Engineering For Social Change
A. Cooper et al. (Eds.)

doi:10.3233/ATDE240852

XR-CISE: Towards Promoting Physical Activity with Inclusive Virtual Reality Exergaming

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Abstract. The metaverse, building on recent advancements in Virtual Reality (VR) technology, will be a significant driver of social change. Impacting how people live their lives and fostering new applications across fields such as entertainment, fitness, and rehabilitation, these technological advancements facilitate higher engagement of users through immersive experiences. In the short-term, this helps users to overcome barriers to physical activity and it promotes lifelong retention of physical and cognitive skills, a fundamental part of healthy ageing. To fulfil this potential, VR technology needs to be able to empower individuals regardless of age, capabilities, and prior VR experience. However, current fitness applications largely target younger users, often overlooking the needs and limitations of older or vulnerable groups. This work, the result of a transdisciplinary collaboration between therapy science, health psychology, and software engineering, introduces a user-centred approach to utilize VR exergaming for promoting physical activity, tailored to individual capabilities and preferences. Our inclusive approach incorporates a comprehensive user model based on static and dynamic ability attributes. These are assessed through questionnaires, sensor data, and a platform for gamified VR fitness tests, such as the presented prototype for reach and mobility. This model allows for personalized recommendations of VR exergames. We showcase several adaptive exergame prototypes that can dynamically adjust challenges based on real-time sensor data, such as heart rate. Addressing inequality in current VR fitness experiences, this work contributes to the broader understanding of VR exergaming to facilitate the development of VR interventions for promoting physical activity among older or vulnerable communities.

Keywords. transdisciplinary engineering, virtual reality, exergaming, physical activity, human computer-interaction

Introduction

Over the last decade, the advancement of Virtual Reality (VR) technology, resulting in affordable, comfortable, and usable consumer-grade headsets, has unlocked the metaverse's significant potential to enrich people's lives [1]. Simultaneously, VR has become an attractive medium for researchers from many different fields [2]. The technology is set to significantly impact people's lives positively in fields such as fitness, physical activity (PA) and medical therapy, driving changes in public health and contributing to the healthy aging of an increasingly older society [1, 3–5].

However, the specific needs and challenges of older adults in virtual worlds are often overlooked with most commercial VR experiences currently targeting the young and healthy, while older or vulnerable groups are generally underrepresented in VR user experience (UX) research [5, 6]. This creates research gaps exist in understanding

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emotional responses and PA-related cognitions during VR exergaming [7], underlining the need to investigate the experience of older participants and the mitigation of technological barriers towards individualized and inclusive PA interventions. However, reliably assessing emotions and cognitions during VR studies poses challenges due to the lack of standardization [8]. Many existing VR assessment tools in the scientific community [9] are limited in practicability due to the technical know-how required by researchers and usability challenges for participants, particularly VR beginners [10].

This contribution describes our three-step transdisciplinary approach - including therapy science, health psychology, and software engineering - towards developing inclusive systems that promote physical activity in healthy, older, and vulnerable groups using VR exergaming: (1) Enable researchers of varied technical backgrounds to assess VR UX of participants conveniently and reliably. (2) Implement VR exergaming prototypes with biofeedback to study the effect of individualized interventions. (3) Design a system to match VR exergames to users based on training goals, preferences, and sensory, cognitive, and physical abilities.

1. Background

Modern immersive VR headsets evoke a sense of presence in the user, creating an illusion of "being there" in the virtual world [1]. Exergames are interactive digital games merging fun gameplay with exercise [11]. By harnessing gamified behavioral change techniques [12] and providing enjoyment [13], exergaming is a powerful motivator for long-term behaviour change [12, 14], maintaining physical [11, 15] and cognitive abilities [4] as part of lifelong learning and healthy aging [3, 16]. The increased immersion enhances user engagement [3], supporting even older users in building new habits [14]. The transition into the virtual world with its gamified distractions empowers users to overcome pain- or trauma-related barriers to PA [17, 18]. VR exergames are ideal to achieve light to moderate exertion [11] and their design requires balancing enjoyment and challenge, tailored to goals and abilities [19]. The perceived exertion levels during moderate-intensity exergaming influence cognitions like mastery experience and self-efficacy in older adults, which are relevant to health behaviour changes [8]. Additionally, human factors like prior experience with VR technology or age significantly affect UX in VR [20].

For reliable VR assessments and effective interventions, environments and tools must be usable and accessible [8]. Becoming immersed in VR poses challenges for older adults [21], as they are generally less likely to accept new technology [22] and most VR content targets younger users without addressing older individuals' needs and preferences [5]. Barriers like physical safety, comfort, frustrations, and other inhibitions require age-sensitive designs and appropriate onboarding in VR studies [6, 23]. Human factors such as diminished vision and mobility [24], motion sickness [25], discomfort [26], and triggers [27] present additional challenges in VR research and application for older users. Therefore, considering safety [24], ethics [27], and accessibility guidelines [28] is crucial for successful research when immersing older adults or VR beginners.

Psychological questionnaires are a common method for assessing UX in VR studies. Study participants having to exit VR for self-reporting is inconvenient, time-consuming, and causes breaks in presence (*BIP*), potentially biasing responses [29, 30]. The quality of assessments is based on primary criteria like validity, reliability, and objectivity, and on secondary factors including efficiency and economy, reasonableness towards demands of participants, and fairness to avoid discrimination based on sociodemographic factors [31]. Immersively integrated VR questionnaires (*inVR-Qs*) provide responses comparable to real-world-results and represent a convenient and robust self-report method that by mitigating *BIPs*, enhancing assessment efficiency and economy as well as reasonableness towards participants [30, 32]. In general, the use of VR assessment tools contributes to greater standardization and transparency in research, leading to improved repeatability and reproducibility [9, 10]. Standardized VR exergaming scenarios, combined with physiological sensors, can provide a deeper understanding of physical PA inhibitors, facilitating the development of effective PA interventions [8]. Several tools exist in the scientific community [9], but few specifically address the needs and barriers faced by older or vulnerable users inexperienced with VR technology [10].

2. Approach

VR exergaming holds promise for broad user engagement across age groups, with potential health benefits and enhanced motivation. The success of these interventions depends on thoughtful design, inclusive research tools, and a focus on UX, ensuring that VR technology is accessible and beneficial for all users. Developing individualized interventions to promote PA among healthy, older, and vulnerable populations requires comprehensive study of factors such as enjoyment, motivation, habits, adherence, and barriers like stress, pain, fear, or lack of motivataion. Transitioning to the distractions of the immersive virtual exergaming environment could help users overcome personal PA barriers through biofeedback in a secure setting. VR technology enables controlled, repeatable exergaming scenarios for standardized data collection to explore the complex relationship between PA, emotional and cognitive impacts, physiological responses, and the benefits of tailored feedback during exercises.

Investigating the complex interplay of the factors on UX across various exergame designs is essential inform the design of interventions. This requires a VR assessment system that meets psychological research standards, encompassing both primary (objectivity, reliability, validity) and secondary (efficiency, economy, reasonableness, fairness) quality criteria. Engineering such a system is complex and demands a transdisciplinary approach. The system is developed in close collaboration with researchers from therapy science and health psychology (ref. Fig. 1).

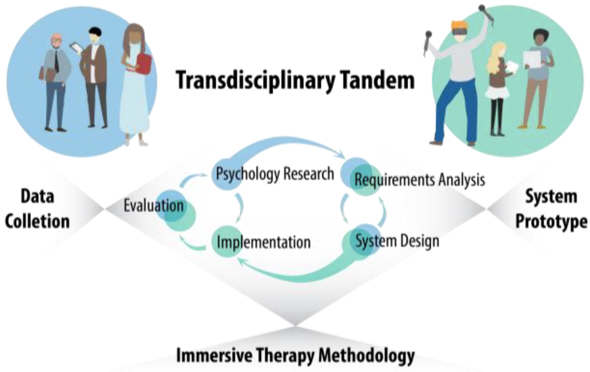

Figure 1. An overview of the iterative design process towards developing immersive therapy methodologies, built on the transdisciplinary collaboration between life sciences (blue) and software engineering (green).

This research and development process aims to establish a comprehensive approach for employing immersive VR technologies in psychological and therapeutic research, focusing on PA promotion through mitigation of barriers. The central transdisciplinary aspect is the integration of prototype evaluations with psychological assessments, building an evolving, mutual understanding of the system prototype and its user impact, making the reliable assessment of user cognitions and emotions during VR exergaming crucial to the process. Traditionally, psychological studies collect such data through self-report questionnaires. Practical, robust, and user-friendly software tools for *inVR-Qs* enhance assessment economy, efficiency, and reasonableness towards participants. The VR assessment tool's usability and accessibility [30], along with thoughtful study onboarding [23], are important considerations to increase reliability in VR UX studies [8], particularly for older or vulnerable first-time VR users [6].

3. System

Robust and accurate measurement of physiological and psychological effects of VR interventions is crucial, particularly when working with respondents who have varying health conditions, preferences, and tech familiarity. Insights from the exploration of heart rate variation, exertion levels, and emotional states can deepen the understanding of VR's impact on PA in these demographics. Our participant-centred research system (ref. Fig. 2) aims to support these assessments in VR studies by combining data from environmental and body sensors with a VR overlay tool to improve instructor-participant communication and enable convenient self-reporting.

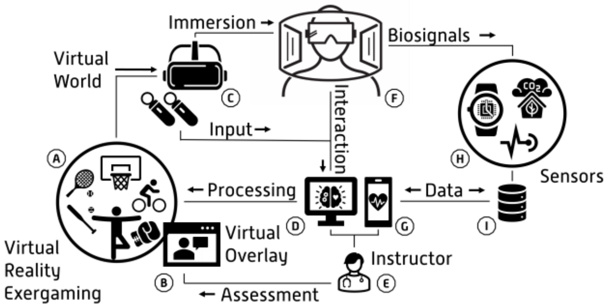

Figure 2. Overview of the VR system for assessing UX during exergaming. The virtual environment, including the exergaming scenario (A) and the overlay content (B), is displayed to the user (F) via a VR headset (C). User interactions with the virtual world, facilitated by VR hardware (C), are processed by the host system (D) to update the virtual world. The system collects bio signals and other sensor data (H) to store in the database (I). This setup enables the instructor (E) to monitor the study and its data using a companion app (G) or the host system (D), controlling the scenario (A) and the assessment overlay (B).

The assessment tool is integrated into the environment of any proprietary SteamVR application and used by instructors to control the studio scenario and to present *inVR-Qs* to participants. Sensor data enrich the participant's self-reported UX, enabling a comparison of subjective exertion levels to actual heart rates and laying groundwork for machine learning analyses. Large datasets of environmental and physiological data can be combined with self-reports of UX for contextualized machine learning applications. This data could be used to infer complex cognitive and emotional states (task load, flow, presence, stress), which are highly relevant to developing PA interventions. Assessment tools, exergame selection and exercise intensity adjustments, must be safe and inclusive to support robust data collection as part of robust UX research in VR exergaming.

3.1. *VR Assessment Tool for User Experience Research*

Our system utilizes the Rating Overlay for Virtual Environments in Research (ROVER), practical VR assessment tool developed iteratively based on literature guidelines, user research, and expert feedback from researchers [10]. Open-source and equipped with convenient features to support researchers of all technical levels in conducting VR studies, ROVER contributes to assessment efficiency, economy, and reasonableness. Its virtual rating station is optimized for user comfort and minimal interaction bias, ensuring fairness and the reliability of psychological data. With a special focus on readability, ergonomic design, and intuitive pointer interactions, ROVER meets the needs of older or vulnerable groups, making assessments robust and inclusive. Additionally, its avatar feature improves instructor-participant communication [9], which, together with the intra-diegetic integration [32], mitigates biases from *BIP*s [29]. Its user-friendly interactions and an instructional tutorial support VR beginners, which is crucial for effective onboarding in VR research [8, 23]. Tested in a study with 23 older adults, ROVER received high usability ratings and positive feedback from participants and psychology researchers, validating its application in UX studies [10].

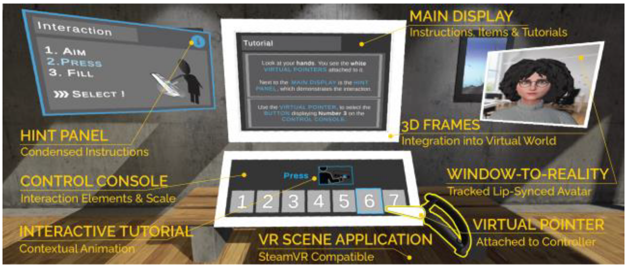

Figure 3. VR assessment tool as a standalone 2D overlay integrated into the 3D VR scene application. [10]

3.2. *Biofeedback in VR Exergaming*

Three VR exergame prototypes have been implemented to investigate the impact of adaptive game mechanisms intended to maintain an effective training heart rate within a moderate-intensity zone on UX during VR exergaming. The games (ref. Fig. 4) can also be played either seated but are mostly designed for endurance training while standing. The difficulty of in-game challenges is adjusted based on heart rate to regulate effort during physical exercises. The first, *FightDummy* (A), features a kung-fu puppet with rotating arms of various difficulties for punching, blocking, or dodging, emphasizing full-body engagement and scoring based on accuracy, speed, and force. *EndlessClimb* (B) focuses on upper-body strength, where users climb a path of procedurally generated difficulty segments, with an artificial stamina system that adjusts to keep heart rates within the target zone. *WaterLock* (C) simulates kayaking in a wave pool, challenging users to collect objects while paddling against force-adjusting currents.

Findings from our evaluation with 11 participants (5 women) aged 13 to 60 highlight the importance of designing VR exergames with simple, inclusive interactions suitable for varying levels of VR experiences. *WaterLock* raised motion sickness concerns even when playing without waves, but the more stationary games caused no discomfort. The evaluation stresses the need for adaptable game mechanisms that enhance the gaming experience without confusing the player, as was the case with *EndlessClimb*'s stamina system. *FightDummy*, subsequently evaluated further with 13 university students (7 women), showed great potential in maintaining target heart rates and engaging users.

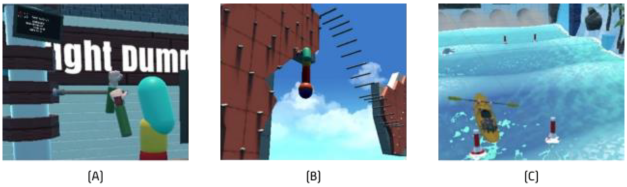

Figure 4. Three VR exergame prototypes with adaptive game mechanisms. From left to right: (A) kung-fu dummy with rotating arms, (B) procedurally generated wall climbing, (C) kayaking in a wave pool.

3.3. *Ability-Based User Model for Matching of Suitable Exergames*

Ability-based design emphasizes creating technology and interfaces tailored to users' abilities rather than limitations [33], resulting in more inclusive and empowering their experiences. We introduce the concept of an ability-based system for determining exergame suitability for research study participants or as part of personal training (ref. Fig. 5). The system is intended to match exergames from a predefined catalogue to user profiles, including more static ability attributes as well as attributes that can change daily. Regular VR fitness tests estimate users' current physical form, so recommendations align with training objectives but avoid overexerting the user. An ability-interaction-matrix determines the relevance of user abilities to a given exergame's intended gameplay interactions on a three-point scale. Some game's accessibility features can modify the gameplay to be more suitable, which is also considered in the model. Recommendations prioritize games matching users' style, theme, and gameplay preferences.

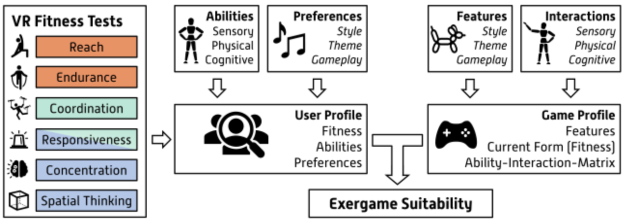

Figure 5. Exergame suitability model. User's preferences, abilities, and results from regular VR fitness tests make up a user profile that is matched against a catalogue of exergame profiles by considering training goals, current form, feature preferences and minimum abilities required for intended gameplay interactions.

The user ability model (ref. Fig. 6) categorizes sensory, cognitive, physical, and hand motor abilities relevant to VR exergaming into full, limited, or non-functional. Virtual environments present diverse challenges and stimuli, highlighting the importance of measuring cognitive ability to prevent user overstimulation. Differentiating between left and right sidedness of arm mobility can be useful, as some games are playable one-handed. Lower body abilities are considered in terms of standing, walking, and running due to their uniform impact on exergame suitability. Hand motor skills are detailed into fine and gross movements, with certain actions like touching being prerequisite for more complex manipulations such as grabbing, catching, and throwing. VR immersion primarily relies on visuals, but tactile and auditory stimuli also shape the UX.

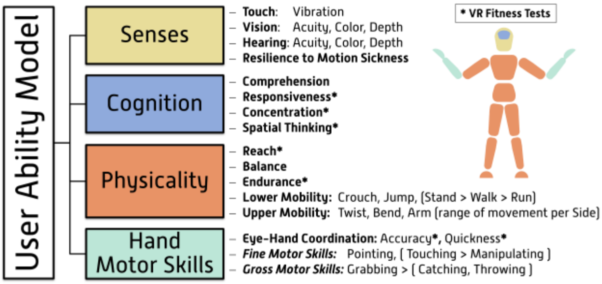

Figure 6. The user model includes sensory, cognitive, and physical abilities as well as hand motor skills.

The suitability model includes VR fitness tests to assess the extent of abilities like reach, endurance, eye-hand coordination, responsiveness, concentration, and spatial thinking. These abilities, despite not being equally relevant in every exergame, are regularly measured to better align recommendations with users' current training goals and current form. We developed *TangledCables,* a prototype inspired by the Functional Reach Test - a clinical predictor for balance and stability. Unlike the traditional test, *TangledCables* offers a VR-safe and gamified alternative, tasking users with connecting plugs to sockets in various exercises, measuring reach, accuracy, and trajectory for a combined mobility score. This score, alongside other VR fitness tests, helps identify suitable exergames for users with mobility challenges.

Figure 7. Showcase of a movement in the reach test from a third-person perspective: The participant reaches for the plug (A) in start position, moves it across his body (B), and plugs it into the end socket (C).

4. Discussion

As part of a transdisciplinary engineering process we designed, implemented, and evaluated three system components to support research into promoting PA through VR exergaming, focusing on inclusivity for older and vulnerable groups. Based on insights from preliminary studies and formative evaluations we present best practices for improving VR UX research and directions for further research into designing individualized PA interventions with VR beginners and older or vulnerable participants.

Reliable and convenient assessment of UX in VR poses a significant challenge. Developed iteratively with feedback from experts and diverse demographics, ROVER facilitates convenient self-reports, minimizing bias from user interaction and enhancing study reliability, contributing strongly to the standardization of UX research in VR. [10]. Comprehensive onboarding protocols mitigate lower affinity for technology interaction and physical discomfort, improving participant familiarity, safety, and trust [8]. Incorporating breaks, ergonomic adjustments, and virtual avatars further enriches study experiences. ROVER's high usability scores from older participants and VR beginners highlight its potential to support these underrepresented groups in VR research by enhancing assessment efficiency, economy and reasonableness [10].

A psychological study using ROVER provided insights into older adults' VR exergaming experiences, confirming PA intensity can be effectively managed through song selection in commercial exergames, evidenced by matching physiological responses and self-reports of perceived exertion along the intended intensity curve [8]. Results showed a positive effect of VR exergaming on emotional affect, enjoyment of PA, and self-efficacy, despite barriers to technology usage. The initial prototypes with biofeedback mechanisms adjusting to users' heart rates showed promise in keeping users motivated with the *FightDummy* prototype performing best in early evaluations due to its immediate feedback and the high clarity of its gameplay response to changing heart rate. It effectively manipulated exercise intensity to provide a challenge without overexerting participants. However, its algorithm relied heavily on squat exercises to increase difficulty, which caused participant heart rate to rise above the targeted range due to delay in individual heart rate responses. Future work will provide a more in-depth analysis. Furthermore, exploring broader biofeedback parameters are essential for a smoother adjustment of exergame challenges to optimize training performance, engagement, perceived safety, and PA-related self-efficacy.

An ability-based user model for individualized exergame recommendations, based on physical and cognitive abilities matched against game profiles, provides a foundation for an inclusive approach to personalized PA interventions and UX research using VR exergaming. By design, our exergame suitability model is limited to the major attributes determined to be most relevant to modern immersive VR exergames. The first of several VR fitness tests have been implemented and positively evaluated. Alongside others it will be used to match exergames in terms of users' individual abilities while prioritizing recommendations based on preference, training goals, and current form.

Reflecting on the development process, which engaged participants across a broad age and experience spectrum, highlights both the successes and areas for future exploration. Early evaluations of the systems focused mainly on younger, healthy individuals due to their availability and safety concerns for older or vulnerable groups. Similarly, the singular emphasis on older adults in VR assessments might not fully capture the experiences of other vulnerable groups. A broader inclusion of ages, abilities, and backgrounds in future studies will enrich our understanding of VR exergaming's impacts and test our approach's wider applicability. This inclusive sampling approach will need to be employed across all three models to ensure thorough evaluation. Additionally, future work will explore leveraging self-reported data to inform machine learning analysis of sensor measurements, including heart rate, galvanic skin response, eye tracking, facial movements, and brain waves. ROVER and other system components are continuously being improved and expanded on. The game mechanisms adapting to biofeedback are being refined and will be evaluated in further user studies for smoother intensity adjustment, suitability for VR beginners, and reduced risk of motion sickness. Researchers from therapy science have endorsed the VR fitness test prototype as a suitable combination of exergame and fitness test. Its exercises will be collaboratively refined including future user studies to more accurately gauge reach and mobility to fill the user ability model as part of the exergame suitability matching. However, VR exergaming with its emphasis on movement and handheld devices is better suited for aerobic exercise over strength exercises, which limits the applicability of such a tool for users and health care professionals when it comes to physical rehabilitation or fitness.

5. Conclusion

With this work, we showcase some of the potential of VR health applications in improving the quality of life in an ageing society. Leveraging VR technology, our transdisciplinary approach aims to increase standardization and inclusiveness in research focused on promoting PA through exergaming. Such interventions can assist individuals in overcoming fear-, pain- or motivation-related barriers, developing healthy habits, and maintaining physical and cognitive functions throughout their lives. By seamlessly integrating questionnaires into VR environments and supporting researchers with a set of versatile features, the ROVER tool streamlines psychological VR assessments, improving the process for VR beginners such as older or vulnerable participants. Enabled by ROVER, UX studies have demonstrated how exercise intensity can be manipulated effectively, enhancing the enjoyment of PA and improving PA-related self-efficacy. Our preliminary findings and engineered systems, including the VR assessment tool, exergaming prototypes with biofeedback mechanisms and our exergame suitability model, pave the way for more inclusive research and applications of VR exergaming, such as capturing and correcting movements of users during exercise to improve training effectiveness and prevent injuries. This work not only contributes to VR UX research but also sets the stage for advancing public health and empowering individuals across diverse age groups and abilities.

Acknowledgement

This work was funded in part by the Ministry for Science and Health of Rhineland-Palatinate as part of the research training group (Forschungskolleg) "Immersive Extended Reality for Physical Activity and Health" (XR-PATH).

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