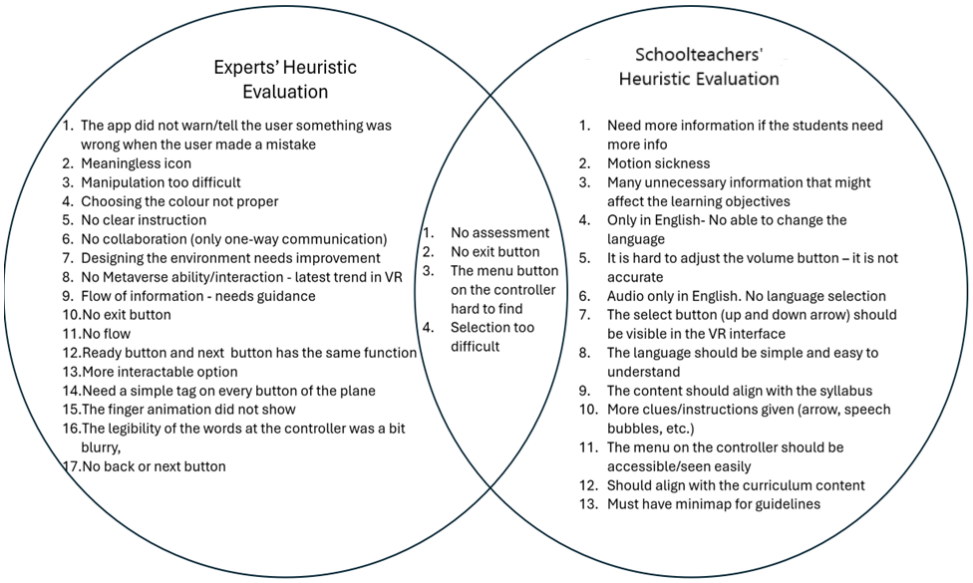


Figure 4.4 Comparing Similarities and Differences in HE both by the experts and schoolteachers

The schoolteacher specified all the essential features a WVREA should include, as outlined in **Figure 4.4**. Based on the proposed features, the researcher applied the thematic analysis method (Thomas, 2006). This method enabled the researcher to derive findings from the most frequent, dominant, or significant themes. The identified themes included accessibility, curriculum alignment, language options and interactive features.

Table 4.15 WVREA Suggested Features by the Teachers

Users	Suggested Features
User1	Offline version
User2	The VR app must align with the science curriculum/science for primary school.
	More fun activities.
User3	Must have BM version as an alternative.
	VR apps should let users ask their avatar questions and get quick replies.
User4	It must have an offline version.
User5	It must have an offline version.
User6	Must have user tutorial.
	Must have online and offline versions.
	It must be in a dual language.
	Must have assessments such as quizzes.
	It must align with the curriculum content.
User7	Dual language BM and BI.
User8	Dual language BM and BI and on par with DSKP.
User9	The menu on the controller is accessible on VR interface.
	More clues are given (arrows, speech bubbles, etc.) while touring the VR apps.
	Apply the bilingual for needy students.
User10	More clues or guidance or instruction given to the users
	No motion sickness
User11	Use the Malay language.
User12	Use dual language for science subjects.
User13	The language used was Bahasa Melayu in particular.
User14	Offline version
User15	Must have an offline version

These themes highlight several critical issues regarding the current limitations of WVREA. Notably, language options (53.3%) emerged as a major concern, particularly the

need for inclusivity and cultural relevance, focusing specifically on Bahasa Melayu. According to teachers, many of their students struggle with English comprehension, and they found that learning in Bahasa Melayu enhances understanding and engagement. Closely following language options was the an offline accessibility (33.3%), driven by frequent interruptions in internet accessibility at their schools. Additionally, there was a strong demand for interactive features (33.3%), reflecting that passive learning experiences are insufficient and highlighting the importance of active learning. Finally, the need for alignment with curriculum standards (20%) indicates a need for digital resources that comply with the curriculum content, thereby facilitating the achievement of learning objectives.

The results obtained from both heuristic evaluations indicate the effectiveness of the WVREA heuristics in identifying issues related to WVREA. These assessments have addressed research question 3 (RQ3).

4.1.8 Stage 8: Refinement stage

During this evaluation, all usability issues reported by the participants can be mapped successfully with the newly developed heuristics. Therefore, no modification has been made to the newly developed heuristic for this domain. Since we could address all usability issues using WVREA heuristics, performing this stage is unnecessary. Therefore, the final set of new heuristics (WVREA) remains at 14.

4.2 Significant contribution

The heuristic development employed in this study has resulted in a novel set of usability heuristics for WVREA, consisting of 14 items. The researcher validated these heuristics using three WVREA. It shows their effectiveness in identifying various usability issues within the domain.

CHAPTER 5

DISCUSSION

This chapter discusses the limitations of heuristics used to evaluate WVREA and presents the development of new domain-specific heuristics. It also assesses the effectiveness of these newly developed heuristics in identifying usability issues related to the research questions of this study.

5.1 The Limitations of current heuristics used to evaluate WVREA

These observations lead to the first research question (RQ1), which is: How can the limitations of current heuristics for evaluating WVREA be identified and addressed, considering their effectiveness, user-friendliness, and alignment with specific goals, tasks and learning contents? To address RQ1, the researcher reviewed the existing literature and identified five studies that focus on the potential of VR in education (i.e. Botha et al., 2021; Minocha & Hardy, 2011; Moore et al., 2020; Young et al., 2020; Zulkifli et al., 2014). Of these, three studies utilised wearable devices like the Oculus Rift, HTC Vive, and Oculus Go, while two employed desktop systems. This research will focus solely on wearable devices.

The researcher examined the limitations of wearable-based studies focusing on Botha et al. (2021), Young et al. (2020) and Moore et al. (2020). The analysis revealed that these studies used general heuristic, which had significant limitations. For example, Botha et al. (2021) employed Nielsen and Molich's (1990) heuristics, which failed to identify some educational issues, such as incorrect results for arterial blood gases and the lack of

clarification regarding room air or oxygen therapy. They also noted the need for a patient's face to show a blue discolouration (cyanosis) to indicate a lack of oxygen".

Based on these findings, the researcher proposed that issues such as "the need for a patient's face to show a blue discolouration (cyanosis) to indicate a lack of oxygen" could be better addressed by implementing the Realistic Feedback guideline from the WVREA 3 framework. This guideline prioritises providing users with feedback and interactions that closely mimic real-life scenarios, surpassing the limitations of Nielsen and Molich's (1990) heuristics. Additionally, issues such as "incorrect results for arterial blood gases and the absence of clarification whether the results were taken with room air or oxygen therapy" align with WVREA 12: Curriculum: Aligned Content, ensuring that VR experiences directly relate to the academic content.

Furthermore, Moore et al. (2020) identified five critical design considerations for VR applications: affordance, agency, diverse input modalities, mental models, and advanced roles. However, the researcher argues that educational apps should incorporate additional features beyond these considerations. Moreover, the small sample sizes in Moore et al.'s study limit the generalisability of findings. In contrast, Young et al. (2020) proposed eight heuristics to evaluate students' attitudes and behaviours towards VR in the classroom, focusing on specific VR use cases and student populations. However, their study failed to assess actual learning outcomes.

These results support Rusu et al.'s (2011) assertion that non-domain-specific heuristics often fail to capture domain-specific usability issues. There is a notable absence of heuristic checklist sets specifically tailored for WVREA in the literature. Given the growing popularity of wearable devices and VR educational applications, a reliable tool for

evaluating these applications is crucial, as it can substantially influence student satisfaction and performance.

5.2 The development of new domain-specific heuristics

A comprehensive literature review revealed an absence of existing heuristics specifically designed for WVREA. To address Research Question 2 (RQ2), the researcher proposed a novel set of heuristics. The methodology developed by Quiñones and Rusu (2019) was adopted due to its rigour and structured approach, validated through expert opinions and multiple case studies. Although the methodology typically involves eight stages, the experimental stage was excluded due the absence of pre-existing WVREA heuristics.

The researcher focused on gathering relevant information about WVREA, including its definition, usability, UX attributes, and existing heuristics that could serve as a baseline. As no specific definition existed in the literature, a novel definition for WVREA was proposed.

Two sets of usability/UX attributes were identified for WVREA. The first set, proposed by Nielsen (2012), includes Learnability, Efficiency, Memorability, Errors and Satisfaction, whilst the second set, developed by the International Organization for Standardization (ISO) in 2011, comprises Effectiveness, Efficiency, Learnability, Operability, User Error Protection, Freedom from Risk and Completeness. While there is some overlap among the attributes of the two sets - such as Learnability, Efficiency and Errors – each set also contains unique elements. For instance, Memorability and Satisfaction are included in Nielsen's but not in the ISO framework. The researcher chose to incorporate the ISO attributes because they offer additional features like Effectiveness, Operability,

Freedom from Risk and Context Completeness which are not present in Nielsen's list. By integrating both sets of usability attributes, the researcher aimed to enhance the effectiveness of the newly developed heuristics in identifying usability issues in WVREA. In terms of UX attributes, the researcher found one set proposed by Tcha-Tokey et al. (2018), which includes Presence, Engagement, Immersion, Flow, Usability, Skill, Emotion, Experience, Consequence, Judgment, and Technology Adoption. The researcher selected these UX attributes for their relevance to VR education.

The literature search yielded four sets of heuristics, including one general set. The researcher chose Nielsen's (1994a) heuristics as the de facto standard. Additionally, three sets of comprehensive heuristics from a similar domain were chosen as a foundation for developing the new checklist: The Virtual World Heuristics by Rusu et al. (2011a), the VR Apps heuristics by Sutcliffe and Gault (2004), and the Virtual Environments characteristics by Gabbard et al. (1997). These three existing heuristics were applied to ensure that the newly developed heuristics would include a comprehensive checklist of features necessary for VR. This approach aimed to enhance the overall effectiveness and completeness of the heuristic framework.

After gathering and reviewing this information, the researcher proceeded to the next process of selecting, organising, and prioritising the WVREA-specific information, usability/UX attributes and existing heuristics. The information presented in the Exploratory Stage was selected according to its importance in the next stage. It was categorised based on its relevance to WVREA, specific features of WVREA, usability/UX attributes, and existing heuristics. Each piece of information was assigned a rating using the following scale: (3) Highly important, (2) Somewhat important and (1) Not important to the domain. The

researcher rated the definition of WVREA and its context of use as somewhat important (2), as this information is crucial for providing clarity about the specific domain that requires new heuristics and for gathering relevant data. The area of use and research justification were prioritised as highly important (3) because they emphasise the applicability of WVREA across various domains, such as education, military, and medicine. This highlights the need for specific usability evaluation guidelines for WVREA, given the limitations of existing general and specific heuristics due to the unique characteristics of WVREA.

The features of WVREA were also rated as highly important (3), as understanding them is crucial for developing the heuristics. Furthermore, the usability and UX attributes received a highly important rating (3) because all identified attributes are relevant for evaluating usability and UX. All four selected sets of existing heuristics were assigned a high importance rating (3) due to their comprehensiveness and their role as the foundation for developing the heuristics specific to WVREA.

A comparative analysis was conducted to determine if existing heuristics could adequately assess WVREA attributes. Heuristics that appeared in multiple sets and addressed core usability concerns were prioritised. For example, "Recovering from Errors" received a high priority score. Conversely, heuristics that are relevant to WVREAs but appear less frequently, such as “Take into account user experience”, received a moderate score.

In the correlational stage, WVREA features were matched with relevant usability and UX attributes, as well as existing heuristics. The researcher analyses the correlation among these features, attributes and existing heuristics to identify overlaps and similarities. This analysis assessed how well they address common usability concerns, whether they use the

same or similar wording for evaluation criteria, and identified potential gaps where existing heuristics may not adequately address the specific usability challenges of WVREA. Through this matching process, the researcher was able to determine which WVREA features lacked corresponding heuristics for evaluation. Notably, it was found that Multi-sensory Learning, Curriculum-aligned Content, Learning Measurement, and Accessibility lacked corresponding heuristics, and thus became the focus of this study.

The selection stage involved the researcher adapting existing heuristics and creating new ones to address WVREA-specific features. For instance, GB Agent2 was adapted to WVREA1 (High fidelity or stylised representational) while a new heuristic, WVREA2 (Engages various sensory experiences), was created. Additionally, The R1: Feedback heuristic was kept and renamed Real-time feedback (WVREA 3). Features such as Interactivity, Pedagogy and Cognition, Engagement and Gamification were combined and adapted into WVREA 4 - Object selection: Non-isomorphic (Non-Realistic magic technique), which correlate with GBSelect2, GBSelect5, GBSelect12 and GBSelect 3. Similarly, WVREA5 - Object Selection: Isomorphic (Realistic), was created from the same WVREA features, also corresponding with GBSelect2, GBSelect5, GBSelect12 and GBSelect3.

Additionally, WVREA 6 - Object Manipulation: Non-isomorphic (non-realistic magic technique) was derived from the same WVREA features and correlated with GBManip1, GBManip12, GBManip2, GBManip3, GBManip4 and GBManip5. In contrast, WVREA 7 - Object Manipulation: Isomorphic (Realistic) was similarly adapted from the features of WVREA features like Interactivity, Pedagogy and Cognition, Engagement and

Gamification, aligning with GBManip6, GBManip7, GBManip8, GBManip9, and GBManip10.

The WVREA features of Sense of Presence, Immersive and Learning Environment were adapted into R9 – Avatar's customisation. Therefore, the researcher keeps these heuristics and tags them as WVREA8. The researcher then adapted GBTask2 and GBTask3, focusing on Collaborative learning, into WVREA 9: Collaborative Learning, and kept R2: Clarity, tagging it WVREA 10: Clarity. This heuristic aligns with the WVREA features of the Easy-to-use interface. The feature of Personalisation was adapted to consider user experience, correlating with GBUser 1, resulting in WVREA11. Furthermore, WVREA12: Curriculum-aligned Content was newly created by the researcher, as no existing heuristic could be correlated with this feature, just like WVREA13: Learning Measurement and WVREA14: Accessibility. These four new heuristics - WVREA 2: Multi-sensory Learning, WVREA 12: Curriculum-aligned Content, WVREA13: Learning Measurement and WVREA14: Accessibility – address gaps in the current literature regarding wearable virtual reality in education application.

In the specification stage, the researcher documents the final set of WVREA heuristics by providing a thorough breakdown of each heuristic to ensure effective application within the WVREA evaluation context. This breakdown includes clear definitions and explanations of each heuristic's purpose, along with its specific relevance to WVREA usability. It also presents illustrative examples demonstrating how to apply each heuristic to identify potential usability issues and highlights the benefits of adhering to each heuristic during the evaluation process. Additionally, it includes a practical checklist, where relevant, to assist evaluators during assessment. By providing this comprehensive

documentation, this detail enhances the clarity, usability, and effectiveness of the newly developed WVREA heuristics, facilitating their practical application in future evaluations.

Finally, the researcher proposed a novel usability heuristic, as illustrated in Table 4.6, to address RQ2.

5.3 The assessment of WVREA heuristics

In addressing Research Question 3 (RQ3), these heuristics underwent three evaluation phases: expert judgement and Heuristic evaluation, both conducted by academicians specialised in human-computer interaction and industry practitioners. They possess knowledge in usability/UX, along with experience in conducting heuristic evaluations and developing domain-specific heuristics and VR technology, as well as HE by schoolteachers.

The expert judgment survey focused on four key dimensions: Utility, Clarity, Ease of Use, and the Necessity of additional Checklist. These dimensions were used to evaluate the heuristic's Utility (D1), Clarity (D2), and Ease of Use (D3), along with the Necessity of an additional checklist (D4). Also, the evaluation focuses on the overall evaluation of the addressing factors such as Easiness, Intention and Completeness.

The heuristics received high scores across multiple evaluation dimensions, with both Utility (D1) and Clarity (D2) exceeding an average of 4.1, indicating that experts found the WVREA heuristics to be both useful and clear. Ease of Use (D3) also scored favourably at 3.9, approaching a 4. This strong correlation among the three dimensions suggests that when the heuristics are perceived as clear and easy to understand, they are also regarded as useful and easy to apply, as suggested by Rusu et al. (2016).

Additionally, the perceived need for an additional checklist dimension (D4) was comparatively lower, with an average score of 3.6. This indicates that while some users considered a separate checklist to be somewhat unnecessary, others saw potential value in having one. The strong positive correlations between utility, clarity, and ease of use suggest a cohesive design that effectively balances usability with achieving the intended goals.

Experts rated the ease of evaluation process highly, with an average score of 4.08, indicating that it was user-friendly. The low standard deviation of 0.4 suggests that expert responses were consistently similar, supporting the assessment. Additionally, experts expressed a strong intent to apply the WVREA heuristics for evaluating similar applications in the future, with an average intention rating of 3.96 and a low standard deviation of 0.455, suggesting the potential for broader adoption among evaluators. Experts also agreed on the comprehensiveness of the heuristics in addressing all usability aspects of WVREA, with an average rating of 4.16 and a low standard deviation of 0.375, indicating strong consensus.

The second phase, the HE, was conducted in two experiments: HE with the experts and HE with the schoolteachers.

a. HE with the experts

The first experiment involved recruiting professionals from academia and industry practitioners, while the second experiment involved schoolteachers who are subject matter experts. Notably, 14 usability issues were mapped to all four newly created heuristics (WVREA2, WVREA12, WVREA13, WVREA14) by the evaluators. Among these, two usability issues were assigned major problems scores (3) and one issue was assigned a minor usability problems score (2) under WVREA2. WVREA12 had one usability problem rated with a score of 4 (catastrophe), indicating that issues related to curriculum-aligned content

should be addressed before reaching intended users. WVREA 13 received the most usability issues among these four newly created heuristics; five evaluators rated a score of 3 (major usability problems), three evaluators rated it with a score of 4, suggesting that learning measurement should be integrated into the WVREA and fixed before it reaches the intended user, while one evaluator rated with a score of 2, indicating that it was just a minor usability problem. WVREA14 was rated with a score of 2, suggesting that it presented only a minor usability issue. This phase provided crucial insights regarding necessary modifications to the heuristics for improved effectiveness.

b. HE with the schoolteachers

The third experiment, which involved evaluations from schoolteachers, also yielded positive results. All identified usability issues corresponded with the WVREA heuristics. Notably, some of the issues identified by both the experts and the schoolteachers related to education can be mapped to four newly created heuristics in this study, including no assessment (WVREA13), not aligned with the curriculum (WVERA12), less interactive (WVREA2) and accessibility (WVREA14). This emphasises the importance of specific heuristics in identifying usability issues related to a specific domain, ensuring that a user can fully utilise this specific application. Without these heuristics, the VR developers might overlook important criteria within WVREA, as it has undergone evaluations involving academicians, practitioners and schoolteachers.

The newly developed WVREA heuristics have the potential to significantly impact VR education. By offering a practical framework for evaluating and improving the usability of WVREA, these heuristics can contribute to the development of more user-friendly and effective educational experiences. Furthermore, they can promote consistent and

standardised evaluation practices within the WVREA development community, fostering better communication and collaboration among developers, researchers, and educators.

The two-phase validation process demonstrated that all identified usability issues could be mapped to the WVREA, confirming its comprehensiveness and indicating no need for further refinement. The final WVREA heuristics consist of 14 key principles, including aligned representation for virtual agents, engaging sensory experiences, realistic feedback, object selection methods (both isomorphic and non-isomorphic), object manipulation techniques (isomorphic and non-isomorphic), avatar customisation options, collaboration features, clarity, UX design, , curriculum-aligned content, learning measurement tools, and accessibility considerations.

All usability issues reported by the participants corresponded with the new heuristics, demonstrating their effectiveness in identifying and classifying issues, thus addressing Research Question 3 (RQ3). Since the evaluators addressed all identified issues using the WVREA heuristics, a refinement stage is unnecessary. As a result, the final set of new heuristics (WVREA) remains at 14.

CHAPTER 6

CONCLUSION, IMPLICATIONS AND FUTURE WORKS

6.1 Conclusion

The integration of VR technology offers immersive and interactive learning experiences through real-time, computer-generated 3D graphics. This allows students to explore abstract concepts in greater depth, resulting in a more meaningful and practical learning experience compared to traditional methods. However, when implementing VR in education, prioritising UX and usability is crucial. By carefully considering these factors, educators can design learning experiences that are both engaging and effective.

This study highlights the importance of properly evaluating WVREA to ensure optimal usability and a UX. Relying on general heuristics for domain-specific applications can overlook specific usability issues, preventing users from achieving desired learning objectives. Therefore, it is essential to employ domain-specific heuristics to optimise usability and UX.

This research addresses three interrelated objectives: (1) assessing the limitations of existing heuristics for evaluating WVREA; (2) developing a novel set of user-friendly and effective heuristics for evaluating the UX of educational apps within the WVREA framework, with a focus on pedagogical aspects; And (3) assessing the effectiveness of the newly developed novel heuristic in identifying issues for WVREA. The key findings of this research can be summarised as follows: -

Objective 1:

To assess the shortcomings of existing heuristics for evaluating WVREA

The research reveals that no specific heuristics have been developed for evaluating WVREA. It was found that only three prior studies have addressed the usability of apps related to WVREA, and they employed general heuristics such as those proposed by Sutcliffe and Gault (2004) and Nielsen and Molich (1990), along with one heuristic specific to WVREA. For example, Moore et al. (2020) utilised Sutcliffe and Gault's heuristics but identified only five critical design considerations for developing similar VR applications: affordance, agency, diverse input modalities, mental models, and advanced roles. In contrast, a study by Botha et al. (2021), which applied Nielsen and Molich's heuristics, found that some educational-related issues could not be detected using those general heuristics. This limitation is highlighted in **Table 4.1**. Furthermore, Young et al. (2020) proposed eight heuristics focused on students' attitudes and behaviours towards VR in the classroom, but this approach did not assess actual learning outcomes. These findings support Rusu et al.'s (2011) that non-domain-specific heuristics fail to capture domain-specific usability issues adequately.

Objective 2:

To develop the WVREA heuristics.

This study addresses a critical gap in virtual reality (VR) education by developing a comprehensive set of usability heuristics, referred to as WVREA, specifically for evaluating Virtual Reality Educational Applications. The development process employed a multi-stage approach that included expert validation surveys conducted in three separate phases, engaging academicians, industry professionals, and educators within the education domain,

leading to the identification of 14 key principles tailored for WVREA. These principles cover areas such as aligned representation for virtual agents, engaging sensory experiences, realistic feedback, object selection methods (both isomorphic and non-isomorphic), object manipulation techniques (isomorphic and non-isomorphic), avatar customisation options, collaboration features, clarity, UX design, curriculum-aligned content, learning measurement tools, and accessibility considerations.

Objective 3:

To assess the effectiveness of the newly developed novel heuristic in identifying issues for WVREA

Expert judgment indicated positive user feedback regarding the overall usability of the heuristics. The experts rated the heuristics as highly useful (mean score of 4.1) and clear (mean score of 4.08). Furthermore, a positive correlation between perceived utility, clarity, and ease of use suggested that the heuristics are well-designed and cohesive. While most users found the heuristics comprehensive, a small percentage indicated the need for additional checklists. The two-phase validation process in heuristics evaluation demonstrated that all identified usability issues could be mapped to the WVREA, confirming its comprehensiveness and requiring no further refinements. The final WVREA heuristics consist of 14 key principles.

In conclusion, the WVREA heuristics emerge as a validated and effective tool for evaluating WVREAs. This user-centred approach empowers both schoolteachers and VR educational application developers to create more effective and engaging learning experiences for students in a virtual environment.

6.2 Implications

The implications of the WVREA heuristics are multifaceted, addressing theoretical, practical, and managerial aspects of virtual reality development and UX. Theoretically, this research advances HCI theory by providing a specialised framework that facilitates the evaluation and enhancements of user experience in virtual environments. It expands the repertoire of usability evaluation methods available to researchers and practitioners by introducing a novel set of guidelines tailored to immersive technologies. Additionally, the heuristics reinforce the significance of user-centred design principles, emphasising the need to prioritise user needs and preferences during the development of VR experiences.

Practically, the newly developed WVREA heuristics can significantly improve UX by making interactions in VR more intuitive, efficient and enjoyable, thereby reducing frustration and cognitive load. In VR-based education, the heuristics enhance learning outcomes by optimising users engagement with content. They help streamline the development process by providing a framework for quickly identifying and fixing usability issues, leading to greater efficiency. Additionally, they promote consistent evaluation practices within the VR development community, encouraging communication and collaboration among developers, researchers, and educators to create more effective VR educational applications.

From a managerial perspective, the WVREA heuristics provide valuable insights for making decisions about resource allocation and project prioritisation. By identifying and addressing usability risks, managers can ensure smoother deployments of VR applications. Organisations that focus on user experience by adopting these heuristics can

gain a competitive edge in the VR market and improve their brand reputation through high user satisfaction, ultimately fostering strong customer loyalty.

6.3 The contribution of this study

This research makes a significant contribution to the field of HCI and educational technology by developing comprehensive heuristics for wearable VR applications in education. The lack of specific heuristics identified in previous studies highlighted the need for a structured approach to instructional design within immersive VR contexts (Lamb et al., 2018; Lege & Bonner, 2020; Makransky et al., 2019; Markowitz et al., 2018). By addressing this gap, the new heuristics consider the usability and UX principles, as well as integration of established learning theories – particularly constructivism and pedagogical approach into the development of VR educational tools, promoting active learning experience and leading to the improvement of student performance.

By focusing on UX, the heuristic addresses common usability issues that may deter students from effectively utilising VR applications. Furthermore, this newly developed heuristic aligns with the principles outlined in the Malaysian Education Blueprint (2013-2025), reinforcing 21st-century pedagogical practices such as collaborative learning, problem-solving, and critical thinking. The heuristics serve as a resource for both developers and educators, guiding the creation of immersive VR experiences that enrich students' knowledge and skills while facilitating a learner-centred approach.

In addition, the heuristic identifies the importance of accessibility in educational VR applications, ensuring that resources cater to students with diverse abilities and addressing equity issues in education. The incorporation of collaboration and real-time feedback within the heuristics fosters a learning environment where students can engage with peers and

monitor their progress, enhancing their overall educational experience. By addressing a significant gap in the existing literature and providing actionable guidelines for the development of WVREA, this research contributes to advancing high-quality, user-centred approaches in educational technology. The findings and heuristics presented in this study promise to foster better communication and collaboration among developers, researchers, and educators, ultimately leading to the creation of more effective educational tools.

6.4 Future Research Directions

While this research establishes a strong foundation for WVREA usability evaluation through the development of the WVREA heuristics, there are several promising directions for research to improve WVREA's usability. One key area is conducting longitudinal studies, which can help researchers understand how heuristics impact WVREA projects over time. By observing the use of these heuristics over extended periods, researchers can assess their impact on user satisfaction, learning outcomes, and engagement. This can reveal areas where the heuristic framework can be improved.

Another important area for future research is expanding the heuristic framework itself. Developing new heuristics to address specific challenges in virtual reality such as spatial audio, haptic feedback, and immersive presence could improve WVREA evaluations. Additionally, incorporating emerging technologies such as eye-tracking and brain-computer interface can enhance how researchers assess user experiences.

Cultural adaptation and internationalisation are also essential for making the WVREA heuristics usable across different cultures. Collaborating with researchers and educators from diverse backgrounds can help tailor and validate these heuristics for various contexts. Developing guidelines for culturally sensitive design and evaluation will foster the

creation of inclusive VR educational experiences. Additionally, exploring localisation and translation can broaden the reach of WVREA to a global audience.

Lastly, a user-centred approach should remain central to WVREA development. Involving users from the beginning to the end of the process can result in more effective and user-friendly VR experiences. Using user-centred design methods like iterative prototyping and user testing helps refine WVREA design based on actual user feedback. Developing new evaluation techniques, such as virtual reality user experience questionnaires and physiological measurements, can provide deeper insights into how users feel and perceive their experiences.

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APPENDICES

Appendix A

Appendix A(i) – Expert Judgment Survey



WEARABLE VIRTUAL REALITY EDUCATION APPLICATION (WVREA) EVALUATION HEURISTIC CHECKLIST: EXPERTS JUDGEMENT SURVEY

Objective: The objective of this survey is to gather your expert opinion to evaluate the suitability of newly proposed heuristics for the Wearable Virtual Reality Education Application (WVREA) domain. As an industry practitioners and Academic specialists in HCI or VR, your input and expertise are highly valued. We greatly appreciated your voluntary participation in this survey and assure you that all the information provided will be treated as confidential. Access to the original data will be restricted to the researchers involved, namely Associate Professor Dr. Mohd Kamal Othman, Dr Norehan Zulkiply and Rahimah Mat.

Background: The Wearable Virtual Reality Education Application (WVREA) is a system that utilizes a head-mounted display and associated hardware to create a fully immersive and interactive learning experience. Users can effortlessly explore virtual environments in a natural and intuitive manner, fostering engagement and interactivity. Moreover, WVREA is designed to support learning objectives by providing engaging, stimulating, and authentic simulations of real-world scenarios or concepts. By offering lifelike experiences, the application enables users to immerse themselves in educational content that closely mirrors real-life situations. The design of WVREA pays careful attention to factors such as ease of use, user comfort, and task efficiency.

Expectation: We aim to explore your perceptions of this new set of heuristics. PART 1 and PART 2 are quantitative surveys with Likert Scales ranging from 1-5 (Strongly Disagree to Strongly Agree). In PART 1, we seek your feedback regarding each heuristic's **utility, clarity, ease of use, and the necessity for more details**. In PART 2, we welcome your feedback on the heuristics' **easiness, intention, and completeness.** Your outstanding cooperation is genuinely valued and deeply appreciated. Thank you sincerely for your exceptional efforts.

Demographics

Description (optional)

1. What is your age range? *

- 25-34
- 35-44
- 45-54
- 55-64
- 65+

2. What is your gender? *

- Male
- Female

3. What is your highest level of education completed? *

- PhD
- Master's degree
- Bachelor's degree
- Other...

4. What is your current job title/role? *

Short-answer text

5. How Frequent do you use Wearable VR technology? *

- Rarely
- Occasionally
- Once a month
- Several times a year
- Weekly
- Daily
- Other...

6. How many years of experience do you have in HCI or VR? *

- 1-3 years
- 4-5 years
- 6-10 years
- More than 10 years
- Other...

7.What specific areas or domains of HCI/VR are you most familiar with? (e.g., user interface design, interaction techniques, virtual reality systems, etc.)

- ○ User Interface Design
- ○ Interaction Techniques
- ○ Virtual Reality System

PART 1: Heuristic's utility, clarity, ease of use, and the necessity for more details

Description (optional)

WVREA 1: Real-world, high-fidelity representation of physical and behavioral agents.

Definition	The physical and behavioral characteristics of the agents in the virtual reality education apps must be represented in a realistic manner.
Explanation	The virtual agents within the application would be designed to closely resemble and exhibit similar behaviours to actual, real-world entities or individuals. This includes their physical appearance, movements and reactions.
Example(s)	Creating virtual avatars that resemble scientists or science teachers, with appropriate attire, hairstyles and accessories.
Benefit(s)	The realistic representation and expertise of the virtual agents create an immersive and educational environment, sparking curiosity and fostering a deeper understanding of a topic.
Checklist	i. Are the physical and behavioral representations of agents closely resembling their real-world counterparts? ii. Does the VR application use high-quality assets and animations?

i. This heuristic is useful to evaluate the Wearable Virtual Reality Education Application *

	1	2	3	4	5	
Strongly Disagree	○	○	○	○	○	Strongly Agree

ii. This heuristic provides a clear definition and evaluation checklist. *

	1	2	3	4	5	
Strongly Disagree	○	○	○	○	○	Strongly Agree

iii. It is easy to use this heuristic to evaluate the Wearable Virtual Reality Education Application. *

	1	2	3	4	5	
Strongly Disagree	○	○	○	○	○	Strongly Agree

iv. It is necessary for the researcher to provide more details for these heuristics. *

	1	2	3	4	5	
Strongly Disagree	○	○	○	○	○	Strongly Agree

WVREA 2: Engages various sensory experience

Definition	Engages multiple senses, including visual, auditory, and tactile, to enhance learning and retention.
Explanation	Creating an immersive learning environment that stimulates multiple senses to enhance the learning experience such as visual, auditory experience, haptic feedback, spatial awareness, Gesture motion and olfactory stimulation.
Example(s)	The application can provide 3D visuals, ambient sounds, character voices, vibrations, pressure, texture variations, sensors to track user movements and gestures, and incorporating smells or scents into the virtual environment.
Benefit(s)	The application creates a more immersive learning environment, enhances memory and information retention, fosters deeper connections with the educational content, increases motivation, and promotes experiential learning, promoting hands-on learning and critical thinking skills.

Checklist	1. **Visuals:** • Are the visuals high-resolution and realistic? • Is the virtual environment visually appealing and immersive? 2. **Auditory Experience:** • Are sound effects used to enhance the virtual environment and interactions? • Is there clear and synchronized narration or explanations for educational content? 3. **Haptic Feedback:** • Does the application provide haptic feedback through the wearable device? • Does the feedback feel realistic and accurately convey the intended sensations • Is haptic feedback appropriately synchronized with the visual and auditory elements? 4. **Gesture and Motion Tracking:** • Does the wearable device accurately track the user's movements and gestures? • Is the tracking responsive and seamless, providing a natural and intuitive experience? 5. **Olfactory Stimulation:** • If applicable, does the application incorporate scents or smells to enhance the virtual environment? • Are the scents appropriately synchronized with the educational content and virtual scenarios? • Is the use of olfactory stimulation safe and considerate of user preferences and sensitivities?

i. This heuristic is useful to evaluate the Wearable Virtual Reality Education Application *

	1	2	3	4	5	
Strongly Disagree	○	○	○	○	○	Strongly Agree

ii. This heuristic provides a clear definition and evaluation checklist. *

	1	2	3	4	5	
Strongly Disagree	○	○	○	○	○	Strongly Agree

iii. It is easy to use this heuristic to evaluate the Wearable Virtual Reality Education Application. *

	1	2	3	4	5	
Strongly Disagree	○	○	○	○	○	Strongly Agree

iv. It is necessary for the researcher to provide more details for these heuristics. *

	1	2	3	4	5	
Strongly Disagree	○	○	○	○	○	Strongly Agree

WVREA 3: Realistic Feedback

Definition	It refers to providing users with responses and interactions that closely resemble those encountered in the real world. It involves creating a sense of presence and authenticity by simulating the consequences of users' actions and enabling them to receive feedback that mirrors real-world scenarios.
Explanation	The application needs to provide users with information about their actions, both during and after their input. This entails ensuring that users have enough depth and position cues during the manipulation of 3D objects. They receive feedback that simulates how things behave or respond in the real world.
Example(s)	Subtle lighting effects, realistic shadow, or different degree of transparency.
Benefit(s)	The realistic feedback could create an immersive learning experience through experiential learning, error correction, retention, and transferable skills, which are all important components of a successful learning experience.

Checklist	**Accurate Physics Simulation:** i. Do objects behave realistically when users interact with them (e.g., proper weight, collision detection, and response? **Real-Time Responsiveness:** i. Does the application provide immediate feedback in response to user actions? ii. Is the feedback synchronized with the user's interactions, ensuring a seamless and natural experience? iii. Are there minimal delays or latency between user input and the corresponding feedback? **Sensory Integration:** i. Do the visual, auditory, and haptic feedback elements work together to create a coherent and immersive experience? ii. Is there consistency between the sensory feedback and the actions performed by the user **Contextual Relevance:** i. Does the feedback provided align with the specific educational context and objectives? ii. Are the responses and interactions relevant to the subject matter being taught?

i. This heuristic is useful to evaluate the Wearable Virtual Reality Education Application *

	1	2	3	4	5	
Strongly Disagree	○	○	○	○	○	Strongly Agree

ii. This heuristic provides a clear definition and evaluation checklist. *

	1	2	3	4	5	
Strongly Disagree	○	○	○	○	○	Strongly Agree

iii. It is easy to use this heuristic to evaluate the Wearable Virtual Reality Education Application. *

	1	2	3	4	5	
Strongly Disagree	○	○	○	○	○	Strongly Agree

iv. It is necessary for the researcher to provide more details for these heuristics. *

	1	2	3	4	5	
Strongly Disagree	○	○	○	○	○	Strongly Agree

WVREA 4: Object selection
(Nonisomorphic/Non-Realistic/magic technique)

Definition	It refers to the process of choosing or interacting with virtual objects in unnatural way which is deviates significantly from strict realism within the VR environment.
Explanation	Nonisomorphic object selection technique refers to unconventional and imaginative ways of selecting object that deviate from traditional real-world interaction.
Example(s)	Enlarging the user's virtual arm, increasing the size of the selection tool, Virtual pointing by using ray casting, grabbing, grasping and clutching by using Go-go, Virtual Pads, Friction Surface, PRISM, adaptive pointing, aperture selection (uses a cone as a selection tool and allows users to manually adjust its apex angle)
Benefit(s)	Allow the user to select objects beyond their area of reach precisely and require less physical movement.
Checklist	i. Are the selected objects easily accessible and interactable within the virtual reality environment? ii. Is there any instruction or tutorial on how to interact with and manipulate the object effectively? iii. Are the instructions or tutorials clear? iv. Is the selection of the object aligned with established pedagogical principles and instructional strategies?

i. This heuristic is useful to evaluate the Wearable Virtual Reality Education Application *

	1	2	3	4	5	
Strongly Disagree	○	○	○	○	○	Strongly Agree

ii. This heuristic provides a clear definition and evaluation checklist. *

	1	2	3	4	5	
Strongly Disagree	○	○	○	○	○	Strongly Agree

iii. It is easy to use this heuristic to evaluate the Wearable Virtual Reality Education Application. *

	1	2	3	4	5	
Strongly Disagree	○	○	○	○	○	Strongly Agree

iv. It is necessary for the researcher to provide more details for these heuristics. *

	1	2	3	4	5	
Strongly Disagree	○	○	○	○	○	Strongly Agree

WVREA 5: Object Selection (isomorphic/Realistic/magic technique)

Definition	The selection of an object in a way that mirrors real-world behaviour.
Explanation	Object selection is the task of acquiring or identifying a particular object or subset of objects from the entire set of objects available in a natural way.
Example(s)	Picking or grabbing up one or more objects with virtual hand (3D cursor: sphere, cube and hand avatar, pointing to one or more objects by using bubble-cursor, silk cursor, ray casting (a ray or a cone), direct image plane, eye-gazed selection, view finder, etc.
Benefit(s)	The selection technique allows the learner to select in a natural way, visualize, explore and understand on the object more effectively.
Checklist	i. Is the object selection seamless and natural for the user? ii. Are there any visual or auditory feedback mechanisms? iii. Is the feedback clear and unambiguous? iv. Is there any support for alternative input methods, such as voice commands or adaptive controllers, to enable users with disabilities to interact with the virtual reality environment effectively? v. Is there any error handling mechanism to handle situations where object recognition or selection fails?

i. This heuristic is useful to evaluate the Wearable Virtual Reality Education Application *

	1	2	3	4	5	
Strongly Disagree	○	○	○	○	○	Strongly Agree

ii. This heuristic provides a clear definition and evaluation checklist. *

	1	2	3	4	5	
Strongly Disagree	○	○	○	○	○	Strongly Agree

iii. It is easy to use this heuristic to evaluate the Wearable Virtual Reality Education Application. *

	1	2	3	4	5	
Strongly Disagree	○	○	○	○	○	Strongly Agree

iv. It is necessary for the researcher to provide more details for these heuristics. *

	1	2	3	4	5	
Strongly Disagree	○	○	○	○	○	Strongly Agree

WVREA 6: Object Manipulation (Nonisomorphic)

Definition	This technique enables users to manipulate objects in ways distinct from the physical world, while still ensuring usability and performance.
Explanation	This departure from strict realism introduces virtual tools with extraordinary capabilities, including, and more, offering users a sense of "magical interaction".
Example(s)	disassembling and reassembling, resizing, stretching or morphing using laser beams, rubber arms, voodoo dolls, Go-go, etc.
Benefit(s)	Flexible virtual environment enables creative exploration and experimentation, providing unique learning opportunities.
Checklist	i. Are the controls and gestures intuitive and easy to understand? ii. Does the application provide users with feedback when manipulating objects in nonisomorphic ways?

i. This heuristic is useful to evaluate the Wearable Virtual Reality Education Application *

	1	2	3	4	5	
Strongly Disagree	○	○	○	○	○	Strongly Agree

ii. This heuristic provides a clear definition and evaluation checklist. *

	1	2	3	4	5	
Strongly Disagree	○	○	○	○	○	Strongly Agree

iii. It is easy to use this heuristic to evaluate the Wearable Virtual Reality Education Application. *

	1	2	3	4	5	
Strongly Disagree	○	○	○	○	○	Strongly Agree

iv. It is necessary for the researcher to provide more details for these heuristics. *

	1	2	3	4	5	
Strongly Disagree	○	○	○	○	○	Strongly Agree

WVREA 7: Object Manipulation (Isomorphic)

Definition	It is an authentic interaction which enable users to interact with the objects in a manner that closely resembles real-world interactions.
Explanation	An interaction technique that are precisely designed for 3D environments, resulting in a virtual reality experience that can be perceived as an enhanced version of reality.
Example(s)	Deformation, reaching, grabbing, gasping, moving, clutching and orienting objects by single virtual hand, Rigid-Body Fingers-based grasping technique, Soft-Body Finger, God Fingers, etc.
Benefit(s)	It will allow users to more accurately examine and learn the object or the VE, which may improve user performance and improve learning with a sense of presence and immersion, lead to user enjoyment.
Checklist	i. Can the user perform a variety of manipulations, such as rotation, translation, scaling and assembly? ii. Are there any restrictions on object manipulation, such as limits on rotation angle or collision avoidance? iii. Are there multiple ways for users to manipulate objects, catering to different preferences and accessibility needs?

i. This heuristic is useful to evaluate the Wearable Virtual Reality Education Application *

	1	2	3	4	5	
Strongly Disagree	○	○	○	○	○	Strongly Agree

ii. This heuristic provides a clear definition and evaluation checklist. *

	1	2	3	4	5	
Strongly Disagree	○	○	○	○	○	Strongly Agree

iii. It is easy to use this heuristic to evaluate the Wearable Virtual Reality Education Application. *

	1	2	3	4	5	
Strongly Disagree	○	○	○	○	○	Strongly Agree

iv. It is necessary for the researcher to provide more details for these heuristics. *

	1	2	3	4	5	
Strongly Disagree	○	○	○	○	○	Strongly Agree

WVREA 8: Avatar's Customization

Definition	It refers to users' ability to personalise and modify the appearance and features of their virtual representation, often known as an avatar.
Explanation	It enables individuals to establish a unique and personalised virtual identity that represents them in the virtual world.
Example(s)	The customization of voice characteristics, body shape and proportions, facial features, clothing, accessories, personal style, avatar movements such as walking, running, sitting, and gesturing.
Benefit(s)	It enables users to develop a virtual representation that corresponds to their preferences, identity, and preferred level of self-expression, increasing their engagement and sense of presence in the virtual environment.
Checklist	i. Does the application provide a variety of customization options to accommodate a wide range of customer preferences? ii. Are the tools for avatar customization user-friendly? iii. Does the VR application provide real-time feedback for users as they customise their avatars?

i. This heuristic is useful to evaluate the Wearable Virtual Reality Education Application *

	1	2	3	4	5	
Strongly Disagree	○	○	○	○	○	Strongly Agree

ii. This heuristic provides a clear definition and evaluation checklist. *

	1	2	3	4	5	
Strongly Disagree	○	○	○	○	○	Strongly Agree

iii. It is easy to use this heuristic to evaluate the Wearable Virtual Reality Education Application. *

	1	2	3	4	5	
Strongly Disagree	○	○	○	○	○	Strongly Agree

iv. It is necessary for the researcher to provide more details for these heuristics. *

	1	2	3	4	5	
Strongly Disagree	○	○	○	○	○	Strongly Agree

WVREA 9: Collaborative Learning

Definition	It refers to a method of education in which several people engage and learn together in a shared virtual environment.
Explanation	Collaborative learning in VE includes features that allow learners to engage, share ideas, and work together towards a common objective.
Example(s)	Collaborative learning elements include instructor facilitation tools, team-based challenges or games, shared whiteboards or canvas, and multi-user environments.
Benefit(s)	Students engage in discussions, problem-solving, and hands-on activities to gain deeper understanding and retention knowledge.

Checklist	i. Does the VE allow multiple users to join the same virtual reality session and interact with each other in real-time through seamless communication, such as voice chat, gestures, or text-based communication, to facilitate collaboration among learners? ii. Does the virtual environment accommodate multiple users simultaneously so that they can move, interact with objects, and engage in activities together? iii. Does the VE implement effective communication tools that enable users to interact and exchange ideas, such as voice chat, text chat, or hand gestures, to facilitate seamless communication and collaboration? iv. Does the VE support collaborative activities and tools such as shared whiteboards, project-based tasks, problem-solving activities, or group discussions that promote teamwork and active engagement among users? v. Does the VE support feature that allow for shared object manipulation, such as joint object handling or synchronised interactions, to support collaborative learning experiences?

WVREA 10: Clarity

Definition	Clarity means that language, system messages and labelling for commands should be simple and concise. The intended functionality, activity and tasks should be set appropriately.
Explanation	The labelling for the commands, language used, and system messages should be simple and easy to understand by users. Real-world examples relate the desired features to everyday objects. The user's activity and tasks are based on relevant settings, making the system practical.
Example(s)	Clear and concise language and labelling for commands, system messages are in a constructive manner, and real-world experiences are mapping desired functionality to everyday items. Relevant settings are used to suggest user activity and tasks, and the system is compatible with the real world.
Benefit(s)	It improves user experience, enable faster task completion, facilitates real-world transferability, reduces errors, and increases accessibility.

Checklist	i. Is the language for commands and instructions within the VR application clear and concise? ii. Are the labels for buttons, menus, and interactive elements descriptive and easily understandable? iii. Are the system's messages and feedback helpful and provide guidance on how to resolve issues or errors? iv. Is the language used encouraging and providing positive reinforcement that can motivate learners and enhance their learning experience? v. Do the objects and activities within the virtual environment use familiar settings that mirror real-world experiences and make the learning content relatable?

i. This heuristic is useful to evaluate the Wearable Virtual Reality Education Application *

	1	2	3	4	5	
Strongly Disagree	○	○	○	○	○	Strongly Agree

ii. This heuristic provides a clear definition and evaluation checklist. *

	1	2	3	4	5	
Strongly Disagree	○	○	○	○	○	Strongly Agree

iii. It is easy to use this heuristic to evaluate the Wearable Virtual Reality Education Application. *

	1	2	3	4	5	
Strongly Disagree	○	○	○	○	○	Strongly Agree

iv. It is necessary for the researcher to provide more details for these heuristics. *

	1	2	3	4	5	
Strongly Disagree	○	○	○	○	○	Strongly Agree

WVREA 11: Consider user experience

Definition	Designing and optimizing the application to meet the needs and expectations of users at different proficiency levels.
Explanation	It caters to a wide range of learners and provide engaging, effective, and tailored experience for users at various skill levels.
Example(s)	i. The expert can choose to skip introductory and focus on more advanced topic or dive deeper into specific areas. ii. The novice user may use tools provided such pre-defined sequence of lessons or activities that guide novices through learning process step by step, allowing them to gradually build their knowledge and skills.
Benefit(s)	The application has the potential to transform the way a user learns and expand educational opportunities. It can adapt to individual needs, customising content, difficulty levels, and pacing to suit each learner's abilities. This personalisation helps to optimise learning outcomes and cater to diverse learning styles.
Checklist	i. Does the VR application offer different levels of difficulty or optional pathways for users to tailor their learning experience based on their proficiency level? ii. Does the VR application provide customization options that allow users to personalise their VR experience based on their preferences and skill levels?

i. This heuristic is useful to evaluate the Wearable Virtual Reality Education Application *

	1	2	3	4	5	
Strongly Disagree	○	○	○	○	○	Strongly Agree

ii. This heuristic provides a clear definition and evaluation checklist. *

	1	2	3	4	5	
Strongly Disagree	○	○	○	○	○	Strongly Agree

iii. It is easy to use this heuristic to evaluate the Wearable Virtual Reality Education Application. *

	1	2	3	4	5	
Strongly Disagree	○	○	○	○	○	Strongly Agree

iv. It is necessary for the researcher to provide more details for these heuristics. *

	1	2	3	4	5	
Strongly Disagree	○	○	○	○	○	Strongly Agree

WVREA 12: Curriculum aligned content

Definition	It refers to educational material or content, experiences, and activities that directly correspond to the learning objectives, topics and standards outline in a specific school curriculum.
Explanation	It ensures that the virtual reality experiences supplied by the app are directly related to the academic content that the students are meant to learn.
Example(s)	i. Students can virtually examine, visualise and understand microscopic organisms, witness biological processes in action, or even simulate ecological experiments.
Benefit(s)	i. Alignment with educational goals ensures that the VR application addresses specific learning outcome, skill, and knowledge that students are expected to acquire, educators can design assessments and track learning outcomes within the VE environment, providing valuable insights into individual student achievements and identifying areas that require further attention. ii. It may be smoothly integrated into educators' lesson planning and instructional strategies. iii. This can help the students to understand complex principles and encourage problem-solving skills.
Checklist	i. Do the VR application's content and activities align with the learning objectives of the curriculum? ii. Do the VR experiences and interactions support the acquisition of knowledge and skills outlined in the curriculum?

i. This heuristic is useful to evaluate the Wearable Virtual Reality Education Application *

	1	2	3	4	5	
Strongly Disagree	○	○	○	○	○	Strongly Agree

ii. This heuristic provides a clear definition and evaluation checklist. *

	1	2	3	4	5	
Strongly Disagree	○	○	○	○	○	Strongly Agree

iii. It is easy to use this heuristic to evaluate the Wearable Virtual Reality Education Application. *

	1	2	3	4	5	
Strongly Disagree	○	○	○	○	○	Strongly Agree

iv. It is necessary for the researcher to provide more details for these heuristics. *

	1	2	3	4	5	
Strongly Disagree	○	○	○	○	○	Strongly Agree

WVREA 13: Learning measurement

Definition	It refers to the process of assessing, evaluating and quantifying the learning outcomes, engagement levels and effectiveness of the VR application in facilitating learning experiences.
Explanation	The VR apps provide tools for assessing the knowledge and skills acquired by learners, measuring their engagement in the VR environment, and facilitates effective learning.
Example(s)	It includes quizzes, assessments, simulations, or performance-based tasks that provide data on learners' achievements, strengths, and areas for improvement.
Benefit(s)	i. It enables educators to assess and evaluate students' learning outcomes from their performance, knowledge acquisition and skills within the VR environment. ii. Learning measurement tools provide real-time feedback, engaging learning, self-reflection, motivation, skill development, and reinforcement to help students understand their strengths and areas for improvement, adjust, and learn more effectively.
Checklist	i. Does the VR application integrate learning measurement to evaluate learners' progress and understanding of the curriculum-aligned content? ii. Does the VR application include formative and summative learning measurement components that provide feedback and track learners' performance?

i. This heuristic is useful to evaluate the Wearable Virtual Reality Education Application *

	1	2	3	4	5	
Strongly Disagree	○	○	○	○	○	Strongly Agree

ii. This heuristic provides a clear definition and evaluation checklist. *

	1	2	3	4	5	
Strongly Disagree	○	○	○	○	○	Strongly Agree

iii. It is easy to use this heuristic to evaluate the Wearable Virtual Reality Education Application. *

	1	2	3	4	5	
Strongly Disagree	○	○	○	○	○	Strongly Agree

iv. It is necessary for the researcher to provide more details for these heuristics. *

	1	2	3	4	5	
Strongly Disagree	○	○	○	○	○	Strongly Agree

WVREA 14: Accessibility

Definition	It refers to the design and implementation of features that enable learners with diverse abilities and needs to access and engage with the content and functionalities of the application.
Explanation	The application provides an educational experience inclusive and usable for people with disabilities or other limitation
Example(s)	For visual accessibility, the VR application provides alternative text or audio descriptions for visual content, offers high contrast options, or implements customizable font sizes.
Benefit(s)	This application can create an inclusive learning environment where users with diverse abilities can fully participate and benefit from the educational content and experience offered.
Checklist	i. Does the VR application provide adjustable font sizes and high contrast options? ii. Does the VR application use colour combinations that are accessible for users with colour blindness? iii. Does the VR application include captions or subtitles for all audio content within the VR experience? iv. Does the VR application provide volume controls and the option to adjust audio settings? v. Are the instructions clear and step-by-step?

i. This heuristic is useful to evaluate the Wearable Virtual Reality Education Application *

	1	2	3	4	5	
Strongly Disagree	○	○	○	○	○	Strongly Agree

ii. This heuristic provides a clear definition and evaluation checklist. *

	1	2	3	4	5	
Strongly Disagree	○	○	○	○	○	Strongly Agree

iii. It is easy to use this heuristic to evaluate the Wearable Virtual Reality Education Application. *

	1	2	3	4	5	
Strongly Disagree	○	○	○	○	○	Strongly Agree

iv. It is necessary for the researcher to provide more details for these heuristics. *

	1	2	3	4	5	
Strongly Disagree	○	○	○	○	○	Strongly Agree

Appendix A(ii) – Heuristic Evaluation (Experts)



Evaluation 2: Heuristic Evaluation

Objective: The objective of this survey is to gather your expert opinion and insights in order to identify usability problems in the Titans of Space Science education application and map the problems with the new heuristics, using a severity rating scale of 0-4 (Nielsen, 1994) to rate the severity of the identified usability issues. Your expertise and knowledge in this area are highly regarded and will significantly contribute to the outcomes of our research.

We kindly request your voluntary participation in this survey, which is designed to be concise and time efficient. Your responses will remain completely confidential and will only be accessible to the researchers involved in the study, namely Associate Professor Dr. Mohd Kamal bin Othman, Dr. Norehan Zulkiply, and Rahimah Binti Mat. Your expertise and collaboration are greatly appreciated, and we sincerely thank you for your valuable contribution to our research efforts.

Background: The Wearable Virtual Reality Education Application (WVREA) is a system that utilizes a head-mounted display and associated hardware to create a fully immersive and interactive learning experience. Users can effortlessly explore virtual environments in a natural and intuitive manner, fostering engagement and interactivity. Moreover, WVREA is designed to support learning objectives by providing engaging, stimulating, and authentic simulations of real-world scenarios or concepts. By offering lifelike experiences, the application enables users to immerse themselves in educational content that closely mirrors real-life situations. The design of WVREA pays careful attention to factors such as ease of use, user comfort, and task efficiency.

Demographics

Description (optional)

1. What is your age range? *

- 22-34
- 35-44
- 45-54
- 55-64
- 65+

2. What is your gender? *

- Male
- Female

3. What is your highest level of education completed? *

- ○ PhD
- ○ Master's degree
- ○ Bachelor's degree
- ○ Other...

4. What is your current job title/role? *

Short-answer text

5. How Frequent do you use Wearable VR technology? *

- ○ Rarely
- ○ Occasionally
- ○ Once a month
- ○ Several times a year
- ○ Weekly
- ○ Daily

PART 2: heuristics' easiness, overall quality, the intention for future use, completeness and the need for additional graphics as a whole.

Description (optional)

1. **Easiness:** How easy it was to perform the expert evaluation, based on this set of usability/UX heuristics? *

- ○ Very difficult
- ○ Difficult
- ○ Neutral
- ○ Easy
- ○ Very Easy

2. **Intention:** Would you use the same set of usability/UX heuristics when evaluating similar software product in the future? *

	1	2	3	4	5	
Strongly Disagree	○	○	○	○	○	Strongly Agree

3. **Completeness:** Do you think the set of usability/UX heuristics covers all usability aspects for this type of software product? *

	1	2	3	4	5	
Strongly Disagree	○	○	○	○	○	Strongly Agree

Do you have any suggestions on how to enhance or refine these newly developed heuristics? Please feel free to share your thoughts. Thank you

Long-answer text

Thank you very much.

Description (optional)

Appendix A(iii) – Heuristic Evaluation (schoolteacher)



Evaluation 3: Heuristic Evaluation (schoolteacher)

Objective:
The objective of this survey is to gather your expert opinion and insights to identify usability problems in three applications: Titans of Space Science education, The Big Table, and The Body VR. We will use new heuristics and a severity rating scale of 0-4 (Nielsen, 1994) to assess the severity of the identified usability issues. This aims to determine whether the usability/UX problems identified in a heuristic evaluation using the new set of heuristics are relevant for users. Additionally, we would like to seek your perception on the features relevant to the wearable virtual reality education application domain. Your expertise and knowledge in this area are highly regarded and will significantly contribute to our research outcomes."

We kindly request your voluntary participation in this survey, which is designed to be concise and time efficient. Your responses will remain completely confidential and will only be accessible to the researchers involved in the study, namely Associate Professor Dr. Mohd Kamal bin Othman, Dr. Norehan Zulkiply, and Rahimah Binti Mat. Your expertise and collaboration are greatly appreciated, and we sincerely thank you for your valuable contribution to our research efforts.

Background: The Wearable Virtual Reality Education Application (WVREA) is a system that utilizes a head-mounted display and associated hardware to create a fully immersive and interactive learning experience. Users can effortlessly explore virtual environments in a natural and intuitive manner, fostering engagement and interactivity. Moreover, WVREA is designed to support learning objectives by providing engaging, stimulating, and authentic simulations of real-world scenarios or concepts. By offering lifelike experiences, the application enables users to immerse themselves in educational content that closely mirrors real-life situations. The design of WVREA pays careful attention to factors such as ease of use, user comfort, and task efficiency.

Demographics

Description (optional)

1. What is your age range? *

- ○ 22-34
- ○ 35-44
- ○ 45-54
- ○ 55-64
- ○ 65+

2. What is your gender *

- ○ Female
- ○ Male

3. What is the name of your school? *

Short-answer text

4. How many years of experience do you have as a science teacher? *

- ○ 1-3 years
- ○ 4-5 years
- ○ 6-10 years
- ○ 11-15 years
- ○ 16-20 years
- ○ more than 20 years

5. What specific science subjects do you teach?

Long-answer text

6. What grade levels do you currently teach? *

Short-answer text

7. Are there any particular topics or concepts in your curriculum where you see potential benefits from VR applications?

Long-answer text

8. If so, could you please specify the reasons behind your perspective?

Long-answer text

9. Have you ever used Virtual Reality applications in your teaching before? *

- [ ] Yes
- [ ] No

10. What features or improvements would you like to se in a VR education application for science subject?

Long-answer text

Thank you very much.

Description (optional)