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Universally Designed Virtual Reality: Creating Inclusive and Immersive Learning Experiences with 'VRinDanger'

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Abstract. This paper presents the design and implementation of VRinDanger, a universally designed (UD) educational virtual reality (VR) application aimed at providing an inclusive and immersive learning experience focused on the world's deadliest animals. A mixed-methods study involving participants with diverse ages, skills, and abilities was conducted to evaluate the application's accessibility, usability, user experience, and educational effectiveness in terms of learning outcomes. The findings demonstrate that integrating UD principles into VR design significantly improves accessibility, enhances user satisfaction, and promotes engagement and retention of educational content for diverse audiences. Furthermore, the study highlights the need for cost-effective, cross-platform VR solutions and the development of VR-specific accessibility guidelines. These insights contribute to the advancement of inclusive VR design and its broader application in educational technology.

Keywords. Virtual Reality, Universal Design, Accessibility, Usability, Inclusive Learning

1. Introduction

The integration of Virtual Reality (VR) in educational settings has gained significant momentum in recent years, marking a transformative shift in the delivery and perception of learning experiences. VR's potential lies in its ability to provide immersive, interactive experiences that traditional methods cannot match. Kavanagh et al. (2017) and Freina & Ott (2015) highlight VR's role in enhancing understanding, engagement, and motivation. VR allows users to explore virtual environments, interact with complex concepts, and experience otherwise inaccessible scenarios.

However, VR adoption in education faces challenges. High costs of proprietary equipment and logistical issues make VR prohibitive for many institutions and students (Vats & Joshi, 2023). Additionally, complying with national (Lovdata, 2018) and international mandates (Kanter, 2006) demanding accessible learning materials to all students, including those with disabilities, is an existing challenge for VRs adoption in educational settings.

VR is often perceived as a barrier maker to accessibility due to its reliance on visuals and its focus on gaming. Game design typically challenges and rewards users' skills and abilities, which contrasts sharply with the inclusive design principles. Predominantly visual VR experiences can exclude users with visual impairments. However, as outlined

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by Chong et al. (2021) and Mott et al. (2019), VR's multisensory nature, when designed with user-centered principles, can facilitate inclusion rather than creating barriers.

Recognizing this gap, Heilemann et al. (2021) reviewed accessibility guidelines for games and VR applications, including the Game Accessibility Guidelines (n.d.) and the XR Accessibility User Requirements (O'Connor et al., 2021). While these guidelines focus on accessibility and users with special needs, they do not address broader considerations such as hardware costs, scalability, availability and user diversity within the same design for all required for inclusive educational settings. National mandates (Lovdata, 2018) require Universal Design (UD) for learning environments, educational materials, and applications, but the intersection of UD and VR remains underexplored in educational technology research.

UD is a framework for creating products and environments accessible and usable to as many people as possible, regardless of abilities (Björk, 2009; Story, 1998). In VR, UD ensures technologies are immersive, educational, inclusive, accessible, and usable for a diverse userbase (Dombrowski et al., 2019). Despite these unique opportunities, the intersection of UD and VR remains a relatively unexplored domain in educational technology research.

This paper aims to contribute to this area by showcasing how UD-guided development of educational VR applications can provide an inclusive learning experience without compromising educational quality or user appeal. The paper contributes to the knowledge base on making VR universally accessible, aligning with the broader goal of creating inclusive educational environments in the digital age. The paper is structured to present (1) implementation (considerations, technological framework, feature and design choices), (2) user validation (user experience, digital inclusion, educational value), and (3) discussion for future research, emphasizing the need for integrating UD in educational technology design and its challenges.

2. The Universal Design of 'VRinDanger'

The development process involved several key steps: 1) mapping user needs, skills, and abilities with Universal Design (UD) principles to create a solution for a diverse user base suitable for the educational theme; 2) aligning technological features and limitations with UD to build a requirement specification; and 3) iteratively refining and updating prototypes through small-scale testing (2-3 users) until achieving the final form. While the detailed development process is beyond this paper's scope, this section provides an overview of the VR application's Universal Design.

Educational Theme and User Needs: The application aims to educate users about the world's deadliest animals, providing both factual and numerical knowledge. It combines a VR gallery with 3D data visualization techniques to create an immersive learning experience. This approach enables users to explore and understand detailed information about dangerous animals within an engaging and interactive virtual environment. Accordingly, the design should adapt to various demographics such as age, skills, digital literacy, motor, sensory (visual, auditory) and cognitive (memory, dyscalculia (Jerin et al., 2020), dyslexia (Wessel et al., 2021)) abilities, preferences regarding the context of use and preferred hardware. To meet user needs, UD and its seven principles (Björk, 2009; Story, 1998) has been chosen as a design aid.

Technological Framework: High development costs, expensive hardware, and limited hardware availability are significant barriers to VR adoption for both developers and end-users. To overcome these challenges, A-Frame, an open-source web framework for building virtual reality experiences, was chosen (A-Frame, n.d.). A-Frame development requires a code editor and knowledge of HTML and JavaScript, eliminating the need for specialized software.

The resulting web-VR application ensures cross-device and cross-platform compatibility, making it usable on various devices, including proprietary head-mounted VR devices, smartphones, tablets, and desktop PCs, if they have a compatible web browser. This approach creates a universally accessible, low-cost VR solution, significantly reducing the costs and hardware barriers for VR in education.

Design Implementation: VRinDanger aims to create an interactive learning environment where users gain knowledge about the deadliest animals and understand the annual number of victims they cause.

The following section details the design implementation of these features built in the seven principles of UD and manifested in supporting:

Figure 1 - A) HMD interaction with the app, B) Application interface, C) Volume visualization, D) Posture chart, E) Cross-platform compatibility, F) Info block, G) Circular VR scene

<u>1. Equitable Use:</u> Providing equal means concerning educational content (same factual and numeric information), multimodal information communication (including audiovisual and tactile feedback), interaction (various modes for navigation, action trigger (touch, pointer)) to cater to users with different motor and sensory skills and preferences (see Fig.1.A,E).

<u>2. Flexibility in Use:</u> Offering various user interaction options, including handheld and head-mounted modalities (see Fig.1.A,D,E). Ensuring cross-platform compatibility (VR headsets, PCs, mobile devices) to accommodate user comfort and available hardware (see Fig.1.E). The application provides consistent access to the same information across all platforms, regardless of hardware cost or quality.

<u>3. Simple and Intuitive Use:</u> The streamlined information architecture combines the user interface and VR content in identical scenes, eliminating submenus and ensuring all essential functions are accessible within the user's immediate environment. The number

of visual elements in the user's field of view is maintained at 5±2 to ensure simplicity (See Fig.1.B). Affordances are designed to enhance the predictability of application functions with clear audiovisual feedback and easy navigation. In HMD mode, no controllers are needed; users trigger actions, walk, and interact using the headset as a head mouse, with immediate audiovisual feedback from UI elements. In handheld mode, the application uses a familiar mobile interaction scheme, utilizing the device's gyroscope for pointer interactions. In desktop mode, users navigate the VR environment with standard methods, such as a mouse, keyboard (WASD keystrokes), or both, providing a simple and intuitive experience regardless of previous VR experience.

4. Perceptible Information**:** Important text is presented with high-contrast colors and sans-serif typeface for readability. High-definition render textures remain sharp up close (see Fig.1.F). Text is paired with synthetic audio narration to aid users with visual impairments or reading difficulties, like dyslexia. Numerical information is conveyed through numeric symbols, auditory descriptions, and visually with 3D red dots in the sky (see Fig.1.B, C). This multimodal approach aids users, including those with dyscalculia, in understanding volumes and numerical differences. Information is grouped into thirds to provide clear structure and enhance contrast and visibility, as shown in Fig.1. F.

5. Tolerance for Error: Providing rapid self-correction mechanisms via the pointer to undo or redo actions, allowing users to recover from accidental triggers without disrupting the application. Ensuring user safety in VR mode by implementing navigation pads (see Fig.1.B, F) for 'teleportation' to reduce the mismatch between vestibular and visual sensory systems, preventing simulator sickness (Martirosov et al., 2022).

6. Low Physical Effort: Achieved by minimizing the effort required to wear a VR headset (head-mounted mode), hold a smartphone (handheld mode), or sit in front of a PC, as shown in Fig.1.A, E.

7. Size and Space for Approach: Minimized by compatibility with various device sizes and accommodating user preferences and physical postures, including standing, sitting, or lying down, while still providing the full experience, as shown in Fig.1. D.

3. Design Validation

The methodology for the summative design validation was crafted to evaluate the effectiveness and inclusivity of 'VRinDanger'. The focus was to assess how users from various backgrounds and with differing abilities interacted with and experienced the VR application.

Participants: The study involved 11 volunteers from the university campus, aged 18 to 65 years, representing a diverse cross-section of the population. The age distribution was: 35-44 years (36.4%, n=4), 18-24 years (27.3%, n=3), 45-54 years (18.2%, n=2), and 65+ years (18.2%, n=2).

Regarding daily ICT device preferences, 90.9% (n=10) preferred smartphones, while one preferred laptops or desktops for learning. Self-assessed learning capabilities were: 45.5% (n=5) average learners, 36.4% (n=4) fast learners, and 18.2% (n=2) slow learners.

Reported impairments included visual impairments such as myopia (45.5%, n=5) and cognitive impairments such as dyslexia and dementia (18.2%, n=2). The majority (54.5%, n=6) had no noted impairments.

Participants' VR experiences varied: 72.7% (n=8) had no experience, 9.1% (n=1) had moderate experience, and 9.1% (n=1) were experts. This selection ensured the study's findings were representative of a broad user spectrum, aligning with the UD principles that 'VRinDanger' was designed to uphold.

Study Procedure and Materials: The study was organized into phases to understand participants' experiences, feelings, and attitudes towards 'VRinDanger.' After obtaining consent, participants were briefed on 'VRinDanger,' focusing on the world's deadliest animals. They first engaged with the content using a Merge AR/VR headset (Merge Education, n.d.), with adjusted straps and lenses. 'VRinDanger' was then demonstrated in handheld mode (Google Pixel 6) and stationary mode (MacBook Pro 14 M1) to showcase flexibility and compatibility. Participants were encouraged to verbalize their thoughts and interact freely for genuine feedback. Next, participants chose their preferred modality or a combination for the learning session, limited to 15 minutes to prevent VR-induced discomfort, with most completing it in 5 to 8 minutes. Afterward, participants completed a survey to share their insights about the application and VR in education and answered a multiple-choice test on the deadliest animals to measure short-term recall. The study concluded with a brief semi-structured interview to reaffirm the researchers' observations.

Data Collection and Analysis: The study employed a mixed-methods approach, integrating quantitative and qualitative data. Quantitative data were gathered through a post-experiment survey, assessing user experience, preferences, inclusion, and opinions on VR in education, and a short-term information recall test on the deadliest animals. Qualitative data were collected through participant observations and brief semi-structured interviews, providing verbal feedback and insights. All participants were informed of the study's purpose, and consent was obtained prior to participation. The study adhered to ethical standards regarding privacy, confidentiality, and participant well-being.

4. Results

User Experience: Participants of various ages, skills, abilities, and VR experience levels expressed high engagement with the application. Specifically, 72.7% (n=8) reported being "highly engaged," 18.2% (n=2) were "moderately engaged," and one indicated a "neutral" level of engagement. All participants appreciated the immersive nature of the application, which stimulated interest in the educational content and maintained user engagement. This suggests that the application's inclusive design does not sacrifice appeal or engagement.

On a scale from 1 to 10, participants rated the intuitiveness of 'VRinDanger' with an average rating of 8.55. Out of the 11 participants, six rated it a 9, one rated it a 10, three rated it an 8, and one rated it a 6. This indicates that the majority found the application intuitive, with 81.8% (n=9) rating it 8 or higher. Regarding the clarity and understandability of the user interface, participants provided highly positive feedback. Nine participants found it "very clear and easy to understand," and two found it "somewhat clear." These responses suggest that the user interface is easy to comprehend, enhancing the overall user experience.

When asked about ease of navigation and interaction, most participants responded positively. Nine (81.8%) found it "very easy to navigate and interact," one found it "somewhat easy," and one was "neutral." This suggests that the application is user-friendly and easy to navigate, contributing to a positive user experience.

The overall user experience received a high average rating of 8.45 on a scale from 1 to 10. This rating underscores the application's effectiveness in providing an engaging and satisfactory user experience, with 81.8% (n=9) of participants rating their experience as 8 or higher, showcasing the positive impact of UD Principle 3 (Simple and Intuitive Use).

Preference for Interaction Modality: Despite the application's cross-platform compatibility, a notable majority of participants (82%, n=9) preferred the head-mounted VR experience for its enhanced immersion and "feel of presence." When asked about interaction modalities, 55% (n=6) preferred both HMD and handheld options, 36% (n=4) preferred VR only, and one participant preferred neither. This underscores the importance of UD Principle 2 (Flexibility in Use), adapting to user needs and preferences.

Inclusivity and Accessibility: All participants (n=11) successfully achieved their goals, interacted with, and learned from the application, as well as managed the information recall test. Features like audio narration and data visualization were especially appreciated by users with specific needs, including those with visual impairments (45%, n=5) and dyslexia (18%, n=2). One participant with dyslexia expressed gratitude for these features. The effectiveness of UD principles, such as Equitable Use (Principle 1) and Perceptible Information (Principle 4), in enhancing accessibility and inclusivity was evident. When asked about accessibility features, nine participants (82%) stated they were "not aware of accessibility features" or felt no need for them. This feedback suggests that accessibility features were seamlessly integrated into the VR experience, enhancing both accessibility and usability, and facilitating inclusion.

Educational Value: Seven participants (63.6%) found the application "highly informative and interesting," while four participants (36.4%) found it "somewhat informative and interesting." This indicates that most participants perceived the application as an effective educational tool.

When asked about the likelihood of recommending 'VRinDanger' to others, 72.7% (n=8) indicated they were very likely to recommend it, 9.1% (n=1) were somewhat likely, and 18.2% (n=2) were neither likely nor unlikely. These findings suggest that VR, when designed with UD principles, can offer an engaging and effective learning experience.

Learning Effectiveness and Recall: The post-use short-term recall test revealed that most participants were able to effectively remember and recount information about the deadliest animals by nearly all respondents (10 out of 11 for Mosquito and 11 out of 11 for Shark), with some errors about middle-rankings. This finding suggests that 'VRinDanger' is not only engaging but also effective in facilitating learning. Participants rated varying levels of confidence in their knowledge after using the application, with many (64%, n=7) feeling confident about their responses, while 36% (n=4) felt neutral.

5. Discussion and Conclusion

This study demonstrates the effectiveness of UD principles in creating an inclusive and immersive learning experience through a cross-platform Web-VR application. This application is accessible, usable, and engaging for a wide range of users, regardless of their skills and abilities.

The findings align with existing VR literature on the efficacy of VR in education by Radianti et al. (2020). The immersive qualities of VR, combined with educational content, create a rich learning environment. The preference for head-mounted VR experiences reaffirms findings from Martín-Gutiérrez et al. (2017), emphasizing the unique sense of 'presence' that VR headsets offer. This indicates that while cross-device availability is crucial, the immersive quality of head-mounted VR is unparalleled.

Moreover, the positive feedback on the application's inclusivity demonstrates the practical applicability of UD principles in VR design. It supports the argument presented by Dombrowski et al. (2019) that VR, when designed with accessibility in mind, can cater to a diverse range of users. The application thus exemplifies how educational technology can be both immersive and inclusive.

The study revealed several previously underexplored aspects, such as reducing cost and hardware requirements, thereby lowering entry barriers for educational VR by offering cross-device and cross-platform compatibility without the need for proprietary HMD devices. Notably, 55% of users preferred this flexibility. This finding is significant because VR is often perceived as being reliant on specific, high-cost devices. Future VR research should further explore alternative mobile (handheld) VR integrations, similar to mobile augmented reality (MAR) solutions (Szentirmai, 2024).

The chosen Web-VR framework (A-Frame) offers easy access via URL and cross-platform compatibility but has limitations. Web applications can appear suspicious to operating systems, requiring more resources than regular websites and triggering security warnings, which may deter users. Browser updates can also disrupt functionality, requiring changes to privacy settings and application code.

An urgent issue for future research is the role of Web-VR in complying with inclusion mandates, which is currently a gray area. Web-VR must be universally designed, but UD's abstract nature can lead to inconsistent evaluations. There is no specific VR framework or success criteria for UD, and WCAG (2.1) lacks guidelines for Spatial 3D interfaces (W3C, 2023). The XR Accessibility User Requirements (O'Connor et al., 2021) are still aspirational rather than a practical framework. Consequently, developers lack established VR guidelines for creating inclusive solutions, and evaluators have no established criteria to assess compliance.

In this study, UD significantly aided in creating an inclusive VR experience, aligning well with VR's spatial aspects. Although UD was originally developed for physical environments, its principles can be adapted to virtual environments. Principles such as size and space for approach and low physical effort are more crucial in VR than in traditional 2D interfaces. The design choices in this paper can serve as guidelines for similar interactive VR gallery applications, but more practical implementations and VR coverage within UD are needed. This would help develop evidence-based recommendations, best practices, and success criteria for inclusive VR applications.

In conclusion, 'VRinDanger' serves as both an educational tool and a model for universally designed VR applications, catering to a wide spectrum of users' needs and preferences.

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