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Review Article

Virtual Reality for the Rehabilitation of Executive Function in Acquired Brain Injury: A Scoping Narrative Review

Jordano-de-Castro Alejandra and Torralba-Muñoz José-María*

NeuroLab, Spain

***Corresponding Author:** Torralba-Muñoz José-María, AGREDACE, Neurolab, Granada, Spain.

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Abstract

This article presents a narrative scoping review of studies on intervention tools for cognitive rehabilitation of executive functions in acquired brain injury. The aim has been to identify the latest advancements of virtual reality applied to the field of neurorehabilitation in acquired brain injury. The review has been carried out following the PRISMA protocol; three databases have been selected from which articles were selected according to established criteria. This yielded a final selection of 14 articles that have been used for the purpose of this narrative scoping review. The literature reviewed in the present article suggests that VR-based intervention protocols for the rehabilitation of executive function have potential to significantly contribute to the field of neurorehabilitation. While challenges and limitations persist, positive trends were observed across diverse patient groups, equipment, software, and severity of ABI.

Keywords: *Virtual Reality Acquired Brain Injury; Executive Function; Dysexecutive Syndrome; Stroke; Traumatic Brain Injury*

Abbreviations

VR: Virtual Reality; ADL: Activities of Daily Living; HDM: Head Mounted Display; TBI: Traumatic Brain Injury

Introduction

Acquired brain injury (ABI) is a major cause of death and disability. The latest survey by the Spanish Federation of Acquired Brain Damage (FEDACE) estimates that 435,000 people in Spain suffer from a form of ABI [1]. ABI is an umbrella term that captures non-progressive disorders that affect the brain and its structural integrity. There are two main types of ABI: traumatic brain injury (TBI) and non-traumatic brain injury. TBI are caused by an external traumatic event that leads to injury to the brain. Examples include car accidents, falls, and violence. Whereas, non-traumatic brain injury, cause by an internal disease that leads to damaged brain tissue. Examples include stroke, anoxia, or infection [2].

Clinical outcomes of ABI are very diverse and are often associated to a wide range of severe and permanent sequelae. ABI survivors can often experience difficulties in several domains including physical, emotional, and cognitive consequences. Among cognitive consequence, deficits in memory, attention, cognitive control, planning and flexibility tend to be the most commonly affected domains [3]. In the literature these deficits are often related to a diagnosis of dysexecutive syndrome [4].

The term dysexecutive syndrome was first introduced by [5] to refer to patients suffering from deficits of executive function. Several cognitive domains are implicated in executive control of behaviour: attention, cognitive flexibility, verbal fluency, inhibition, working memory, planification and decision making [6]. Deficits of executive function are amongst the most common and most limiting to survivors.

Deficits in executive function and working memory after ABI are among the most limiting consequences to an individual's quality of life. Notably, executive functions have been described as the essential mental abilities that allow an individual to adopt an effective, creative, and socially accepted behaviour [7]. Individuals suffering from dysexecutive syndrome have many difficulties navigating different aspects of activities of daily living [8]. The term activities of daily living (ADL) refers to all the frequent activities that an individual might carry out in their day to day associated to personal upkeep and survival. ADLs are linked to personal independence and autonomy, and include a wide range of activities, such as personal grooming, mobility, communication, family relations, and household maintenance [9]. Indeed, cognitive consequences of ABI, including deficits in attention, working memory, long-term memory and inhibitory control have been related to poorer quality of life and decreased personal independence and autonomy [9].

ADL have gained increased attention in the field of ABI neurorehabilitation and prognosis. In their latest systematic review on cognitive rehabilitation in adults with non-progressive ABI [10] highlight possible promising results from further research into virtual reality (VR) based interventions.

Virtual reality interventions provide numerous advantages over traditional methods of neurorehabilitation. In first instance, VR provides a safe and consistent ecological environment both during an intervention and between individuals [11]. Moreover, increased ecological validity and enhanced immersion of virtual environments is thought to favour the transference of cognitive domains trained in VR to daily activities [12].

Virtual reality also offers both clinicians and researchers the ability to record accurately a wide range of patient responses. These include eye movements, head movements, reaction time, and increased accuracy of response [13]. This allows for a more precise understanding of patient performance, which in turn also benefits the ability to provide a more accurate individualized treatment plan [11]. For instance, VR offers the possibility of interventions be continued long-distance of from patient's home [10]. Since many individuals with ABI have mobility issues this facilitates the intervention to be completed in its entirety.

Indeed, there is a wide diversity in the consequences of ABI [3], and VR offers the opportunity to have more adaptable interventions. Several VR offer game structured based interventions. This allows to adjust the difficulty of certain task to patient performance and increase its difficulty according to patient progress [13]. In addition, VR interventions have shown to increase treatment adherence and mood benefits [14]. Researchers have hypothesized this to be a desirable side effect of the intervention having a game-based structure that is thought to be motivational for participants [11].

Overall, there are many advantages that suggests VR could offer many benefits as a tool in the neurorehabilitation of patients affected by acquired brain injury. This narrative review will evaluate the evidence for the use of virtual reality in the rehabilitation of executive functions in acquired brain injury.

Materials and Methods

A scoping review was conducted using available data bases including Web of Science, Pubmed and Cochrane databases. Criteria was set to include articles published in English between 2010 and 2023. The search included the following terms: ("virtual reality" OR "virtual" AND "reality") AND ("neurorehabilitation" OR "cognitive stimulation" OR "rehabilitation") AND ("acquired brain injury" OR "acquired brain damage" OR "stroke" OR "traumatic brain injury" OR "acquired" AND "brain" AND "injury" OR "damage") AND ("executive function"

OR "dysexecutive syndrome"). Articles were evaluated according to the title, abstract, and text. Articles selected included studies that explore VR as an intervention tool in acquired brain injury for the rehabilitation of executive functions. Duplicate articles were removed resulting in a total of 14 articles being included in the present review (See table 1).

Study	Design	Participants	VR Tool	Major findings
(Shen., *et al.*)	Pilot study	Paediatric sample of 10 participants including 4 with TBI	HTC Vive VR HMD	Results showed adequate satisfaction ratings with the hardware and software components of the VR system
(Faria., *et al.*)	Randomized controlled trial	18 stroke survivors divided in two groups, VR and time-matched cognitive training	Reh@City virtual environment displayed in LCD monitor	Compared to traditional rehabilitation methods Reh@City had more impact in the rehabilitation of attention, memory and visuospatial abilities in both within and between group analyses.
(Burdea., *et al.*)	Feasibility study	8 chronic post-stroke, age 64.14 ± 16 individuals and 8 carers	Computer, and bimanual game controller	Participants showed significant improvements in grasp strength, depression and executive functions, showing the feasibility and efficacy of home-based interventions using VR systems. The system acceptance was very good with system rating by participants at 3.7/5 and by caregivers at 3.5/5.
(Faria., *et al.*)	Randomized controlled trial	36 Stroke patients allocated to VR group or Task Generator group	Reh@City virtual environment displayed in LCD monitor	A within-group revealed improvements in general cognitive functioning, attention, visuospatial ability, and executive functions. A between group analysis revealed the VR intervention to have superiority compared to content matched traditional methods of rehabilitation. One month follow up showed processing speed and verbal memory improvements were maintained.
(Maier., *et al.*)	Randomized controlled trial	30 stroke survivors with Mild to Severe cognitive impairment. Age 65 ± 6	Desktop computer, Microsoft Kinect and Tobii EyeTracker T120	Adaptive training using a VR-based system reduced the impairment in attention, general cognitive function, and spatial awareness. In addition, a positive change in the mental wellbeing of the patients was observed
(Manuli., *et al.*)	Randomized controlled trial	90 participants with chronic stroke, age 43.7 ± 11.3, divided in three groups: robotic rehab with VR; Robotic Rehab; Conventional Rehab	Lokomat Pro (with VR)	Rehabilitation with Lokomat Pro (with VR) showed significant improvement in cognitive flexibility and shifting skills, selective attention/visual research, besides a significant increase in quality of life in ADL
(Liu., *et al.*)	Randomized controlled trial	30 participants with mild cognitive impairment post stroke divided in two groups: traditional cognitive training and Immersive VR puzzle therapy	HMD	Immersive VR group showed significant improvements in executive and visuospatial function after VR intervention

(Man., *et al.*)	Randomized controlled trial	40 participants with mild to moderate TBI divided in two groups: conventional psycho-educational intervention	Artificial Intelligence VR training program	VR group performed more favourably than the therapist-led group with improvements in problem-solving abilities, work performance and self-efficacy
(Maggio., *et al.*)	Retrospective case-control study	56 participants with TBI, age 35.5 ± 5.3, divided in two groups: Lokomat with VR and Lokomat without VR	Lokomat with VR HMD	The VR rehabilitation group showed significant improvement in global cognitive function, executive function (preservation, planning and classification, cognitive flexibility and shifting, selective attention/virtual search). And significant improvement in the quality of life in perception of the mental and physical state.
(Dahdah., *et al.*)	Prospective study	21 participants, 9 diagnosed with stroke, 6 with TBI, 2 with anoxic injury, 3 with brain tumour, and 1 with amyloid angiopathy	Stroop task on a Z800 3D Visor HMD	Results showed immersive VR was effective in improving executive functions, namely complex attention, cognitive flexibility, inhibition, and information processing speed which could not be purely attribute to the subacute period
(Jacoby., *et al.*)	Randomized controlled trial	12 participants with TBI divided in two groups: VR intervention and conventional occupational therapy	VMall environment, GestureTek's Interactive Rehabilitation and Exercise System (IREX) video capture system	Results showed a trend towards an advantage to VR therapy compared to cognitive retraining without VR, as it leads to greater improvement in complex everyday activities
(Pennington., *et al.*)	Pilot study	Veteran sample of 30 adults with TBI divided into 3 groups: Exercise only, Gameplay control and VR-Executive function training	Oculus Rift HMD	The VR executive function intervention showed cognitive improvements in domains related to the specific cognitive challenges of the VR-EFT condition administered, which included visual scanning, cognitive inhibition-switching, cognitive flexibility.
(Gamito., *et al.*)	Controlled trial, between subjects	17 stroke survivors age 51 ± 14, divided in two groups: HMD VR and desktop screen based VR	HMD-based VR; and desktop screen-based display	Increased working memory and sustained attention from initial to final assessment regardless of the VR device used
(Moraes., *et al.*)	Prospective, quasi-experimental study	13 participants age 34.86 ± 11.12 with moderate to severe TBI	HMD Oculus Rift™ Development Kit-II (OR-DK2)	VR intervention showed to be feasible and safe for patients with TBI to use an HMD. We also observed positive effects on EF and future studies should consider a home-based approach

Table 1: *Shows the main studies exploring the efficacy of VR in the rehabilitation of executive functions after ABI.*

Results

VR shows promising results in the rehabilitation of executive functions in patients with acquired brain injury. Several studies exploring the efficacy of VR on the rehabilitation of executive functions using different patient populations, including, pediatric samples [15], chronic stroke [12,16-21], traumatic brain injury [22,23] and different forms of acquired brain damage [24] suggest beneficial effects of intervention protocols using VR. This indicates there is a potential for versatility of VR and a wide range of applicability. Indeed, the reviewed studies show positive effects have been shown in a wide range of executive functions, including problem solving, decision making, planning, attention control, inhibition, and flexibility. Long term effects of the VR intervention on executive functions has been shown to sustain improvements up to a three month follow-up period [16,24]. Moreover, studies using a comparative approach to evaluate different approaches withing VR intervention and more traditional therapies held identity the most effective methods and techniques withing the VR framework [16,18,20-22].

Several studies suggest these improvements also exert a positive effect in independence and autonomy in activities of daily living [16,20,21,25]. This suggest there is a transfer of skills from VR training to a function domain that impacts survivors of ABI quality of life.

The immersive and interactive nature of VR environments combined with the game based ludic structure of these interventions potentially makes engaging in this type of therapy motivating leading to increased treatment adherence and improved [17]. Several studies explore the feasibility and acceptability to VR interventions, showing these are generally well received by patients [15] and carers [17].

Several studies have explored the combined approach of physical activity and VR in rehabilitation interventions. This holistic approach to rehabilitation has also yielded positive effects of VR in the rehabilitation of executive functions. [20] using a VR HMD in combination with Lokomat, a robotic gait rehabilitation tool concluded there was a significant effect of VR compared a Lokomat intervention alone.

Results and Discussion

VR tools show potential as a versatile tool for targeting rehabilitation of executive functions. The studies included in this narrative scoping review show consistent findings on the significant effect of VR intervention on executive functions. Studies showed that patients with diverse profiles of ABI, stroke [16-18,21,26,27,29], traumatic brain injury [15,23-26,28] and veterans [26] benefited from VR interventions. The results were consistent across the lifespan with adults and older adults showing improvements in executive functioning after VR based interventions [20,23]. This highlights the applicability of VR-based interventions across different age groups and levels of cognitive impairment.

The research articles encompassed in this analysis reflect there is a wide range of VR equipment available. The hardware used for VR-based interventions included desktop computers, HMD, robotic neurorehabilitation systems, and finger touch projector. Several studies compared the efficacy of VR-based intervention to traditional methods of rehabilitation [18] or a physical intervention with and without VR [23]. These studies showed significant increased benefits of VR on executive function compared to other interventions [18,20]. [27] compared head mounted displays to screen exposure hardware using the same virtual environment in stoke patients. In this study both HMD and computer screen groups improved memory and attention regardless of the equipment use. However, since this study was published there has been significant advancements in technology that allow HMD to have better graphics and a higher degree of immersion. For example, VR headsets can now track hand movements allowing for individuals to interact with the environment without the need for controllers. Thus, potentially creating a more immersive environment. In a more recent study, [23] compared the efficacy of Lokomat, a robotic device motor and functional recovery, with a screen display and an HMD. While both groups reported improvements in self-perceived physical health, only the VR group had a significant improvement in global cognitive, executive functions and attention. These types of studies contribute to refine our understanding of the potential of VR-based interventions in clinical practice and if in refining the most effective approaches withing the VR framework. Future studies should consider comparing the efficacy of more immersive VR interventions to computer desktop and traditional methods of intervention delivery to determine the effect of immersion on the rehabilitation of executive functions.

While some authors create novel environments, creating dedicated narratives for the virtual environment developed [15], others focused on real life scenarios [16,21,25]. ADL based VR interventions allow ABI survivors to practice ADL skills in different levels of difficulty while also showing improvement of executive functions. It is thought that the creation of an immersive and interactive environment likely contributes to patient engagement, treatment adherence and motivation. The mechanisms through which VR interventions can improve cognitive functions are yet to be determined. Other authors have suggested that the VR environment stimulates cerebral blood flow and neurotransmitter release, resulting in the activation of several cortical functions. It has been suggested that the combined sensory activation provided by VR environments activates brain regions associates with executive function [30]. Thus, VR environments that engage patients in immersive environments promoting the interaction with the virtual surroundings through the completion of different tasks while offering prompts, auditory and physical feedback, stimulates the senses and leading to improved cognitive function [21].

The available studies and data on the effectiveness of VR as a rehabilitation tool for ABI shows great potential for the cognitive stimulation of executive functions. Nonetheless, there are several limitations that hinder the ability to reach solid conclusions. Firstly, quite a few of the articles included in this review labelled as pilot or feasibility studies. While these provide valuable insight into the potential use of VR for the rehabilitation of executive functions, larger and more rigorous randomized controlled trials are needed to establish conclusive evidence.

Among the studies, there is a high degree of variability in the intervention protocols and assessments used. This includes the length of training sessions, the number of sessions, neuropsychological batteries, and follow-up assessments. This variety can introduce inconsistencies that hinder the ability to compare and synthesize results. Future studies should consider standardised protocols that would allow for the comparison between VR tools efficacy, as well as provide more robust evidence.

Only two studies considered the long-term effects of the intervention. Faria, Andrade., *et al*. explored the long-term effects of the intervention one month after its conclusion, showing processing speed and verbal memory improvements were maintained. Similarly, Dahdah., *et al*. also found the improvements in executive function were maintained three months post-intervention. Future studies should consider exploring the long-term effects of the intervention, to determine whether there is a maintenance of the improvement in function and impact of the intervention beyond the intervention period. Moreover, future studies should consider exploring if there is a transfer of skills and generalisation of the VR-intervention of executive functions on ADL skills, autonomy, independence, and quality of life of ABI survivors. This would allow to evidence if VR interventions can offer beneficial outcomes that impact the individual's day to day life. Indeed, future studies should consider this study design implications with larger sample sizes to increase the reliability of results.

Conclusion

In conclusion, the literature reviewed in the present article suggests that VR-based intervention protocols for the rehabilitation of executive function have potential to significantly contribute to the field of neurorehabilitation. While challenges and limitations persist, positive trends were observed across diverse patient groups, equipment, software, and severity of ABI. Thus, highlighting the potential impact of VR technology as a tool for neurorehabilitation. Future research should explore the efficacy of VR using standardized protocols with larger sample sizes.

Conflict of Interest

There are no conflicts of interest to be declared.

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