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Virtual Reality in Cognitive Rehabilitation: Engineering user Experiences

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ABSTRACT

Virtual Reality (VR) has emerged as a transformative tool in cognitive rehabilitation, offering immersive, interactive, and adaptable therapeutic experiences. This paper examines the role of VR in enhancing cognitive functions for individuals with impairments, focusing on user experience design principles that optimize engagement and effectiveness. By integrating motion-tracking, multisensory feedback, and real-time performance monitoring, VR therapy surpasses traditional rehabilitation methods. We propose a structured engineering workflow to develop user-centered VR applications, emphasizing accessibility, personalization, and ecological validity. Case studies illustrate the practical benefits of VR-based cognitive rehabilitation, while challenges such as motion sickness, privacy concerns, and interdisciplinary collaboration are discussed. Future directions highlight the need for ethical frameworks, funding strategies, and iterative design approaches to refine VR interventions.

Keywords: Virtual Reality, Cognitive Rehabilitation, User Experience, Neurorehabilitation, Human-Computer Interaction, Motion Tracking, Multisensory Feedback.

INTRODUCTION

Exposure to virtual reality enhances the utilization of neural networks in the learning process, promoting memory retention and transfer to real life. Technological progress over the last few decades has driven the applications of VR in many different subject areas, including experimental psychology, cognitive science, neuro-ergonomics, rehabilitation, military training, and entertainment. In the domain of motor learning, VR has been used as an observational learning tool to exhibit a clearer visual demonstration of task execution and as an alternate training paradigm to replace outdated clinical routines. These early attempts soon paved the way for exploring novel training paradigms, such as biofeedback and neurofeedback, multitask motor learning, and teleoperated therapy devices. Virtual reality-enhanced therapy offers advantages over traditional treatments. For instance, it can contain haptic biofeedback of muscular activation and forces; consequently, patients are capable of getting multisensory feedback in an impedance therapeutic setting, while rehabilitation experts are permitted to tailor feedback determined by the impairments. It permits the construction of arbitrary goals, brands the rehabilitation surroundings more interesting to individuals, and prices the same for users differently for the same treatments. Moreover, in VR-training setups, knowledge of patient performance over time can be gathered and returned in various ways. As a consequence, there are compelling reasons to speak of VR as a user experience phenomenon rather than a technology alone, where the technological focus shifts from the stability of hardware to designing appealing and effective user experiences. It is widely suggested that during training, performance feedback is given to the patient. Indeed, the provision of cognitive feedback

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(CF) may enhance learning. Traditionally, CF is verbal, telling the subject what they did and what they should do differently [1, 2].

Understanding Cognitive Rehabilitation

This paper aims to contribute to researchers and practitioners by reviewing the state of research in designing virtual reality (VR) based systems for cognitive rehabilitation and providing a framework for enhancing user experiences, and thereby, the outcomes of these systems. The importance of cognitive rehabilitation as a therapeutic means to strengthen, restore, and train cognitive functions in patients with cognitive impairments is discussed. The challenges of designing effective systems that support cognitive rehabilitation and a discussion on how embodiment in VR might facilitate cognitive rehabilitation are provided. Finally, implications for devising effective cognitive VR applications for cognitive rehabilitation and a design framework to engineer user experiences of VR applications are discussed. Recent advancements align the development of non-medical VR systems and the emergence of affordable, off-the-shelf head-mounted displays in particular—coupled with the success of VR in motor rehabilitation—make it likely that VR will become more attractive in the development of future cognitive rehabilitation systems. Whereas existing reviews on the use of VR in cognitive rehabilitation and related fields to date have tended to focus on the technological aspects of such applications or reviews of specific clinical domains, this text takes a psychologist's and interaction designer's perspective on designing cognitive VR systems. Key terms like cognitive rehabilitation and cognitive functions, and brain are briefly defined. It also strives to inform and inspire broader research interest among Human-Computer Interaction (HCI) and Virtual Reality (VR) researchers on designing effective, user-friendly cognitive VR applications. Broadly defined, cognitive rehabilitation is a therapeutic means to strengthen, restore, and train cognitive functions in patients with cognitive impairments. Major goals are typically to improve bio-psychosocial outcomes, well-being, and quality of life. While its effectiveness may be debated depending on the target population and within the research, cognitive training can have both near and far transfer effects. At the brain level, structural and functional changes as a result of training have been documented [3, 4].

The Role of Virtual Reality in Therapy

The rehabilitation process can benefit from different user experience design strategies that are currently being used in the entertainment industry. The successful employment of Virtual Reality (VR) systems in rehabilitation applications is closely linked to how user experiences are designed. The use of VR environments for therapeutic or rehabilitation purposes has grown over the last decade. VR is increasingly being employed in the rehabilitation process of individuals recovering from physical and cognitive insults like stroke, cerebral palsy, spinal cord injury, or traumatic brain injury. These types of injuries can lead to motor, cognitive, and perceptual deficits, which in turn can severely compromise the patient's normal life and autonomy. These impairments may also prevent the patients from using regular interactive systems or controlling devices. The application of VR in therapy promotes the involvement of patients in their recovery process and is focused on reducing the risk of developing a condition of learned nonuse of the injured limb by giving rewards and motivators to the patients. In these systems, the typical setting involves a motion tracking system that works in real time, such as optical or magnetic trackers. The overall setup typically involves several sensors, a data processing unit, and an interactively linked computer. Early evaluations show the efficacy of these systems, with improvements in amount and quality of movement, as well as the applicability of treatment protocols not possible with traditional methods [5, 6].

User Experience Design Principles

The software outlined in this paper plans to optimize patient engagement after leaving hospital care by utilizing automated remote and virtual reality therapies. The user-centric engagement design principles are discovered through a two-year in situ deployment. The disclosure includes how user-centric engagement design is coped with in the design of a platform to provide at-home use of evidence-based cognitive games after hospital discharge. This is novel in its applied approach, ensuring at-home engagement with cognitive games. Ideas about the engagement design of platforms to provide at-home use of cognitive games are also discussed. A typical player of a cognitive game will log in to the game on their computer screen and use it for a 20-minute session. The newer alternative utilizes a low-cost desktop virtual reality set-up in which patients will be engaged differently with the game exercise platform. Players are teleported to a virtual boxing gym where targets appear in various locations for them to hit. With this new set-up, the Balls Become Brains game was reprogrammed to Balls in Boxes and is user-controlled by a control. Before utilizing this new version, the MVP version was field-tested and built on with a two-year deployment. Software design, user requirements, and capabilities and limitations of the hardware were established collectively with the game development team. The design iterations focused on gameplay, software immersion, usability, and motivations. Console design iterations were also gradual as the game development team built up expertise. These limitations in advance, the aim was - at the end of the trial - to be well-placed to adapt and further design both the remote player and game environment. It was in this context that a two-year deployment was undertaken to refine the game environment and to assess these hardware and software components in the real-world setting [7, 8].

Technological Frameworks for VR Applications

Virtual Reality (VR) technologies are increasingly used for cognitive rehabilitation, raising questions about designing environments that promote effective action planning, challenge impairments, and encourage knowledge transfer to daily life. This project aims to develop an engineering workflow for systematically creating User Experiences (UEs) in VR cognitive rehabilitation. UEs are defined by users' perceptions from interactions, including emotions, feelings, and long-term memories. The project aims to generalize VR applications via a web-deployable platform and create a shared repository for non-expert developers to build effective VR cognitive rehabilitation tools. 2. User-Experience-Aware Engineering Workflow There is significant research on the technology and therapy aspects of VR interactions in fields like physical therapy. A review of current practices in VR for cognitive rehabilitation revealed many research gaps in UE design. Consequently, a User-Experience-Aware engineering workflow is developed, which focuses on an iterative process enhancing user perceptions and actions. The primary goal is to shape interlinked User Experience Goals (UEG) from therapeutic objectives. A UEG reflects high-level improvements in user performance based on therapeutic and strategic considerations, emphasizing gradual advancement during therapy. The workflow includes User's Viewpoint Goals (UVG) aiming to elicit specific perceptions that complement the UEG. It plans the development of UEs and categorizes them as User-Experience Outputs and Goals [9, 10].

Designing Effective VR Environments

The use of virtual environments in cognitive rehabilitation has increased over the past decade, aiding attention, memory, and executive functions. To enhance cognitive improvements, adherence, and daily living transfers, combining task-oriented interventions with high-ecological-validity virtual reality technologies is essential. This paper discusses guiding principles for designing effective virtual environments that support cognitive rehabilitation. Clinicians and researchers explore how society, culture, and cognition interrelate. A focus on open-world systems allows exposure to complex situations, necessitating analysis of interaction data produced during experiences. Virtual worlds enable detailed investigations of scenarios and calibration of various independent variables. This paper introduces a data-driven methodology for the design and study of experimental paradigms in virtual reality research and outlines a validated approach for assessing learning and memory in these open environments. It showcases round-trip validation by replicating a seminal study to demonstrate the methodology's efficacy in a simulated "Big Data" context. Several principles are suggested to guide developers in engineering effective virtual reality environments, aiding the evaluation of existing cognitive rehabilitation tools, and fostering the technology's acceptance in clinical practice [11, 12].

Assessment and Evaluation Methods

This platform is built using the Unity game engine for developing real-time 3D (RT3D) interactive systems, and its library and controllers are written in Microsoft C#. During the assessment task, a smartwatch was used to read physiological signals, including heart rate variability (HRV) and galvanic skin response (GSR), while participants navigated an immersive virtual reality (VR) environment. These data were then sent to a cloud service for storage through an Android mobile phone app to supplement analysis on stress. The platform also supports user navigation of the VR environment through a joystick, as well as a software-based joystick. The VE interface is rendered through the HMD and provides a photorealistic environment with a continuous field of view around the user. We also designed the interface by identifying and incorporating guidelines for older users. Over multiple iterations, the system was then revised and refined based on input and feedback from clinical neuropsychologists, who have extensive experience in cognitive assessment for individuals living with MCI. The simplicity of the interface is by design, for which a set of design propositions was recently developed for a minimal and intuitive VR system. Here, describe how those propositions were integrated into the design of VR-CogAssess. At each step, this team reported the involvement of users (research participants) who self-reported low computer literacy and had minimal previous exposure to VR [13, 14].

Case Studies in Cognitive Rehabilitation

Virtual Reality (VR) and Mixed Reality (MR) have recently demonstrated growing potential as interventions for cognitive rehabilitation. These experiences can be engineered for treating different cognitive deficits, actively engaging users toward the intended rehabilitation tasks. This paper presents a novel methodology for engineering user experiences in VR and MR. By employing empirical studies, it is shown how these engineering methods can be used to develop VR and MR applications that can be adapted to an outcome-based approach currently utilized in physical rehabilitation research. Virtual and Mixed Reality Support for Activities of Daily Living (ADL) Tasks: Strokes often result in long-term deficits that limit a patient's ability to independently perform Activities of Daily Living (ADL) essential for their survival. The recall, temporal order memory, location memory, visual scanning, and selective attention of patients are often impaired. There is a growing body of evidence that VR and MR can be used to generate rehabilitative activities for ADL tasks that can recover these cognitive functions. This paper presents the case studies and their underpinning rehabilitation methods before detailing the proposed theoretical framework. This is followed by an explanation of the methodologies employed for engineering user experiences in VR and MR, including empirical work to demonstrate how these engineering methods can be employed and address specific VR and MR applications developed to address ADL tasks [15, 16].

Challenges In VR Implementation

Virtual reality provides new advances for solutions to current challenges. Virtual Reality presents a new set of challenges and opportunities for both engineers and neuroscientists. Virtual Reality (VR) and Augmented Reality (AR) technology has significantly improved over the last decade, creating an unprecedented parallel interest on both the academic and industrial side. On the front, immersive technologies promise to revolutionize digital simulation, training and teaching, robot-human interaction, tourism, and entertainment, and also medical diagnostics, rehabilitation, and surgery. On the industrial side, AR and VR devices are attractive smart objects that can play an important role in the forthcoming era of 5G telecommunication, Edge-computing networks, the Internet of Things, Industry, and the cities. The implementation of VR/AR/MR (Mixed Reality) simulators and training is of utmost importance since it can significantly improve safety, increase performances, and reduce the economic costs and environmental impact, as it can drastically limit the need of real equipment, facilities, and working hours. In this work, an overview of the goals, approaches, and some results is provided from a multi-disciplinary programme designed within a consortium of psychologists, neuroscientists, and VR/AR/MR specialists to address some of the most outstanding issues and potentials of the field. The research ranges from very low-level technology problems concerning human visual and auditory perception when captured, processed, and rendered in the digital domain to very high-level educational and neuro-scientific issues. A combination of psychophysical, electrophysiological, and neuroimaging experiments are presented and explained, illustrating how different research methodologies can be applied to different problems concerning the VR/AR/MR. At the sensory level of interpretation, virtual reality systems somehow fail to simulate all aspects of a virtual world, observer's response ranges from an innocent belief to a degradation in the immersive experience that can range from mild annoyance to profound nausea. On the other hand, at a more cognitive level, the observer in virtual worlds might experience environments in which social, emotional, and physical norms are violated in ways never possible in the real world. In parallel, reconstructions or novel realities might use the illusion of VR to investigate and manipulate cognitive systems in ways never before considered [17, 18].

Future Directions in VR Research

In this paper, we summarized ten years of our formative research with designing Virtual Rehabilitation platforms oriented towards enhancing Cognitive Rehabilitation outcomes, and explained how these serve to engineer persuasive User Experiences that empower older adults to adhere to rehabilitation tasks that are not just physically stimulating, but also cognitively engaging. The need for new methodologies and technologies that better support older populations in their endeavors to maintain quality of life and functional autonomy is indisputable, especially in the context of the estimated exponential growth rate of the share of the younger population that is at or over 60 years old within the next 20 years. Current approaches to encourage functional autonomy and to maintain health are based either on clinical practices, which tend to be expensive, of limited access, and of variable outcomes, or on sporadic advising sessions, which tend to lack continuity and a clear understanding of personal context. Given that many of the challenges towards adopting a healthier lifestyle and maintaining a good quality of life derive from

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cognitive obstacles, technologies that could help to unclog cognitive loads with the minimum intrusiveness possible are warranted. Moreover, it is also these more easily accessible forms of assistance that may be more prone to fostering the elderly becoming dependent rather than autonomous and empowered. Researchers and developers of Assistive Technologies might use the growth of the "third age", digital literacy, and personal tracking as leverage points in the interest of attention to promote different, more empowering forms of assistance. Virtual Reality based platforms are proposed as an instance of this as it is possible to target such forms of assistance at both the source, by deflecting cognitive loads related to executive functions, and the target, since, at the least, a well-designed VR platform is needed for the contents of this proposal to be enacted fully [19, 20].

Ethical Considerations

In this study, an analysis of the collection and processing of personal data for remote user studies is presented using a VR game developed for cognitive rehabilitation. An investigation on privacy risks within adversarial VR game design. A framework for remote studying ethical considerations is proposed, assessing the processing and collection of personal data during remote VR user studies. Structuring and reasoning the ethics involved in the collection, storage, and processing of personal data in a virtual reality environment. The findings can be generalized to similar scenarios and propose public policy recommendations for Facebook so that social hazards can be mitigated adequately and the rights and freedoms of individuals safeguarded from potential harm. Relatively recent virtual reality (VR) technologies have been flourishing in gaming, health, social, and many other sectors. Traditionally, academic work has shown keen interest in immersive experiences offered by hardware, gadgets, and cognitive effects on abilities. While informative, the potential datafication and privacy concerns have been largely overlooked. Research focused on collecting data for developing VR games for cognitive rehabilitation, ethical issues may arise in remote user studies. A growing body of publicly available data leaks suggests that Oculus platforms are actively used for data collection and processing. All due care of the study conduction is used when interacting with Oculus platforms and their data-intensive digital assets to minimize potential damages due to lockdowns. An adversarial VR game was developed to identify privacy risks and associated aspects of Oculus Home and the Oculus Platform. An ethical framework is proposed for assessing and mitigating the adversarial design of VR games used in remote user studies [21, 22].

Interdisciplinary Collaboration

The development of successful engineering User Experiences (UX) for virtual reality (VR)–based cognitive training is a multi-faceted challenge, which involves collaboration and understanding across multiple domains. Such a bridge needs to span diverse fields, such as VR technology, User Centered Design (UCD), psychology and cognitive interventions, but also therapy practice, neuroscience, and neurorehabilitation. For the audience to better understand the challenges and how to address them, the most pressing questions about the engineering of VR-based systems for cognitive rehabilitation are observed. What are the biggest challenges for an effective engineering of user experiences for VR-mediated cognitive rehabilitation? Besides the technological challenges, the first problem faced by any VR-based intervention is to provide a User Experience that goes beyond state-of-the-art: the key elements to maximize ecological or cognitive "transfer" must be identified and integrated into well-accepted and common-use multimodal devices or paradigms. The experience must be engaging and enjoyable but also efficient for cognition activation and training tasks. The role of multimodality and embodiment for a successful VR experience is clear. However, what is still unclear is how such ongoing stimuli must interfere with the training task to enhance its effectiveness. Some works presented research protocols but not final implementations, features, or codes. From the assistance's perspective, such proposals often overlook crucial design and implementation issues. This may lead to the failure of an otherwise good idea and waste of resources in an already hard-to-fund research area. It is acknowledged that the development of interactive technologies and computer graphics requires complex pipelines beyond the reach of many researchers, but such platforms exist independently from this arena and may be the best starting point for multidisciplinary collaboration. A collaboration agreement may strengthen such a vision to obtain funding for more specifically focused works. The same holds for the proposed MRI-compatible VR system, which could fall within the interests of both biomedic and IT companies [23, 24].

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Funding and Resources

A comprehensive engineering model consists of five stages, including (1) user needs analysis (U), (2) performance requirements definition (P), (3) system architecture design (S), (4) system implementation (I), and (5) verification and validation (V). This model combines the VR hardware system and VR software system. The same letters are reused at different author places. User needs analysis. A precise and complete user needs analysis (U) is always beneficial for the success of a VR product. For this type of application, PL2 establishes the following recommendations for U. (1) Focus on needs related to daily living, which bring possibilities of service integration in the home environment. (2) "User" should be extended to healthcare providers and caregivers. (3) Ensure robust end-user interaction (environment, wheelchair type, disabilities). Healthcare context description should be enriched with data on wheelchair users. (4) Define the general requirements of a VR system to be used in a care environment. For this, list the most common types of wheelchairs, constraints, and devices involved. Types of trials, floor plans of rooms, and types of simulations proposed should also be provided. (5) Present "driveability" between home and community with main restrictions. Performance requirements definition. The output of PL2 translates the clinical needs to the laboratory requirements. This should be represented in the VR system by the limitations and conditions. To enable the definition of performance requirements (PR4), PL2's output detailing the clinical requirements of the system is reused. Here are also listed the limitations and conditions detected by the consortium: (1) The kinematics of the wheelchair simulator in intra and extra-dwelling activities are different from the ones observed within ICF. (2) Virtual scenarios must also be able to simulate extra-dwelling activities. (3) The kinect-based kinematics analysis replicates to a certain extent those made using a kinematic analysis system and will be used as an additional synchronization tool. The kinect-based walking analysis results will be used as a reference. Additionally, any further kinematic analysis should note the several ICF documents. (4) The output will only be expected after month 33. Just a brief meeting to discuss this will take place, and some small adjustments are still possible even after the output validation. (5) Six different clinical training protocols will test the simulator in their later development phase, between months 18 and 30. Clinicians will also previously train. The use of PR will be maximized in these tests. In the emerging field of virtual reality (VR) -based cognitive rehabilitation, much effort is going into building effective VR systems. This generally follows an engineering model to develop hardware and software systems. However, corresponding user experience design is rarely conducted. After a VR system is built, the user experience is usually evaluated, and it may bring essential design modifications in the early development. Therefore, this paper presents a comprehensive design methodology that accompanies the user experience design during system building, an engineering model where user experience design is integrated at each phase composed of five stages [25, 26].

Training and Support for Practitioners

The system developed under the name "Virtual and Mixed Reality Support for Activities of Daily Living" is the result of over a decade of pioneering research in supporting conditions of daily living for older adults and individuals with disabilities and/or incapacities. It provides training and support to service providers by combining best practice videos with portable virtual and mixed reality tools to create an engaging and captivating learning environment. This off-the-shelf system is now used by staff and carers to provide training and improve the service daily across the UK and worldwide. Training and support for practitioners are of growing importance due to the complexity of tasks associated with virtual reality interventions. As a result, alternative modalities for improving the effectiveness of the intervention are being considered. An attractive area of study involves developing technology-augmented methods for augmenting therapist knowledge and understanding. The design and evaluation of a novel mixed and virtual reality training system to support practitioners involved in conducting rehabilitation interventions is described. To the best of this best knowledge, it is believed the herein presented work is a unique study which is dedicated to investigating how mixed and virtual reality training and feedback could assist practitioners in conducting therapy treatments. To scaffold practitioner understanding and knowledge, a training intervention was engineered that employs a combination of informative best practice video, embodied visual feedback visualising practice methods, and situated learning within a virtual representation of the task. Such a training system was successfully integrated with a VR-based rehabilitation system for standing practice. Two training modalities were considered: personal on-demand training via a head-mounted display and in-depth practice with a large-scale interactive holographic display [27, 28].

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User Feedback and Iterative Design

This exhaustive inventory of components of VR used for cognitive rehabilitation is intended to guide decisions in the design and development of new systems. It reveals that critical selections lie in issues of equal weight concerning effectiveness, efficiency, user satisfaction, and immersion. For example, the range lies between fully immersive and 360° versus semi-immersive headsets. Therefore, many design decisions have compromises, and this illustrates a need for more informative evidence on which to base the design process. In the absence of general guidelines, VR content developers or purchasers must make decisions or select trade-offs in the presence of an extensive variety of options and possibilities. This is pertinent information for system developers, but it also has implications that may be of interest to end-users. Careful consideration of the range of components identified will allow people to develop or select VR systems better tailored to the needs of users or specific research requirements, set-up, or applications. Development and commercial options have and continue to evolve rapidly, rendering previous literature limited in applicability. Therefore, more recent publications are needed to inform current decision-making. In summarizing this later literature, VR used in cognitive rehabilitation (mainly across neurologically impaired populations) this eclectic selection has revealed five specific research areas which repeat with different foci but collected under the sub-headings here. Each of these papers is devoted to these broad areas of research, followed by a more tentative synthesis on what these findings suggest for designing VR for cognitive rehabilitation [29, 30].

CONCLUSION

VR presents a promising future for cognitive rehabilitation by providing engaging, personalized, and effective therapeutic solutions. Its ability to create immersive, adaptable environments enhances cognitive function recovery and encourages sustained patient participation. However, challenges such as technological limitations, privacy concerns, and interdisciplinary integration must be addressed to ensure widespread adoption. Advancing VR-based rehabilitation requires collaborative research, ethical considerations, and continuous user feedback to refine therapeutic applications. By leveraging digital literacy and personalized tracking, VR can revolutionize cognitive rehabilitation, promoting autonomy and improving the quality of life for individuals with cognitive impairments.

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