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WVREA heuristics: A comprehensive framework for evaluating usability in wearable virtual reality educational applications (WVREA)

Mohd Kamal Othman[1] · **Rahimah Mat**[1] · **Norehan Zulkiply**[1]

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Abstract
This research addresses the critical need for robust usability evaluation tools in Wearable Virtual Reality Educational Applications. We developed a comprehensive set of Wearable Virtual Reality Educational Applications usability heuristics through a multi-stage process. Initial heuristics were established through a literature review. Validation occurred in three phases, first with academics and industry practitioners (n = 25), second with experts in academics and industry (n = 15), and third with end-user schoolteachers (n = 15) and finally, refinement based on feedback from all phases. Expert validation surveys refined the heuristics based on feedback regarding utility, clarity, ease of use, and the need for additional checklists. The revised heuristics received positive feedback from experts in human–computer interaction and virtual reality, as well as school teachers, indicating their effectiveness in addressing usability issues. This research establishes a foundation for standardised WVREA usability practices, providing a valuable tool for the WVREA development community. Future exploration could involve longitudinal studies and developing additional user interface-focused heuristics.

Keywords Wearable virtual reality education application · Usability heuristics · Heuristic Evaluation · Heuristic development · Domain-specific heuristics

1 Introduction

Usability evaluation is a cornerstone in software development, ensuring products are efficient, effective, and user-friendly (Ismael Figueroa et al., 2019). Traditionally, user testing and focus groups can be time-consuming, especially during development

✉ Mohd Kamal Othman
omkamal@unimas.my

1 Present Address: Fakulti Sains Kognitif Dan Pembangunan Manusia, Universiti Malaysia Sarawak, Kota Samarahan, Sarawak, Malaysia

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(Nielsen, 1994a). In this research, we explore the use of heuristic evaluation (HE) as a valuable alternative, offering a cost-effective and efficient method for identifying potential usability issues in user interfaces (Mujuru & Lopez, 2021; Thompson, 2020), specifically in the context of wearable Virtual Reality Education Applications (WVREAs).

Heuristic evaluation utilises established principles (heuristics) to evaluate interfaces. Experts assess the interface based on these heuristics, identifying potential usability problems. Due to its effectiveness (Mujuru & Lopez, 2021; Thompson, 2020), HE has become a widely used method (Nielsen, 1994a; Quiñones & Rusu, 2017). 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 features of specific domains like WVREA, highlighting the need for WVREA-specific heuristics.

Over the past decade, Virtual Reality (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). Research suggests VR holds transformative potential by fostering deeper engagement and knowledge retention than traditional methods (Southgate, 2020). However, the success of VR in education hinges not just on the technology itself but also on the pedagogical innovation embedded within VR applications (Southgate, 2020). WVREAs represent a novel and rapidly developing domain within educational technology. They combine VR's immersive and interactive capabilities with pedagogical principles to create engaging learning experiences (Young et al., 2020). The rise of VR in teaching and learning has led to a surge in the use of wearable VR devices such as Oculus Quest 2 and HTC Vive (Hara et al., 2021; Qu et al., 2021; Young et al., 2020). These wearables contribute significantly to the immersive qualities of the VR experience by stimulating multiple senses and enhancing the feeling of presence – a complex psychological feeling of "being there" within the virtual world (Borgnis et al., 2022). Beyond presence, other crucial aspects of a user's VR experience include embodiment, empathy, and flow. Embodiment refers to the sensation of having a virtual body within the VR environment (Gall et al., 2021). Another valuable aspect is the ability to foster empathy and emotional connection through VR experiences (Christopoulos et al., 2020). Flow, a state of complete absorption in an activity, can also be enhanced by VR experiences (Smutny et al., 2019).

In VR application evaluation, usability considerations extend beyond traditional concerns like learnability and efficiency. They encompass the unique characteristics of VR that contribute to the user experience (UX) (Southgate, 2020). These characteristics, including immersion, presence, and embodiment, necessitate a more comprehensive approach to usability evaluation in VR. Furthermore, when developing specific VR applications, such as those for education, additional criteria must be considered to ensure alignment with the application's pedagogical goals.

Several existing heuristic sets have been developed to evaluate VR applications in general (Rusu et al., 2011; Sutcliffe & Gault, 2004) and specifically VR education (Young et al., 2020). However, these heuristics often fail to address wearable VR education applications' specific needs and functionalities. For instance, Young et al. (2020) focused solely on creating student-centred lesson plans for wearables, not evaluating existing applications.

These limitations of existing heuristics for WVREA highlight the critical need for a new set specifically designed to evaluate the usability of these applications. Such heuristics should have essential usability characteristics and a strong pedagogical foundation. Failing to account for these crucial aspects can lead to educational VR applications that are challenging to use, ultimately hindering student engagement and learning outcomes (Solano et al., 2016). The gap in the current landscape of VR usability evaluation motivated the present study. We aimed to develop and validate the first comprehensive set of usability heuristics tailored to wearable VR education applications (WVREA). We employed a well-established eight-stage methodology by Quiñones and Rusu (2019) to ensure a rigorous and effective development process. The following sections detailed this methodology (Sect. 3), the development and validation process of the WVREA heuristics (Sect. 4), and the discussion and conclusions derived from our findings (Sect. 5).

2 Literature review and related works

2.1 Heuristic evaluation and its limitations in VR

Heuristic evaluation (HE), introduced by Nielsen et al. (1990), offers a valuable method for assessing user interfaces (UIs) across various domains. Its effectiveness stems from its simplicity and ability to identify usability issues early in the design process, leveraging established usability principles. It typically involves skilled evaluators, such as researchers or domain specialists, who utilise a set of heuristics to review interfaces and identify potential user challenges systematically. Furthermore, HE often involves three to five experts focusing on key tasks representing core user interactions (Nielsen, 1995). By comparing user tasks to established heuristics, evaluators can pinpoint areas where the interface might be confusing or difficult to use. The key advantage of HE lies in its ability to identify potential problems early on, before significant development resources are invested, leading to a more user-friendly product and a superior user experience (Nik Ahmad et al., 2021).

However, reliance on general-purpose heuristics can be insufficient when evaluating interfaces designed for three-dimensional (3D) and spatially immersive environments like VR (Stadler et al., 2023; Zhang & Simeone, 2021). Several studies have highlighted the limitations of using general heuristics in VR contexts (Botha et al., 2021; Paes & Irizarry, 2018). For instance, Gammanpila et al. (2019) employed Nielsen's heuristics (1994b) to design a VR learning environment assessment system. While they acknowledged the use of these heuristics, the specifics of their implementation remain unclear. Similarly, Stadler et al. (2023) applied Nielsen & Molich's heuristics (1990) to evaluate VR dynamic guidance systems and discovered issues like cybersickness, a problem not typically identified through traditional usability heuristics. This underscores the need to explore the generalizability of HE across diverse VR applications.

Further limitations of general heuristics in VR contexts are evident in studies by Paes and Irizarry (2018) and Botha et al. (2021). Paes and Irizarry (2018) evaluated VR games using Nielsen et al.'s (1990) heuristics and revealed that these general-purpose guidelines did not adequately capture issues specific to multiple head-mounted displays (HMDs) and natural language interactions. Similarly, Botha et al. (2021) evaluated VR clinic simulations and identified disorienting and nauseating effects within the VR environment, issues beyond Nielsen's heuristics. Abd Hamid et al. (2016) applied Nielsen's heuristics (1994a) to evaluate a virtual Umrah experience, successfully detecting UI usability issues but failing to address usability problems specific to the virtual environment (VE), such as interaction and manipulation within that space.

Van Wyk and De Villiers (2014) further emphasised the need for improved evaluation frameworks in VR training programs. Their Design-based Research heuristic identified inadequacies in existing methods, highlighting general heuristics' limitations for VR training applications. These studies collectively underscore the shortcomings of general-purpose heuristics in capturing the unique usability challenges posed by VR environments. General heuristics often overlook crucial aspects specific to VR, such as immersion, presence, embodiment, and flow (Stadler et al., 2023; Wang et al., 2019). With advancements in VR technology, domain-specific heuristics become increasingly critical, as traditional ones are demonstrably unsuitable for effectively evaluating VR interfaces.

2.2 The need for wearable vr educational application (WVREA)-specific heuristics

This gap in the literature regarding a well-defined set of heuristics specifically tailored to WVREAs is a key focus of this study. WVREA-specific heuristics would offer significant value by highlighting crucial usability aspects unique to this domain. Recognising this gap, the primary objective of this research is to address the need for specific heuristics designed for wearable VR education applications. This will provide a comprehensive set of guidelines for VR developers, enabling them to create effective VR applications suitable for classroom use. This study aims to bridge the existing gap in the literature and offer a refined set of heuristics that align with the evolving landscape of educational wearable VR technology.

2.2.1 Beyond general-purpose heuristics: towards VR usability evaluation in education

Researchers have recognised the limitations of general-purpose heuristics in evaluating interfaces designed for three-dimensional (3D) and spatially immersive environments like VR (Stadler et al., 2023; Zhang & Simeone, 2021). Several studies have explored VR-specific evaluation methods to address these shortcomings. Early efforts include Rusu et al.'s (2011) development of 16 VR heuristics based on Nielsen's heuristics, which captured more usability issues in a VR application than the original set. Similarly, Desurvire and Kreminski (2018) introduced the VR PLAY framework, adapting existing game usability principles for VR experiences.

Research has also investigated the effectiveness of combining existing evaluation methods. Ismael Figueroa et al. (2019) found that combining Nielsen's heuristics with Virtual Learning Environment heuristics yielded more domain-specific VR problems compared to Nielsen's set alone. This highlights the potential benefits of tailoring evaluation methods to specific VR application areas, such as education. Several studies have developed VR heuristics specifically for evaluating applications in educational settings. For example, Botha et al. (2021) derived VR heuristics based on Nielsen's and cognitive walkthroughs to assess VR applications in nursing education. Hara et al. (2021) evaluated a VR nursing education game using Nielsen's heuristics and the Playability Heuristic Evaluation for Educational Computer Games (PHEG) instrument. These studies demonstrate the value of domain-specific VR heuristics for identifying usability issues in educational contexts.

Frameworks like MAUVE by Stanney et al. (2003) provide a more comprehensive approach to VR usability evaluation. MAUVE categorises VR usability into system interface and user interface aspects, addressing issues like motion sickness and user comfort. Abd Majid et al. (2021) extended this approach by developing usability guidelines for VR experiences designed for pediatric cancer patients using MAUVE criteria. These frameworks highlight the importance of considering numerous factors beyond traditional interface design when evaluating VR applications.

Another key focus area in VR usability evaluation is presence and immersion. Sutcliffe and Gault (2004) introduced a set of 12 heuristics specifically addressing usability and presence in VR environments. These heuristics have been applied in numerous studies (e.g., Hvannberg et al., 2012; Kabassi et al., 2019), emphasising the importance of UX factors beyond basic usability. Building upon these foundations, Young et al. (2020) developed eight heuristics for designing VR learning experiences. These heuristics incorporate learning theories and focus on learner engagement and exploration within a VR environment. However, the heuristics only focused on assessing students' attitudes and behaviour towards VR in the classroom, specifically targeting certain VR use cases and student populations, but did not measure learning outcomes. Additionally, no research currently focuses on developing VR applications aligned with pedagogical aspects emphasised in the Malaysian Education Blueprint, such as problem-solving skills and collaboration. These limitations highlight the need for a refined set of heuristics specifically designed for WVREAs. This study aims to address this gap by developing WVREA-specific heuristics that consider this emerging technology's unique pedagogical and usability aspects.

3 Methodology

3.1 Heuristic development methodology

This study employs a well-established and comprehensive systematic methodology developed by Quiñones and Rusu (2019) for creating WVREA. This methodology has been validated through expert opinions and successfully applied in various case studies, including creating a new set of heuristics (Quiñones et al., 2018). Effective heuristics, developed based on a well-defined methodology, encompass a standardised literature search, formalised definitions, expert validation, heuristic score comparison, and user testing with refinement (Quiñones et al., 2018; Saavedra et al., 2019). These stages, outlined in Quiñones and Rusu's (2019) methodology, aim to uncover specific usability issues within the application's domain during the early validation stage (Fig. 1). While appearing sequential, these stages can be performed iteratively to improve the heuristics and validate new experiments. Additionally, some stages may overlap or be revisited as needed.

3.1.1 Exploratory stage

In the exploratory stage, we conducted a comprehensive literature review to identify key features, usability attributes, and user experience (UX) factors of WVREAs. We catalogued relevant information and collected established general and specific heuristics applicable to the domain. Following Quiñones and Rusu's (2019) methodology, we gathered related information on WVREAs (see Appendix 4.6.3). Our review focused on (1) Defining WVREAs and their essential characteristics, (2) Identifying usability and UX attributes as described by various authors, and (3) Compiling a range of proposals for assessing usability and UX to ensure a thorough understanding. In the subsequent descriptive stage (stage 3), we will evaluate these proposals to select the most suitable for assessing WVREAs. Additionally, we will apply a well-established set of heuristics relevant to WVREAs. Our review sources included scientific articles, theses, books, and reputable websites that provided reliable and credible information on the topic.

3.1.2 Experimental stage

Given VR education's novelty and unique usability requirements, we focused on developing a new set of usability heuristics. A comprehensive literature review revealed a lack of existing research on VR education usability heuristics.

3.1.3 Descriptive stage

This stage involved establishing new usability heuristics for evaluating WVREAs. Building upon the exploratory stage, we revisited the data gathered (see Appendix 4.6.3), which included usability and UX attributes relevant to VR education. We employed a two-step selection process based on the significance of information for WVREA usability evaluation, following Quiñones et al. (2018).

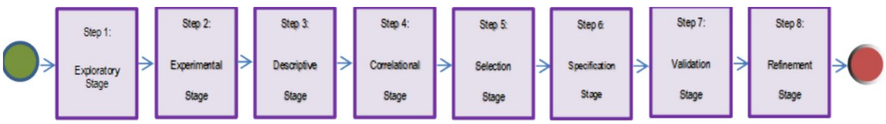

Fig. 1 Stages of the methodology developed by Quiñones and Rusu (2019) (Adapted from Quiñones & Rusu, 2019)

Data selection and analysis We assigned an importance score to each piece of information based on its relevance to WVREA usability: 3 for highly important, 2 for somewhat important, and 1 for not important. Only information with scores of 2 or 3 was further analysed and categorised (see Table 2 in Sect. 4.2).

Comparative analysis and heuristic prioritisation We conducted a comparative analysis of existing usability heuristics to determine their suitability for assessing VR education-specific usability attributes (Appendix 4.7). The analysis served two purposes: first, prioritisation of existing heuristics. Heuristics that appeared frequently in existing sets and addressed core WVREA usability concerns were prioritised (score of 3). This ensured that the new framework incorporated well-established and relevant evaluation criteria. Second, the analysis aimed to identify knowledge gaps. Heuristics not found in existing sets or those that could not be fully adapted to WVREAs were considered potential knowledge gaps. These were assigned a score of 1 and earmarked for further development and refinement, ensuring that the new framework addressed the unique usability needs of VR educational applications.

3.1.4 Correlational stage (Matching features to heuristics)

In the correlational stage, we examined the relationships between features and usability in VR educational applications. By revisiting previously identified features, we established correlations between these features and the prioritised usability attributes from the descriptive stage. This process involved matching features to attributes. We leveraged the analysis from the descriptive stage to connect VR education's usability attributes with existing and newly proposed heuristics. This matching helped determine which benchmarks are most relevant for assessing the usability of specific VR educational features. To align features with usability, UX attributes, and existing heuristics, we gathered previous information on WVREAs, specific features, and relevant usability or UX attributes. We then matched these elements with established heuristics. We used Nielsen's 10 heuristics as a foundation and supplemented them with three additional heuristics specifically tailored to VE: Rusu et al.'s (2011) heuristics, Sutcliffe and Gault's (2004) heuristics, and Gabbard et al.'s VR taxonomy (1997). By categorising the elements of the new heuristics in relation to the existing ones, we identified the most relevant benchmarks for assessing the usability of specific VR educational features.

3.1.5 Selection stage

The selection stage involved determining the most suitable heuristics for evaluating WVREAs. Building upon the correlational stage, we conducted two key analyses: First, heuristic-feature matching. We matched high-priority heuristics with key WVREA features and their corresponding usability attributes to understand how existing heuristics aligned with WVREA functionalities and UX considerations. Second, we identified knowledge gaps where existing heuristics might be insufficient, informing the development of new, WVREA-specific heuristics. Based on these analyses, we categorised each heuristic: Core heuristics addressing essential

WVREA features, and usability concerns were designated for "keep." Heuristics with potential but requiring modifications to fit WVREA attributes were assigned an "adapt" designation. Finally, irrelevant, or redundant heuristics were eliminated from the final WVREA heuristic set, although they may be revisited in future studies. This selection process ensured that the final WVREA heuristic set was comprehensive and applicable to the unique characteristics of VR educational applications.

3.1.6 Specification stage

In the specification stage, we formally documented the newly developed VR education usability heuristics. To ensure clarity and comprehensiveness, we followed the guidelines outlined by Quiñones et al. (2018). These guidelines provide a structured framework for documenting each heuristic, encompassing six key elements:

1. Unique Identifier
2. Concise Name and Purpose
3. Detailed Explanation (linking to relevant usability principles, potential issues, and existing heuristics)
4. Specific Examples (of violations and successful implementations)
5. Benefits of following the heuristic
6. Potential Problems from misunderstanding or misinterpreting the heuristic.

By adhering to this structured approach, we ensure the newly developed heuristics are well-defined, informative, and readily applicable for evaluating the usability of VR educational applications. In the following stage, these proposed heuristics underwent a series of validation procedures.

3.1.7 Validation stage

The proposed VR education usability heuristics will undergo an expert validation process to ensure their effectiveness and usefulness.

Phase 1: Expert judgment To ensure the effectiveness and usefulness of the proposed VR education usability heuristics, we conducted an expert validation process. Two groups of experts participated. First, 15 researchers or academics with 10–15 years of experience in Human–Computer Interaction (HCI) and VR technology, and second, 10 industry practitioners with 3–10 years of experience in conducting HE. Prior to the evaluation, we obtained informed consent from all participants, guaranteeing their understanding of their rights and data treatment procedures. The evaluation was conducted using an online Google Form. The first section assessed each heuristic 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 Need for additional checklist (D4). The second section assessed factors such as Easiness, Intention, and Completeness. This comprehensive evaluation ensured that all aspects of the heuristics were thoroughly assessed.

***Phase* 2: Heuristic evaluation of VR educational apps with WVREA (Expert evaluations)** The validation phase aimed to assess the effectiveness of the newly developed WVREA heuristics through HE. Three educational applications, Titans of Space PLUS, The Body VR, and The Big Table (as depicted in Fig. 2), were chosen for evaluation.

A total of sixteen participants were recruited for the HE via email invitation, encompassing a diverse range of expertise, including HCI lecturers (n = 3) specialising in VR education (4–15 years of experience), VR lecturers (more than ten 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 researcher (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. Prior to the evaluation, informed consent was obtained from all participants to ensure their understanding of their rights and data treatment procedures.

The evaluation process involved providing participants with the newly developed WVREA heuristics (detailed in Appendix 6) along with representative tasks specific to each application (see Appendix 9). Evaluators were allocated a minimum of 15 min to familiarise themselves with each VR application before commencing the formal evaluation. During the evaluation, participants identified and reported usability issues encountered while using the applications. These issues were then mapped to the corresponding WVREA heuristics and assigned a severity rating based on a 0–4 scale established by Nielsen (1992). This scale ranged from "Not a usability issue" (0) to "Catastrophe issue" (4), allowing for a nuanced assessment of the severity of identified problems.

Phase 3: Heuristic evaluations with users Following the expert HE, we conducted a user validation phase to gain insights into UX and identify potential usability issues in real-world scenarios. We recruited sixteen experienced science schoolteachers through snowball sampling for face-to-face HE. However, one participant withdrew due to motion sickness, resulting in a final group of fifteen users. Prior to testing, we obtained informed consent from all participants.

During the user validation, participants focused solely on the Titans of Space PLUS VR application. We provided them with a pre-defined list of fifteen representative tasks (detailed in Appendix 9) to complete. Using a severity rating scale (0–4, established by Nielsen, 1992), users assessed encountered usability issues. The process involved a researcher briefing participants, obtaining informed consent, and providing training on using the VR controller. Participants were given time to familiarise themselves with the application before attempting the tasks. Throughout

Fig. 2 Three educational apps (Left to Right): Titans of Space Plus, The Big Table and The Body VR

the evaluation, we encouraged users to think aloud and report any difficulties they encountered while interacting with the VR environment. This approach allowed us to gain valuable insights into the user experience and identify potential areas for improvement within the WVREA heuristics.

3.1.8 Refinement stage

In the refinement stage, we refined the newly proposed heuristics based on the validation stage's results. We defined the specific heuristics that were created, refined, or deleted, along with the reasons for these changes and the methods used to implement them.

4 Results and discussions

4.1 Stage 1: Exploratory stage

Our exploration stage laid the groundwork for crafting a robust set of WVREA heuristics. This initial phase yielded three critical outputs:

1. WVREA Details, which provides a comprehensive overview of relevant WVREA information (Appendix 4.6.3).
2. Usability and UX Attributes: To establish a solid foundation for heuristic development, we identified a comprehensive array of usability and UX attributes that are essential for evaluating WVREAs. These attributes were meticulously amassed from three well-established frameworks:
    a. The Quality in Use Model (ISO, 2011) emphasises seven key aspects: effectiveness, efficiency, learnability, operability, user error protection, freedom from risk, and context completeness.
    b. Nielsen's Usability Attributes (2012) focus on five core areas: learnability, efficiency, memorability, errors, and satisfaction.
    c. Tcha-Tokey et al.'s 10 UX Factors for Immersive VE (2018) broaden the perspective beyond core usability to encompass a wider range of UX considerations, including presence, engagement, immersion, flow, usability, skill, emotion, experience consequence, judgment, and technology adoption.

    By drawing upon attributes from these frameworks, we constructed a strong foundation for developing effective WVREA usability heuristics.
3. Existing Heuristics: To leverage existing knowledge and expedite the development process, we identified four sets of established VR and usability heuristics that could serve as a springboard for the next stage. These heuristics, outlined in Appendix 4.7, were developed by prominent researchers in the field, including Rusu et al. (2011), Sutcliffe and Gault (2004), Gabbard et al. (1997), and Nielsen (1994b).

Furthermore, to understand the impact of the proposed heuristics on a broader scale, we compared features between less immersive VR educational applications (typically designed for desktops or mobile devices) and WVREA (detailed in Table 1).

4.2 Stage 3: Descriptive stage

Our analysis, guided by the selection process outlined previously, yielded a comprehensive set of criteria for WVREA usability. Table 2 categorises and presents this data, highlighting the information deemed highly important (score of 3) and somewhat important (score of 2) for WVREA usability evaluation. This table provides valuable insights into the key aspects that need to be considered when assessing the usability of VR educational applications.

Before prioritising existing heuristics for WVREA-specific development, we conducted a comparative analysis, as recommended by Quiñones et al. (2018). This analysis aimed to identify overlaps and similarities in the criteria evaluated by each heuristic set. We examined each set to determine how they addressed similar usability concerns, whether they used the same or similar wording for evaluation criteria and any gaps where existing heuristics might not fully address WVREA-specific usability challenges. The detailed results of this comparative analysis are provided in Appendix 4.7.

Based on the identified criteria in Table 2, this comparative analysis (Appendix 4.7) informed the prioritisation of heuristics for WVREA evaluation. Heuristics appearing in multiple sets and addressing core usability concerns (e.g., Recovering from Errors) were assigned high importance. Heuristics relevant to WVREAs but with less prevalence received a moderate score. Domain-specific heuristics or those requiring adaptation for WVREAs were assigned a lower score but will be further reviewed for potential inclusion.

4.3 Stage 4: Correlational stage

The Correlational Stage analysis focused on aligning high-priority heuristics (identified in Stage 3) with relevant features specific to WVREAs. This analysis aimed to identify gaps in existing heuristics regarding their ability to address these domain-specific features. By comparing heuristic priorities and WVREA features, we achieved two key results:

1. Well-matched heuristics: We identified several existing heuristics with high-priority scores that directly correspond to key WVREA features. This correspondence indicates their strong applicability for evaluating WVREA usability. Appendix 5 provides a detailed breakdown of these well-matched heuristics, including the corresponding features and attributes.
2. Gaps in Heuristics: The analysis also revealed features specific to WVREAs that lacked corresponding high-priority heuristics. These gaps represent areas where new heuristics might be crucial for effectively evaluating WVREA usability. Appendix 5 provides details on these identified gaps, highlighting the specific features and attributes that require the development of new heuristics.

Table 1 Comparison of immersive VR Education Apps with Wearable VR Education Applications

Features	Less immersive VR Education apps	Wearable VR Education 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; Chen, 2016; Gabbard et al., 1997; Garzotto et al., 2017; Gelsomini et al., 2016; Miguel-Alonso et al., 2023; Newbutt 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 (Banerjee et al., 2023; Pedram et al., 2021)	High; Users fully immerse themselves 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; Wang et al., 2022; Pellas et al., 2020a, b; 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 user experience within a fully immersive environment
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) (Banerjee et al., 2023; Paes et al., 2021)	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 et al., 2020a; Segura et al., 2020 Fernandes & Werner, 2019; Al-Azawi et al., 2019; Concannon et al., 2019; Makransky et al., 2017; Maheshwari & Maheshwari, 2020; Han, 2020; Makransky 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
Visualisation	2D (Monoscopic perspective) (Paes et al., 2021; Rusu et al., 2011)	3D scene (Banerjee et al., 2023; Han, 2020)	Heuristics might address potential limitations in visual fidelity due to hardware constraints and ensure clear and focused visuals to avoid user strain

Table 1 (continued)

Features	Less immersive VR Education apps	Wearable VR Education Application	Impact on New Heuristics
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 the immersive nature of WVREAs 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; Chen, 2016; Gabbard et al., 1997; Garzotto et al., 2017; Gelsomini et al., 2016; Miguel-Alonso et al., 2023; Newbutt et al., 2017; Sun et al., 2021)	Heuristics could address potential limitations caused by the VR headset's processing power or battery life
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 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 heuristics (e.g., Nielsen, 1994a) and the unique features of WVREAs
The main features of WVREA	3	Categorizes 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. (2011)—16 usability heuristics for virtual worlds (2) Sutcliffe and Gault (2004)—12 heuristics for VR applications (3) Gabbard et al. (1997)—Taxonomy of Usability of Characteristics in Virtual Environments (4) Nielsen (1994b)—10 usability heuristics for user interface design

The findings from this stage will inform the development of new, WVREA-specific heuristics in the next stage. Appendix 5 serves as a valuable resource, providing a comprehensive breakdown of matched features, attributes, and existing heuristics alongside the identified gaps in heuristic coverage.

4.4 Stage 5: Selection stage

Building upon the insights gleaned from the Correlational Stage analysis (Stage 4) – detailed in Appendix 5, Stage 5 focused on selecting the most suitable heuristics for evaluating WVREAs. Appendix 4 presents the comprehensive results of this selection process, including the designations assigned to each heuristic.

4.5 Stage 6: Specification stage

The specification stage focused on formally documenting the final set of usability heuristics for WVREAs. To ensure a concise and manageable set, we prioritised maintaining a reasonable number of heuristics, as recommended by Quiñones et al. (2018). Informed by the heuristic selection process outlined in Stage 5 (detailed in Appendix 5.1), we established a final set of heuristics. Table 3 summarises these key heuristics, including:

1. *Heuristic ID:* A unique identifier for each heuristic for ease of reference.
2. *Heuristic Name:* A concise and descriptive name that captures the essence of the heuristic.

Appendix 6 provides a comprehensive breakdown of each heuristic to ensure its effective application within the WVREA evaluation context. This breakdown includes (1) a clear definition and explanation of the heuristic's purpose and its specific relevance to WVREA usability, (2) illustrative examples demonstrating how to utilise the heuristic to identify potential usability issues, (3) benefits gained by following each heuristic during the evaluation process and (4) include practical checklists, when relevant to the specific heuristic, to guide evaluators during assessment. By providing this comprehensive documentation, Appendix 6 ensures the clarity, usability, and effectiveness of the newly developed WVREA heuristics. This comprehensive approach facilitates the practical application of these heuristics in future WVREA evaluations.

4.6 Stage 7: Validation Stage

4.6.1 Phase 1: Usability assessment

An expert validation survey assessed the usability of the newly developed WVREA heuristics. The survey focused on four key dimensions: Utility (usefulness), Clarity

Table 3 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

(understandability), Ease of Use (application during evaluation), and the Need for an Additional Checklist. The overall findings, detailed in Table 4, were positive.

The mean score across all heuristics and dimensions was 3.9, indicating user satisfaction. Notably, the "Utility" dimension received the highest mean score (4.1), demonstrating that users found the heuristics highly valuable for evaluating WVREA usability. Similarly, the "Clarity" dimension scored high (4.1), indicating that the heuristics were clear and easy to understand. "Ease of Use" also received a favourable mean score (3.9), suggesting users found the heuristics straightforward to apply during the evaluation process. However, opinions on the "Need for an Additional Checklist" were mixed, with the mean score being the lowest (3.6). This suggests that while some users felt a separate checklist was unnecessary, others might have found it helpful. Further investigation into user preferences for checklists might be beneficial.

In conclusion, the expert validation survey revealed positive feedback on the usability of the newly developed WVREA heuristics. They were useful, clear, and relatively easy to use. While opinions on checklists were mixed, further exploration can inform future decisions on their inclusion.

The expert validation survey assessed the mean usability scores and explored the relationships between user perceptions using correlation coefficients. These findings are visualised in Fig. 3 and further analysed below.

High ratings for utility and clarity Participants provided positive feedback on the newly developed heuristics, particularly their utility. With a mean rating of 4.11 out of 5 on the utility dimension (Fig. 3), users found the heuristics highly valuable in achieving their goals. Similarly, the clarity dimension received a strong mean score of 4.08 out of 5, indicating that the participants found the heuristics clear and easy to understand. These consistent ratings demonstrate user agreement on the usefulness and clarity of the heuristics.

Table 4 The Mean Usability of Each WVREA Heuristic based on Expert Validation Surveys

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

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

Fig. 3 Mean perception of overall WVREA usability heuristics

Positive feedback on ease of use, mixed views on checklists The ease-of-use dimension received a mean rating of 3.91 out of 5, suggesting that participants generally found the heuristics straightforward. However, there were some variations in opinion, with some finding them easier to use than others. The need for an additional checklist received the lowest mean rating (3.61 out of 5). This suggests a moderate need for checklists to complement the existing heuristics. However, the ratings showed significant variability. Some participants strongly needed additional checklists, while others found them unnecessary. Participants gave the newly developed heuristics an impressive mean utility dimension rating of 4.11 out of 5. They found the heuristics highly useful in achieving their goals. Regarding clarity, the participants rated the dimension mean of 4.08 out of 5. This indicates that the heuristics were easily understood and clear to most participants. The ratings were consistent, showing that most people found the heuristics clear.

Correlations reveal interesting relationships Figure 4 elucidates 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 0.809) and ease of use (correlation coefficient of 0.602). This indicates that participants who found the heuristics more useful also perceived them as clearer and easier to use.
2. Weak Negative Correlation: There is a weak negative correlation between utility and needing an additional checklist (correlation coefficient of −0.420). 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 0.636). 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 −0.231) or between ease of use and the need for an additional checklist (correlation coefficient of −0.066). 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

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).

Fig. 4 Correlation Coefficients for mean perception scores among WVREA heuristics 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.

Overall user experience with the evaluation process Figure 5 explores the participants' overall experience with the expert evaluation process using the newly developed heuristics. The findings suggest a good UX across several key areas.

1. Easiness: The experts rated the ease of performing the expert evaluation process highly, with a mean score of 4.08, indicating that they found it to be user-friendly. The low standard deviation of 0.400 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 rating 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 expressed a high perception of the heuristics' completeness in addressing all usability aspects of wearable virtual reality education applications. With a mean rating of 4.16 and a low standard deviation of 0.374, the consistency of the ratings indicates a strong consensus among the experts. This high mean value suggests that most experts agree on the comprehensiveness of the heuristics.

Overall, these good ratings suggest that the newly developed heuristics facilitated a reasonably user-friendly evaluation process. However, the variability in some

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		

Fig. 5 Mean perception of overall WVREA usability heuristics

responses highlights opportunities for further refinement and exploration of user needs to ensure the heuristics are both easy to use and comprehensive for future evaluations.

4.6.2 Phase 2: Validation through experts HE

Table 5 summarises the demographic analysis of all participants involved in HE. We recruited 16 participants; however, one withdrew due to motion sickness, resulting in a final of fifteen participants.

The HE identified a concerning number of usability problems across all three VR applications. Titans of Space Plus had the most catastrophic issues (13 rated 4), highlighting significant problems that need immediate attention before release. Notably, The Body VR also contained 7 catastrophic usability issues. While The Big Table VR had no catastrophic issues, it still presented 13 major problems requiring focus. Summary of all issues identified as follows:

1. Titans of Space Plus: (13 catastrophic, 13 major, 14 minor, 3 cosmetic)
2. The Big Table VR: (13 major, 7 minor, 1 cosmetic)
3. The Body VR: (7 catastrophic, 13 major, 7 minor)

These findings emphasise the need for thorough usability testing and addressing these issues to ensure a smooth and effective learning experience for students using these VR educational apps. Appendix 7 details the usability issues identified by users, their severity and WVREA corresponding.

4.6.3 Phase 2: 4.6.3 Validation through users HE

Fifteen science schoolteachers participated in the users' HE, with a majority (46.7%) possessing 11–15 years of teaching experience. Similarly, with expert testing, one

Table 5 Demographics analysis for Experts HE

Participant Category	Total Participants	Years of Experience
Lecturer in HCI	2	6–10 years
Lecturer in HCI	1	4–6 years
Instructor in AR/VR	1	6–10 years
Lecturer in AR/VR	1	> 10 years
VR Consultant	1	> 10 years
Research and Product Development Executive	1	1–3 years
VR developers	3	1–3 years
VR developers	4	4–5 years
Graphic Designer	1	1–3 years
UX researcher	1	1–3 years

participant withdrew due to motion sickness, resulting in a final of fifteen participants. The users' HE confirmed the presence of several usability issues already identified during the experts' HE (e.g., missing the quit button). It also revealed new user-specific issues related to the learning experience, such as the lack of instructions or another language option. Appendix 8 details the usability issues identified by users, their severity and WVREA corresponding. Figure 6 illustrates the similarities and differences uncovered in the heuristic evaluation between experts and users of Titans of Space Plus VR apps.

4.7 Stage 8: Refinement Stage

Stage 8 focused on refining the newly developed WVREA heuristics based on the findings from the validation stage (Stage 7: Phases 1 to 3). This stage aimed to address user feedback and enhance the overall usability and effectiveness of the heuristics. The findings from HE by experts and user feedback (Stage 7: Phases 2 and 3) suggested that all usability issues can be mapped with the heuristics, thus validating our WVREA without further changes.

5 Conclusion, implications and future work

This study addressed a critical gap in VR education by developing a comprehensive set of usability heuristics (WVREA) for evaluating WVREAs. The development process involved a multi-stage approach, with expert validation surveys conducted in three separate phases, engaging academicians, industry professionals, and educators in the education domain.

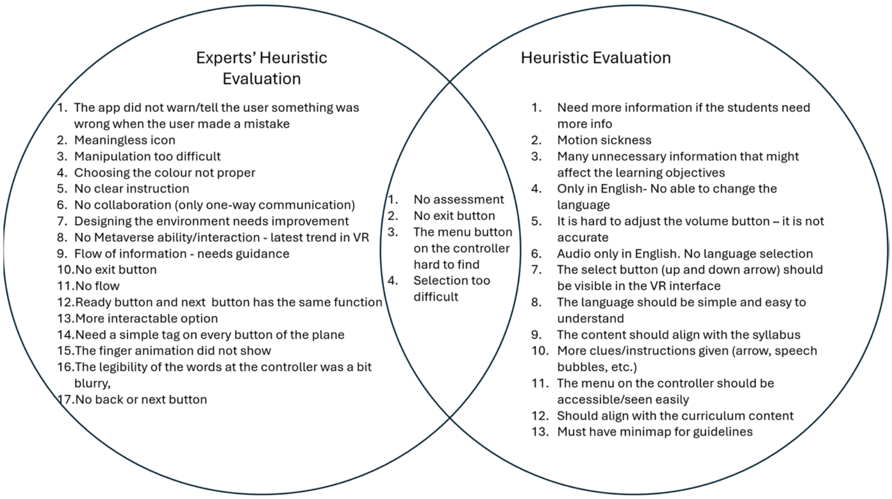

Fig. 6 Comparing Similarities and Differences in Heuristic Evaluation between Experts and Users

The findings revealed positive user feedback on the overall usability of the heuristics. Users found them highly useful (mean score of 4.11) and clear (mean score of 4.08). Additionally, a positive correlation between perceived utility, clarity, and ease of use suggested a well-designed and cohesive set of heuristics. However, while the majority of users found the heuristics comprehensive, a small percentage suggested the need for additional checklists. User opinions regarding specific heuristics' clarity and ease of use were also mixed.

The three-phase validation process 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, 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, user experience design, curriculum-aligned content, learning measurement tools, and accessibility considerations.

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

Implications and future work While this research establishes a foundation for WVREA usability evaluation with the development of the WVREA heuristics, there are opportunities for further exploration to enhance their effectiveness and user-friendliness. Beyond immediate refinement, several promising directions can broaden the impact of the WVREA heuristics. Longitudinal studies, by tracking the use of the heuristics in real-world WVREA development projects, can yield valuable insights into their effectiveness in practical settings and identify areas for potential future refinements. Also, developing additional heuristics specifically targeting UI design aspects of WVREAs could provide a more comprehensive framework for evaluating and optimising the user experience within the VE. Finally, Adapting and validating the heuristics for different cultural contexts can broaden their applicability for global WVREA development. This internationalisation effort, by ensuring cultural relevance, can empower a wider range of educators and developers to create effective VR educational experiences for a global audience.

The newly developed WVREA heuristics have the potential to significantly impact VR education. They offer a practical framework for evaluating and improving WVREA usability, ultimately contributing to the development of more user-friendly and effective educational experiences. Furthermore, the heuristics can promote consistent and standardised evaluation practices within the WVREA development community. This standardisation can foster communication and collaboration among developers, researchers, and educators, leading to the creation of even more effective VR educational tools. By addressing future work opportunities and considering the broader implications, this research can contribute to advancements in high-quality and user-centred WVREA development for educational purposes.

6 Appendix 1

Table 6

Table 6 Summary of Related Information on Wearable VR Educational Applications (WVREAs)

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., 2018; 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 through direct experiences and active engagement	Bernardo & Duarte, 2023; Di Natale et al., 2020; Junge et al., 2023; Adi Badiozaman et al., 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., 2018; Rupp et al., 2019; Lamb et al., 2018; Sankaranarayanan et al., 2018; Cho & Lim, 2017; Johnston et al., 2018; Dede 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; Becker et al., 2023
	Motivation: Enhancing student motivation through a highly interactive and immersive learning environment	Parmar et al., 2023; Byukusenge et al., 2023; Becker et al., 2023; Di Natale et al., 2020; Makransky et al., 2019; Dirin & Laine, 2023; Newbutt et al., 2017; Gelsomini et al., 2016; Lee et al., 2017; Parong & Mayer, 2018

Table 6 (continued)

Category	Description	References
	Collaboration: Facilitating collaborative problem-solving scenarios where learners work together	Pellas, et al., 2020a, b; 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., 2018; Chen et al., 2017; Siddhpura et al., 2020; Qu et al., 2021; Grassini et al., 2020; Neuwirth et al., 2018; 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
	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., 2018; 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 et al., 2020a, b
	Motion sickness: Some users may experience nausea when using VR, especially if unfamiliar with VEs	Garzotto et al., 2017; Pellas et al., 2020a, b; Tychsen & Foeller, 2020; Newbutt et al., 2017

Table 6 (continued)

Category	Description	References
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 et al., 2020a, b; 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, 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., 2018; 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 et al., 2020a, b; 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
	Presence: Evokes a strong sense of presence or "being there" within the VE	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 et al., 2020a, b; 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	

Table 6 (continued)

Category	Description	References
	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., 2018; Kadri et al., 2024,
	Interactivity: Dynamic and engaging features enable users to actively participate in learning	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 al., 2022; Moore et al., 2020;Pellas et al., 2020a, b; 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 et al., 2020a, b; 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 et al., 2020a, b; Segura et al., 2020; Fernandes & Werner, 2019; Al-Azawi et al., 2019; Concannon et al., 2019; Hite et al., 2019

Table 6 (continued)

Category	Description	References
	Pedagogy & Cognition: Immerses users in realistic environments for experiential learning through simulations, role-playing scenarios, critical thinking challenges, and problem-based learning activities	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., 2018; 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 et al., 2020a, b; 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., 2018; Kadri et al., 2024
	Personalisation: Tailors learning experiences to individual needs by 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; A. Wang et al., 2022; Moore et al., 2020; Pellas et al., 2020a, b; Segura et al., 2020; Fernandes & Werner, 2019; Al-Azawi et al., 2019; Concannon et al., 2019; Maheshwari & Maheshwari, 2020
	Learning Measurement: Integrates measurement tools to track and evaluate learner progress and performance with real-time feedback	Qorbani et al., 2021; Christopoulos et al., 2020; Pellas & Kazanidis, 2014; Pellas et al., 2020a, b; Chien et al., 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., 2018; 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	

7 Appendix 2

Table 7 Comparative Analysis of existing heuristics

Value	Heuristics			
	Virtual World Heuristics (Rusu et al., 2011)	**VR apps Heuristics** (Sutcliffe & Gault, 2004)	**VE Characteristic** (Gabbard et al., 1997)	**User Interface Design Heuristics** (Nielsen, 1994b)
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
3	**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) **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 **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	**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

Table 7 (continued)

Value	Heuristics			
	Virtual World Heuristics (Rusu et al., 2011)	**VR apps Heuristics** (Sutcliffe & Gault, 2004)	**VE Characteristic** (Gabbard et al., 1997)	**User Interface Design Heuristics** (Nielsen, 1994b)
3	**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	-	**GBAgents1**: Include agents that are relevant to user tasks and Goals **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)	**N8: Aesthetic and minimalist design** 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) **GBSysInfo3:** Strive to maintain interface consistency across applications	**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
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 devices such as joysticks and wands which, in effect, place themselves between users and environments	**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
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 a detailed presentation of the 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

Table 7 (continued)

Value	Heuristics			
	Virtual World Heuristics (Rusu et al., 2011)	**VR apps Heuristics** (Sutcliffe & Gault, 2004)	**VE Characteristic** (Gabbard et al., 1997)	**User Interface Design Heuristics** (Nielsen, 1994b)
3	**-**	**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	**GBUserRep5**: User embodiments should be as efficient as possible (e.g., 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 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 kinesthetic 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 application-specific data, providing insight not possible through other presentation means	

Table 7 (continued)

Value	Heuristics			
	Virtual World Heuristics (Rusu et al., 2011)	**VR apps Heuristics** (Sutcliffe & Gault, 2004)	**VE Characteristic** (Gabbard et al., 1997)	**User Interface Design Heuristics** (Nielsen, 1994b)
3	**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 'real' world should be as natural as possible	**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 **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 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? 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 & Sibert, 1995) design principles	

Table 7 (continued)

Value	Heuristics			
	Virtual World Heuristics (Rusu et al., 2011)	**VR apps Heuristics** (Sutcliffe & Gault, 2004)	**VE Characteristic** (Gabbard et al., 1997)	**User Interface Design Heuristics** (Nielsen, 1994b)
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 clear messages, hopefully indicating causes and solutions for errors		**GBTask7: Stackable**- Provide stepwise, subtask refinement, including the ability to undo **GBTask6**: Design interaction mechanisms and methods to support user performance of serial tasks and tasks sequences	**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
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 actions that user may perform over the objects	**SG10: Support for learning.** Active objects should be cued and if necessary, explain themselves to promote learning of VEs	-	-

Table 7 (continued)

Value	Heuristics			
	Virtual World Heuristics (Rusu et al., 2011)	**VR apps Heuristics** (Sutcliffe & Gault, 2004)	**VE Characteristic** (Gabbard et al., 1997)	**User Interface Design Heuristics** (Nielsen, 1994b)
3	**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)	-
1	-	-	**GBUsers2: Domain Knowledge-**Support users with varying degrees of domain knowledge (Expert/Novice users)	-

Table 7 (continued)

Value	Heuristics			
	Virtual World Heuristics (Rusu et al., 2011)	**VR apps Heuristics** (Sutcliffe & Gault, 2004)	**VE Characteristic** (Gabbard et al., 1997)	**User Interface Design Heuristics** (Nielsen, 1994b)
1	-	**-**	**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 **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 **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 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 social organisation, construction, and execution of plans (e.g., group communication, role-play, informal interaction)	-

8 Appendix 3

Table 8 Result from Correlational stage (stage 4)

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
Multi-sensory Learning: 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)	
Interactivity: Users can interact with the VE using natural gestures and movements. This allows for a more intuitive and immersive learning experience **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 (Adi Badiozaman et al., 2022; Kadri et al., 2024; Vats & Joshi, 2024) **Gamification:** Incorporating gamification elements can increase user engagement and motivation (Kadri et al., 2024; Pellas & Kazanidis, 2014; Scavarelli et al., 2021; Segura et al., 2020)	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 **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 **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) **GBManip11**: When possible, combine query formation with selection methods **GBManip12**: Support interface query for users to determine what actions are available for objects

Table 8 (continued)

Features	Attributes	Heuristics
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 **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 8 (continued)

Features	Attributes	Heuristics
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 consequence 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)
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**

Table 8 (continued)

Features	Attributes	Heuristics
Easy-to-use interface: A user-friendly interface ensures accessibility and a positive learning experience for all ages and backgrounds. (Al-Azawi et al., 2019; Concannon et al., 2019; Fernandes & Werner, 2019; Moore et al., 2020; Qorbani et al., 2021; Segura et al., 2020; Wolfartsberger, 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) **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 **GBSetting4:** Employ rendering techniques that support detailed presentation of setting without introducing **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 8 (continued)

Features	Attributes	Heuristics
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 et al., 2020a)	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 al., 2018; Scavarelli et al., 2021; Fealy et al., 2019; Detyna & Kadiri, 2020)	1. Context Completeness (ISO, 2011) 2. Tcha-Tokey et al. (2018) i. Flow ii. Emotion iii. Experience Consequence iv. Judgement	**GBUsers2: Domain Knowledge-**Support users with varying degrees of domain knowledge (Expert/Novice users)

9 Appendix 4

Table 9 Heuristic 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			
	Engages multiple visual, auditory, and tactile senses to enhance learning and retention	Create	**Engages various sensory experience**	**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	Object Selection — Non-isomorphic	**Adapt (as WVREA 4)** Nonisomorphic (Non-Realistic magic technique)	Interactivity Pedagogy & Cognition Engagement Gamification	**WVREA 4**
	Object Selection — Isomorphic	**Adapt (as WVREA 5)** Isomorphic (Realistic)		**WVREA 5**

Table 9 (continued)

Existing ID	Heuristics		Action	WVREA Features Covered	New ID
GBManip1 GBManip12 GBManip2	Object Manipulation	Nonisomorphic	**Adapt (as WVREA 6)** Nonisomorphic (Non-Realistic magic technique)	Interactivity Pedagogy & Cognition Engagement Gamification	**WVREA 6**
GBManip3 GBManip4 GBManip5 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				
GBUserRep3	Provide an egocentric point of view(s) when users must experience a strong 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 9 (continued)

Existing ID	Heuristics		Action	WVREA Features Covered	New ID
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**
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**
	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**

10 Appendix 5

Table 10 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 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
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

Table 10 (continued)

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:** Are the visuals high-resolution and realistic? Is the virtual environment visually appealing and immersive? **Auditory Experience:** Are sound effects used to enhance the virtual environment and interactions? Is there clear and synchronised narration or explanations for educational content? **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 synchronised with the visual and auditory elements? **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? **Olfactory Stimulation:** If applicable, does the application incorporate scents or smells to enhance the virtual environment? Are the scents appropriately synchronised with the educational content and virtual scenarios? 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
Checklist	**Accurate Physics Simulation:** Do objects behave realistically when users interact with them (e.g., proper weight, collision detection, and response? **Real-Time Responsiveness:** Does the application provide immediate feedback in response to user actions? Is the feedback synchronised with the user's interactions, ensuring a seamless and natural experience? Are there minimal delays or latency between user input and the corresponding feedback? **Sensory Integration:** Do the visual, auditory, and haptic feedback elements work together to create a coherent, immersive experience? Is there consistency between the sensory feedback and the actions performed by the user? **Contextual Relevance:** Does the feedback provided align with the specific educational context and objectives? Are the responses and interactions relevant to the subject matter being taught?

Table 10 (continued)

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
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	Are the selected objects easily accessible and interactable in virtual reality? Is there any instruction or tutorial on interacting with and manipulating the object effectively? Are the instructions or tutorials clear? 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
Benefit(s)	The selection technique allows the learner to select naturally, visualise, explore, and understand the object more effectively
Checklist	Is the object selection seamless and natural for the user? Are there any visual or auditory feedback mechanisms? Is the feedback unambiguous? 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? 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	Are the controls and gestures intuitive and easy to understand? Does the application provide users with feedback when manipulating objects non-isomorphically?

Table 10 (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	Can the user perform a variety of manipulations, such as rotation, translation, scaling, and assembly? Are there any restrictions on object manipulation, such as limits on rotation angle or collision avoidance? Are there multiple ways for users to manipulate objects, catering to different preferences and accessibility needs?
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	Does the application provide various customisation options to accommodate various customer preferences? Are the tools for avatar customisation user-friendly? 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
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

Table 10 (continued)

Checklist	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? Does the virtual environment accommodate multiple users simultaneously so that they can move, interact with objects, and engage in activities together? 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? 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? Does the VE support features that allow for shared object manipulation, such as joint object handling or synchronised interactions, to support collaborative learning experiences?
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	Is the VR application's language for commands and instructions clear and concise? Are the labels for buttons, menus, and interactive elements descriptive and easily understandable? Are the system's messages and feedback helpful in resolving issues or errors? Is the language used encouraging and providing positive reinforcement that can motivate learners and enhance their learning experience? Do the objects and activities within the virtual environment use familiar settings that mirror real-world experiences 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.

Table 10 (continued)

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 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 personalizing the learning experience, VR apps can optimize knowledge retention and skill development.
Checklist	Multiple Learning Paths: Does the VR application offer different learning paths or difficulty levels that users can choose from based on their proficiency? Progressive Scaffolding: Does the application provide instructional scaffolding, such as tutorials, hints, or guided activities, to support novice users? Mastery Opportunities: Does the VR experience offer challenges, complex tasks, or opportunities for independent exploration for advanced learners? Personalization Options: Can users customize their VR experience by adjusting settings like speed, difficulty, or the level of guidance provided??
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)	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 It may be smoothly integrated into educators' lesson planning and instructional strategies This can help the students to understand complex principles and encourage problem-solving skills
Checklist	Do the VR application's content and activities align with the curriculum's learning objectives? Do the VR experiences and interactions support acquiring knowledge and skills outlined in the curriculum?
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

Table 10 (continued)

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	Does the VR application integrate learning measurement to evaluate learners' progress and understanding of the curriculum-aligned content? Does the VR application include formative and summative learning measurement components that provide feedback and track learners' performance?
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	Does the VR application provide adjustable font sizes and high contrast options? Does the VR application use colour combinations that are accessible for users with colour blindness? Does the VR application include captions or subtitles for all audio content within the VR experience? Does the VR application provide volume controls and the option to adjust audio settings? Are the instructions clear and step-by-step?

11 Appendix 6

Evaluators	Usability Issues for Titan Apps	Severity Ratings	WVREA
E1	There is no clear instruction on how to teleport	4	4
	The app did not warn/tell the user something was wrong when the user made a mistake	3	4
	There is 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 is 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's knowledge or understands	3	13
	The exit button should be displayed in the menu but only visible in the setting	3	10
	The controller navigation button at home is not labelled properly. Users will be confused	2	10
	The app is non-collaborative because the user has no interaction with other user	4	9
E6	No Metaverse ability/interaction—latest trend in VR	3	9
	No quizzes/assessments for users	3	13
	User Interface—aesthetic value, less trendy	1	10
	User Interface- icon not organised	2	10
	The flow of information—needs guidance	3	10
E7	Content interface (guidelines during the program e.g. exit button, back button)	2	10
E8	Program flow and interactive functions are well coordinated but need more simplified functions (such as backtrack 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
	The exit button should be displayed at the menu but only visible in the setting	3	10
	The ready button and next button have the same function	3	10
	icon meaningless	4	10
E11	icon meaningless	2	10
E12	No exit button	4	10
	There are no clear instructions on how to manipulate the object	4	4
	Meaningless icon	4	10
	Nouser's assessment to test the user knowledge or understands	4	13
E13	A navigation button should be on the controller	2	10
	more interactable option	2	4
E14	Need a simple tag on every button of the plane	1	10
E15	The finger animation did not show that the finger is positioned on top of the button for "oculus."	3	14
	The legibility of the words at the controller was blurry, especially for the word 'Oculus' since it was written in purple font colour	2	3
E16	icon meaningless	3	10
	There is no assessment to test the user's knowledge or 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

Evaluators	Usability Issues for The Big Table Apps	Severity Ratings	WVREA
E3	Find it difficult to teleport	4	4
	Usability problem	4	10
	Instruction for the first-time user is not clear	4	10
E4	No guidelines for performing 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 (did not have proper instruction)	3	10
E8	Unorganise program flow	3	10
	Preferable simplified the development and interactive 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
	The button is not really functioning	3	4
E12	hard to understand the task	3	11
	Instruction for the first-time user is not clear	3	10
	No exit button	3	10
E14	The caption is too high	2	10
E15	Some robots should not be picked up and placed on the burner, but I did it anyway because there was not 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 assessment	2	13
	Not user friendly	2	10
Evaluators	**Usability Issues for The Body VR App**	**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 the user	4	10
	not user-friendly due to the location of the button/option is not suitable	2	10
	There is no assessment to test user knowledge and understanding	4	13
	The controller's button is not fully utilised. Only 1 button can be used	3	4
	non-collaborative	4	9

12 Appendix 7

Table 11 Usability Issues Identified During Users' HE

Users	Usability issue of Titan of Space plus VR app	Severity Ratings	WVREA
User 1	Need more information if the students need more info	2	10
	Motion sickness	2	2
	Many unnecessary information that might affect the learning objectives	3	10
	Only in English- No able to change the language	4	14
User 2	It is hard to adjust the volume button—it is not accurate	2	11
User 5	Audio only in English. No language selection	4	14
	The select button (up and down arrow) should be visible in the VR interface	4	11
User 6	No quizzes or assessments to assess student's understanding	4	13
	the language should be simple and easy to understand	4	10
	the content should align with the syllabus	4	12
User 7	No Quit button	1	11
User 9	More clues/instructions given (arrow, speech bubbles, etc.)	1	10
	The menu on the controller should be accessible/seen easily	1	11
User 10	It is hard to grab the object	1	7
User 11	The menu button on the controller is hard to find	4	11
User 12	No Exit button	2	11
User 13	Hard to find the quit button	4	11
	Should align with the curriculum content	3	12
User 14	The VR app is not aligned with the school curriculum content	3	12
User 15	Must have mini-map for guidelines	3	11

13 Appendix 8 Table 12

Table 12 List of Tasks for Evaluators:

The Titans of Space PLUS VR application Tasks	
Task 1	Select the English Language
Task 2	Choose sitting or standing at the setting
Task 3	Choose sensitiveness to motion
Task 4	Grab the Earth
Task 5	Spin the Earth to the left and the right
Task 6	Activate the tour guide by pressing the orange button on your left
Task 7	Press the purple button on your left to aim, launch, and then coast
Task 8	Go back to the previous and next tour
Task 9	Press the green button on your left to find the diameter of all the planets
Task 10	Where is the position of the Venus?
Task 11	Find the diameter of a mercury
Task 12	Turn off the music
Task 13	Find additional facts about the Earth
Task 14	Press the silver button and move towards the Earth
Task 15	Quit the apps
The Big Table VR application Tasks	
Task 1	Press the start button
Task 2	Pull down the lever to activate
Task 3	Point and pull the trigger to pick up the cube
Task 4	Pull the trigger to teleport
Task 5	Grab the access cube
Task 6	Select the ice cube and place it on the analyser
Task 7	Go to the sixth station
Task 8	Choose graphite, place it on the analyser and pull the lever down
Task 9	Go to the fourth station
Task 10	Choose any of the items (ice cube, soda can, steel spoon, gold bar) to see which one is a great conductor and a poor conductor. Place it on the analyser
Task 11	Quit the apps
The Body VR application Tasks	
Task 1	Choose the third menu and press the start button
Task 2	Look back at the red blood cell shown to you grab it
Task 3	Adjust the narration volume to 85%
Task 4	Adjust the music volume to 70%
Task 5	Set the language to English
Task 6	Go to the third menu
Task 7	Go to the previous scene
Task 8	Go to the next scene
Task 9	Pause the lesson
Task 10	Quit from the lesson

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 playback button from a certain topic	2	10
E8	Very little interaction and control of the program environment	3	2
	Positioning of interactive instruction at the user's eye level area	3	10
	Reduce serious elements to ensure users enjoy the content	2	10
E10	No next or previous button	3	10
	Cannot teleport	4	4
	There is no assessment to test user knowledge and 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
	There is no assessment to test user knowledge and understanding	4	13
	less interaction with the object	3	2
E15	The displayed information was lower than the usual gaze position, causing me to bend down a bit	2	10
	The options for Main menu reorientation, etc. are too low and 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 is not at the right position	3	10
	There is no assessment to test user knowledge and understanding	3	13
	not user-friendly due to the location of the button/option is not suitable	3	10

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