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Games in Rehabilitation:
Part 2—Original Articles

Using Virtual Reality and Videogames for Traumatic Brain Injury Rehabilitation: A Structured Literature Review

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Abstract

Objective: This article reviews the available literature about the use of novel methods of rehabilitation using virtual reality interventions for people living with posttraumatic brain injuries.
Materials and Methods: The MEDLINE, EMBASE, SCOPUS, and Cochrane Library databases were searched using the terms ''virtual reality'' OR ''video games'' AND ''traumatic brain injury.'' Included studies investigated therapeutic use of virtual reality in adults with a brain trauma resulting from acquired closed head injury, reported outcomes that included measures of motor or cognitive functionality, and were published in a peer-reviewed journal written in English.
Results: Eighteen articles fulfilled inclusion criteria. Eight were case studies, five studies had a quasi-experimental design with a pre–post comparison, and five were pilot randomized control trials or comparative studies. The virtual reality systems used were commercial or custom designed for the study and ranged from expensive, fully immersive systems to cheap online games or videogames. In before–after comparisons, improvements in balance were seen in four case studies and two small randomized control trials. Between-group comparisons in these randomized control trials showed no difference between virtual reality and traditional therapy. Post-training improvements were also seen for upper extremity functions (five small studies) and for various cognitive function measures (four case studies and one pilot randomized control trial). Attitudes of participants toward virtual reality interventions was more positive than for traditional therapy (three studies).
Conclusions: The evidence that the use of virtual reality in rehabilitation of traumatic brain injury improves motor and cognitive functionality is currently very limited. However, this approach has the potential to provide alternative, possibly more affordable and available rehabilitation therapy for traumatic brain injury in settings where access to therapy is limited by geographical or financial constraints.

Introduction

Annually, an estimated 1.7 million people in the United States sustain a traumatic brain injury (TBI). Of them, 52,000 die, and 275,000 are hospitalized. About 75 percent of TBIs are concussions or other forms of mild TBI, cases of which are generally treated and released from an emergency department.[1,2] There is strong evidence that most patients make a good recovery from mild TBI without additional specific intervention.[3] However, a nonfatal moderate to severe TBI may result in an extended period of unconsciousness (coma) or amnesia after the injury. For individuals hospitalized after a TBI, almost half (43 percent) have a related disability 1 year after the injury.[4] Approximately 5.3 million Americans are living with a TBI-related disability.[1] The consequences of moderate to severe TBI can affect all aspects of an individual's life. TBI may lead to a wide range of short- or long-term deficits affecting (1) motor function (e.g., extremity weakness, impaired coordination, and balance), (2) cognitive function (e.g., attention and memory), (3) sensation (e.g., hearing, vision, impaired perception, and touch), and (4) emotion (e.g., depression, anxiety, aggression, impulse control, and personality changes).[1] These deficits can impact the ability of TBI survivors to work, do household tasks, drive, or participate in other activities of daily living, as well as affect relationships with family and friends. The estimated economic cost of TBI in 2010, including direct and indirect medical costs, is estimated to be approximately $76.5 billion.[1,5]

Rehabilitation of TBI patients with moderate and severe injuries generally consists of two phases: The inpatient phase

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and the outpatient phase. This article focuses on the outpatient or community rehabilitation phase. This phase may continue for 1–2 years, depending on patients' age, severity of injury, and residual disability. Patients may benefit from training that promotes household independence, vocational rehabilitation, driving retraining, and remediation of visuospatial deficits.[6]

There is increasing evidence that a neurologically injured brain has the potential for remodeling, if it undergoes proper rehabilitation training.[7] For neuroplasticity to occur, this training has to be challenging, repetitive, task-specific, motivating, salient, and intensive.[8] Recent systematic reviews indicate that more intensive therapies of longer duration are more effective than those that are shorter and less intensive,[3] with intensive rehabilitation training for up to 20 hours/week having the most positive outcome in the motor recovery process.[9]

Current resources are generally unable to fulfill the intensity requirement. The shortage of rehabilitation providers and resources has limited the provision of adequate and appropriate rehabilitation services to TBI survivors in various regions, especially in rural areas. In view of these limitations, novel rehabilitation strategies have recently been developed, including activities using robotics, virtual reality (VR), and Internet-enabled technologies.

VR, defined for the purpose of this article as an artificial world that consists of images and sounds created by a computer and that is affected by the actions of a person who is experiencing it, is one of the therapies that is increasingly used for rehabilitation of acquired brain injury. Evidence from systematic reviews demonstrates that VR is effective in the population of stroke survivors, where older adults predominate.[10,11] However, the evidence base for the effectiveness of rehabilitation following TBI in younger adults is not yet established.

The aim of this structured review is to examine the latest literature on the feasibility and effectiveness of using VR and videogames in TBI rehabilitation.

Materials and Methods

The Cochrane, MEDLINE, SCOPUS, and EMBASE databases were searched using the following search terms: (virtual reality OR video games OR exergaming OR active video gaming) AND (traumatic brain injury OR brain injuries OR TBI). The searches were performed on July 19, 2013 by one of the authors (E.P.).

Inclusion criteria

To be included, the studies had (1) to investigate adult participants with a brain trauma resulting from acquired closed head injury, (2) to use various form of VR (immersive, non-immersive, videogames) for rehabilitation, and (3) to report patient-related outcomes and (4) articles had to be published in English in peer-reviewed journals. All study designs including single-person case studies were included. Structured abstracts were also included.

The inclusion and exclusion criteria were developed by all three authors. Articles were initially selected by E.P., and the selection was confirmed by a second author (A.M.). Disagreements were discussed until a consensus was reached.

Exclusion criteria

Articles were excluded if (1) participants were children or adolescents, (2) they investigated brain trauma that resulted from a disease process, especially stroke, or from open brain injuries, (3) rehabilitation interventions used robotics in addition to VR, and (4) any inclusion criteria were not fulfilled.

Results

Search results

One hundred fifty-eight titles were identified by electronic search. After examination of abstracts, 37 full text articles were downloaded. Two of the included articles were found after examination of the reference lists. Altogether, 18 articles fulfilled inclusion criteria. The details of article selection are presented in Figure 1. One article was a 1-year follow-up on the previous study.[12,13] Eight of the included articles were case studies.[12–19] Five studies had a quasi-experimental design with a pre–post comparison,[20–24] and five were designed as pilot randomized controlled trials (RCTs)/comparative studies.[25–29] Details of these studies' characteristics and outcomes are presented in Table 1.

Quality of studies

Those studies that compared VR therapies with traditional therapies using random assignment of participants were small because of their preliminary nature. No power calculations demonstrating the ability of the research to detect between group differences in outcomes were included in the articles. It is even more difficult to assess the quality of case studies. Therefore, these studies only suggest potential benefits from VR therapies compared with traditional therapies, and the overall strength of evidence is weak.

Severity of TBI injury

The severity of subjects' TBI was assessed as severe in four studies[14,15,17,22] and as moderate to severe in two.[26,28] In six studies the information about severity of TBI was not clearly stated, although based on the described symptoms and functional deficits of the subjects it appeared to be at the severe or moderate to severe stage.[16,19–21,27,29] Six studies investigated subjects with moderate,[12,13] mild to moderate,[23–25] and mild[18] TBI.

Rehabilitation focus of the VR therapies

The VR therapies in included studies concentrated on rehabilitation of motor and cognitive functions. Rehabilitation of motor functions involved effects on balance[14–16,18,26] and balance confidence,[28] upper extremity functions,[20–22] and arm–postural coordination[23,24] and skills.[25] Rehabilitation of cognitive functions investigated effects on memory and/or attention,[12,13,17,29] prospective memory,[27] ability to function independently,[19] and perceptions related to program.[28] One study investigated the effect of the therapy on skills and emotions, specifically on road rage.[25]

Interventions

The intervention generally consisted of 8–12 sessions, conducted three times per week. There were only a few studies with a higher number of sessions (18[26,28] and 32[20]). Two studies used a single training session.[23,24] The duration of training sessions ranged from 30 to 90 minutes.

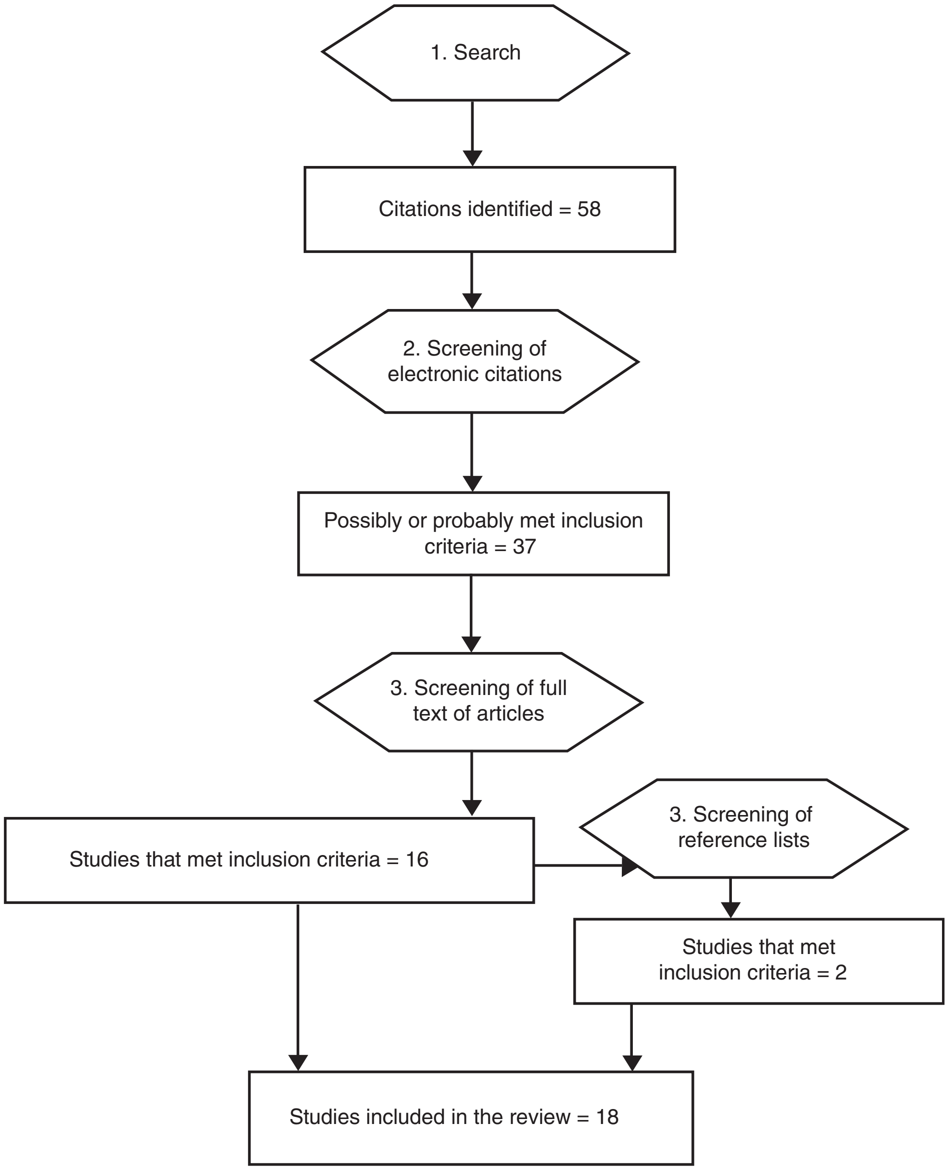

FIG. 1. Flow diagram for article inclusion.

VR systems

The VR systems used in the included studies were equally divided between commercial systems[12,13,16–18,25,26,28,29] and systems custom-designed for the study.[14,15,19–24,27]

Motor functions: Commercial systems. For rehabilitation of motor function, the commercial systems ranged from unique, fully immersive systems like the Computer Assisted Rehabilitation Environment (CAREN) or the Virtual Test Track Experiment (VIRTTEX) T driver simulator to freely available game systems like the Nintendo® (Kyoto, Japan) ''Wii™ Fit.'' The cost of the commercial systems varied substantially.

CAREN, developed by Motek Medical (New York, NY), is a very expensive (US $250,000–1.5M) system for registration, evaluation, and training of functional human behavior. It was used by one study for balance training.[18] CAREN's fully immersive VR environments combine motion platforms, instrumented treadmills, motion capture systems, and surround sound. The technology uses multisensory real-time feedback and enables the creation of a variety of experiments in a controlled and repeatable environment.[30]

One study used the VIRTTEX T driving simulator, developed by Ford (Dearborn, MI), for retraining of driving skills.[25] The complex and expensive (cost not explicitly reported) system is a fully immersive, full-motion-based driving simulator, which provides a complete virtual experience for testing driving skills.

Two studies used the Interactive Rehabilitation Exercise System (IREX™), produced by GestureTek Health Canada (Toronto, ON, Canada), for balance and gait training[26] and balance confidence.[28] Immersive video technology projected a patient's real-time image into virtual environments. Patients performed clinician-prescribed exercises, games, and activities, using body movement to control the program. The cost of the IREX system is about $13,000.[31] The final study using a commercial system used the Nintendo ''Wii Fit''

Table 1. Characteristics and Outcomes of Included Studies

Topic, reference (year), country	*Study characteristics*	*Interventions and outcome measures*	*Outcomes*
Motor functions			
Balance			
Betker et al.[15] (2006), Canada	Objectives: Effect on physical functions (standing balance) Design: Case study Setting: University hospital outpatient clinic, Canada Participant: 41-year-old male with severe TBI sustained 5 years previously. The subject was wheelchair bound, had poor sitting balance, and was very inattentive.	System: Study-designed. It consists of a flexible pressure-sensitive mat with a grid of piezoresistive sensors, COP-controlled exercise videogame, and FSA software, which sends the pressure data from the mat to the PC. Games: ''Under Pressure'' and ''Memory Match,'' with adjustable difficulty levels Intervention: Eight exercise sessions, over 3 weeks. Games were played 70 percent and 30 percent of the time, respectively. Games were played in a standing position; the subject held onto a table for support and was also supported by a physiotherapist. Main outcome measures: Because of the subject's reliance on support during standing, a COP standing assessment could not be performed, and a qualitative assessment is provided.	At baseline, the subject would only stand and attend to balance exercises for 20–30 seconds, with the training sessions typically lasting for only 10–15 minutes. Post-intervention, the subject was able: • To increase the duration of training sessions threefold, from 10–15 minutes to 40 minutes. • To maintain standing position without hand support for up to 20 seconds (compared with inability to perform the exercise before training). • To maintain concentration on standing balance exercises for up to 10 minutes at a time.
Betker et al.[14] (2007), Canada	Effect on physical functions (sitting balance) and psychosocial function (perceptions related to program). Rest as above	System: As above. Intervention: Twelve 30–45-minute exercise sessions, 2–3 times/week. Games were played in a sitting position on a small treatment plinth and the pressure mat. Main outcome measures: • Clinical Test of Sensory Interaction and Balance to measure dynamic sitting balance • Attitude to the program: a questionnaire; 5 questions regarding fun, motivation, levels of challenge and difficulty and preference for videogame-based versus traditional balance exercises	• Before exercise, the patient had 12 falls and required hand support during all six tasks on both surfaces (cushion and disk). • Post-intervention, the patient was able to maintain independent sitting balance for 20 seconds during all tasks on both surfaces. • The duration of the exercises increased from 20-second intervals for 10–15 minutes to 2-minute intervals for 20–30 minutes. • The patient scored all the questionnaire questions (fun, motivation, levels of challenge and difficulty, and preference for videogame exercises) at 5 on the 0–5 scale.
Eisenzopf et al.[16] (2010), United States	Objectives: Effect on motor function (balance) Design: Case study Setting: School-based, New York Participant: A 17-year old girl with TBI, presented with right side hemiparesis, balance deficits, and unsteady gait Note: Only abstract available	System: Commercial, Nintendo ''Wii Fit.'' Games included activities for training balance, weight bearing, strength, aerobics, and yoga games. Intervention: 10 weekly sessions of 20–30 minutes in duration Main outcome measures: • BBS • Weight distribution symmetry during standing, measured by the ''Wii Fit'' age	Post-intervention, the patient showed improvements in: • The BBS (no numerical values were available in the abstract). • The symmetry of weight distribution during standing.

(*continued*)

Table 1. (Continued)

Topic, reference (year), country	Study characteristics	Interventions and outcome measures	Outcomes
Rabago and Wilken[18] (2011), United States	Objectives: Effect on motor functions (postural and gait balance) Design: Case study Setting: Military performance laboratory, United States, outpatient Participant: 31-year-old male with mild TBI sustained playing sports 36 days earlier. He presented with vertigo, severe motion intolerance (visual and physical), and impaired static balance.	System: Commercial, CAREN, developed by Motek Medical for diagnostic, rehabilitation, and evaluation of balance. The system works in real time and enables the creation of a variety of experiments in a controlled and repeatable environment. Intervention: Six 1-hour sessions over 3 weeks Phase 1 of the intervention consisted of clinical techniques targeting specific impairments. Phase 2 training consisted of weapon handling and target recognition tasks. Main outcome measures: • Ability to perform during challenges without increases in symptoms • Measurements of postural and gait balance during cognitive, visual, and vestibular challenges within VR environment	Post-treatment, the patient showed: • Improvement on measures of static and dynamic balance. • Gains on all executive function and dual-task tests. • Reduction of visual vertigo symptoms • Markedly reduced gait deviations. • His post-concussion symptom scale score decreased from 41 to 0. The patient demonstrated a near-complete resolution of all post-concussion symptoms and successfully returned to full duty.
Sveistrup et al.[26] (2003), Canada	Objectives: Effect on motor function (balance) Design: RCT $n=14$, 3 groups Setting: Rehabilitation center, Ottawa, Canada Participant: Participants with moderate or severe TBI sustained at least 6 months earlier. Their balance deficits varied, but they were able to stand without aid for 2 minutes.	System: Commercial, IREX (developed by GestureTek Health Canada) Intervention 1: Eighteen 1-hour sessions of balance training, 3 times/week. Multiple VR scenarios required reaching, moving within the base of support, stepping, sit-to-stand, hopping, jumping, and jogging. Intervention 2: As above but performed as conventional exercise Control: No exercise Main outcome measures: • The Community Balance and Mobility Scale • A performance-based measuring quiet stance, gait speed, and activity-specific confidence	• Improvements on Balance and Mobility Scale were seen in VR and conventional exercise groups. • Both participants and family members reported increased confidence. • However, improvements were also seen in 2 out of 4 patients in the control (no balance training) group, which may reflect the process of natural recovery that occurs over the first 2 years post-injury.
Balance confidence, lower extremities function, perceptions related to program			
Thornton et al.[28] (2005), Canada	Objectives: Effect on motor (balance confidence) and psychosocial function (perceptions related to program) Design: RCT (quasirandom) $n=27$ Setting: Rehabilitation center, Ottawa, Canada Participants: Adults with moderate to severe TBI, 18–66 years of age, injury sustained at least 6 months prior. Had balance problems but were able to stand independently for 2 minutes	System: Commercial, modified IREX. It required participants to make large full-body movements to interact with virtual objects. Intervention: Eighteen 50-minute sessions, 3 times/week for 6 weeks Control: Traditional activity balance training that incorporated walking, running, and exercises with balls and stools Main outcome measures: Assessment performed at baseline, after training, and at 3-month follow up: • Balance and function questionnaires: ○ ABC ○ LEFS • Focus groups to obtain broad feedback on the exercise program, balance confidence, and lower extremity function	• Both groups improved on physical and psychosocial measures, but the changes were not statistically or clinically significant. • Clinically significant improvements were seen in individual patients: • ≥ 7 points on the ABC test for 3 participants in the control and in 5 participants in the VR group. • ≥ 9 on the LEFS for 2 participants in each group. • Attitudes: The VR participants demonstrated greater enthusiasm, expressing enjoyment and improved confidence. Comments indicated that if the VR were more available, it would be used.

(*continued*)

Table 1. (Continued)

Topic, reference (year), country	Study characteristics	Interventions and outcome measures	Outcomes
Upper extremity functions			
Holden et al.[20] (2001), United States	Objectives: Effect on motor function (relearning of a pouring task) Design: Pre- and post-quasi-experimental, $n=4$ Setting: Research setting, United States Participant: Male subjects with TBI sustained 3–18 years prior; 16–37 years of age. Three subjects had much greater impairment on the right side, one on the left.	System: Study-designed. It consisted of a computer, specially developed software, and a motion-tracking device. The prerecorded arm movements of a ''teacher'' and the arm movements of the patient are simultaneously displayed on the computer screen, and the patient is learning by imitation. The difference in trajectories provides the augmented feedback. Games (task): Pouring from a cup Intervention: 32 1-hour sessions, 3 times/week Main outcome measures: • ''Virtual'' motor test; pouring from one virtual cup to another, but without teacher feedback • ''Real World'' test, pouring from one real cup to another • F-M Test of Motor Recovery • Emory UE Test (timed tasks)	• Three of 4 subjects demonstrated qualitative improvement in end-point trajectories (cup path) performed during the virtual and real-world tests. The trajectories were smoother, straighter, and more accurate, compared with baseline. For 2 subjects changes were large; for 1 subject, slight; and 1 subject showed no change. • Clinical test scores also improved: FM Test in 2 subjects, Emory UE Test in 3 subjects. • Subjects were able to learn a movement in VE and generalize this ability to real-world performance of similar tasks.
Mumford et al.[21] (2010), Australia	Objectives: Effect on motor function (upper extremity) Design: Pre- and post-quasi-experimental $n=3$ Setting: Epworth Hospital, Melbourne, Australia Participant: Male patients (P1, P2, P3) 20–21 years of age, with TBI sustained as a result of an automobile accident, 8 months to 4 years prior. P3 was an inpatient and required assistance to walk.	System: Study-designed. It consisted of the proprietary software, a computer with a large horizontal screen, and a motion-tracking system. Participants move an object over the screen to cued locations while receiving augmented movement feedback to reinforce speed, trajectory, and placement. Intervention: 12 1-hour sessions, 3 times/week for 4 weeks VR therapy was concurrent with traditional rehabilitation. Performance was assessed at the conclusion of each session. Main outcome measures: • BBT • MAND • Three system-measured variables: Accuracy, speed, and efficiency	Participants demonstrated some improvements on movement accuracy, efficiency, and bimanual dexterity: • Accuracy: P1 and P3, both hands • Speed: no improvements • Efficiency: P2 and P3, right hands Standardized measures: • BBT: P1's left hand, P2's right hand, and P3's left hand • MAND: Generally no improvements on the nuts-and-bolts task; for the bead threading task, significant improvements for P1 and P2
Mumford et al.[22] (2012), Australia	Objectives: Effect on motor function (upper limb) Design: Pre- and post-quasi-experimental $n=9$ Setting: Rehabilitation hospital, Melbourne, Australia Participants: Patients with severe TBI, 18–48 years of age, injury sustained 3–178 months (median, 9 months) prior. Recruited from the TBI rehabilitation unit at the hospital. None was living independently.	System: As above Intervention: Twelve 1-hour sessions, 3 times/week, in addition to usual care. Each session consisted of 40 minutes of four goal-oriented tasks for both hands, followed by graphical feedback on performance and 5–10 minutes of three exploratory VEs. Main outcome measures: • System-rated measures: Speed, accuracy, and efficiency • Standardized tests: (1) BBT for general upper-limb function (2) MAND for bimanual dexterity (3) NFI for general neurobehavioral symptoms	Treatment resulted in significant improvements in system-rated measures and on standard tests: • Accuracy improved for both the left ($P=0.01$) and right hand ($P=0.02$) hand. • Speed and efficiency improved for the right hand ($P=0.01$ and $P=0.002$, respectively), but not for the left hand. • BBT improved for both hands ($P=0.04$ and $P=0.007$, respectively). • NFI total scores improved ($P=0.005$), and improvements were seen in the memory/attention subscales ($P=0.049$). • MAND did not change.

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Table 1. (Continued)

Topic, reference (year), country	Study characteristics	Interventions and outcome measures	Outcomes
Arm–postural coordination			
Ustinova et al.[23,24] (2011), United States	Objectives: Effect on motor function (arm–postural coordination) Design: Pre- and post-quasi-experimental $n=6$[23] and $n=13$[24] Setting: Rehabilitation center, United States Participant: Participants 20–44 years of age, with mild to moderate TBI and mild to moderate coordination deficits affecting gait, postural control, and upper extremity movements	System: Study-designed. It consisted of a custom-made 3D immersive videogame, ''Octopus,'' built with WorldViz Vizard software and a six-camera motion-capture device. VR scenarios required reaching and popping virtual bubbles with a hand and flexible use of the postural segments (trunk and legs) for balance and arm training. Intervention: Single 1-hour gaming session Main outcome measures: • Whole-body kinematics analyzed using principal component analysis	• The participants improved in game performance, arm movement time, trajectory curvature, arm–postural coordination, forward reach, and single-leg stance time. • These game performance changes were partially retained over the 30-minute retention interval: ○ In particular, the number of bubbles popped increased 42 percent[23] and 47 percent.[24] ○ The time of bubble trajectory interception (seconds) decreased by 24 percent ($P<0.05$)[23] and by 16 percent ($P=0.010$).[24]
Physical skills			
Cox et al.[25] (2010), United States	Objectives: Effect on physical functions (skills) Design: RCT $n=11$ Setting: Residential rehabilitation in a military brain injury center in Virginia Participants: Acute care patients with mild to moderate, war-related TBI, undergoing intensive inpatient rehabilitation	System: Commercial, Ford T driving simulator, developed by Virttex. VR scenarios provide the same road course, but differing traffic patterns and driving demands. Training involved practicing progressively more complex driving skills (lane position, speed control, etc.) through progressively more demanding traffic. Intervention: 4–6 sessions, each 60–90 minutes in duration Control: No training Main outcome measures: • Simulator driving skills (performance variables)	• Driving performance improved significantly only in the VR group ($P<0.01$). • The VR driving simulator was well received and considered realistic and effective, with no reported simulation sickness. • In particular, improvements were seen in five of seven performance variables: steering on the open roads and when executing turns, better accommodation to unexpected events, improved compliance to the simulator's instructions, and adherence to traffic laws.
Mental functions			
Memory and attention			
Caglio et al.[12,13] (2009, 2012) Italy	Objectives: Effect on cognitive functions (spatial and verbal memory) Design: Case study Setting: Not reported; presumably a university hospital outpatient clinic in Italy Participant: A 24-year-old male with moderate to severe TBI caused by a car accident sustained 7 months prior. He underwent standard rehabilitation protocols for 5 months.	System: Commercial, computer-based driving simulator (''Midtown Madness 2''; Microsoft Game Studios) Intervention: 15 sessions, 3 times/week, 1.5 hours in duration, with a 7-minute break after 20 minutes of navigation. The goal of the game was to run into and cut down a maximum number of poles and trees. Assessment was performed at baseline, post-intervention, and at follow-up at 1 and 2 months[12] and 1 year.[13] Main outcome measures: Short-term spatial memory; visuospatial memory; working memory; verbal learning; executive functions; general cognitive impairment, everyday memory	Post-intervention, the patient appeared to show a better performance on most neuropsychological tests: • Visuospatial memory: On RAVLT and Corsi tests for immediate and delayed recall, score improved from 1 to 3. • Verbal Learning: The Rey Auditory score improved from 0 to 3. • Executive functions: The Phomemic Fluency test score improved from 1 to 4. • There were no improvements in verbal memory and in executive and attention functions. • Improvement in spatial (but not verbal) memory appeared to be sustained after a 1-year no-contact follow-up period.

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Table 1. (Continued)

Topic, reference (year), country	*Study characteristics*	*Interventions and outcome measures*	*Outcomes*
Gamito et al.[17] (2011), Portugal	Objectives: Effect on cognitive functions (memory and attention) Design: Case study Setting: Psychology department of a rehabilitation center, Lisbon, Portugal Participant: 20-year-old male with severe TBI resulting from a car accident sustained >3 months previously, presenting with memory and attention deficits	System: Commercial; online 3D platform developed using a commercial tool, Unity 2.5. The patient interacted with the VR head-mounted display, mouse, and laptop keyboard. The VR scenario consisted of a small town with several buildings, a minimarket, and an apartment. The participant was able to move around and to grab objects. The patient's avatar had to perform some everyday tasks in the apartment, buy items from the minimarket, and find the way around town. Intervention: 10 online VR sessions Main outcome measures: • Working memory and attention measured by PASAT	• From the first to the final assessment, the percentage of correct responses increased significantly, indicating that there was a significant increase in working memory and attention levels. • The average time for task conclusion was 5 minutes (it is not clear what the time was at baseline).
Grealy et al.[29] (1999), Scotland	Objectives: Effect on cognitive functions (memory) Design: Comparative (with historical control), before–after blind assessment $n = 13 + 25$ Setting: Brain injury rehabilitation unit, Scotland Participants: A consecutive sample of 13 adults 19–64 years of age, with severe TBI sustained 1.7–178 weeks prior; ambulatory and with no perceptual disabilities. Control ($n > 25$): Matched former TBI patients of the same hospital	System: Semi-commercial; bike riding simulator. Commercial immersive VR was combined with actual physical exercise provided by a gyroscope-mounted exercise bike. Three VEs were used: A Caribbean island, a country town, and ski runs. Intervention: 12 sessions, 3 times/week, for 4 weeks, 25 minutes in duration Main outcome measures: • Tests of attention: information processing Digit Span (forward and backward), Digit Symbol (WAIS-R), and the Trails A and B tests • Learning and memory functions (Auditory Verbal Learning (Rey), Visual Learning (AMIPB), Logical Memory (AMIPB), and Complex Figure (Rey) tests)	• Post-intervention patients performed significantly better than controls on the following tests: ○ Digit symbol ($P < 0.01$) ○ Verbal learning tasks ($P < 0.01$) ○ Visual learning tasks ($P < 0.05$) • Memory functions did not improve.
Yip and Man[27] (2013), Hong Kong	Objectives: Effect on cognitive functions (prospective memory) Design: RCT, blind assessment $n = 37$ Setting: Outpatients in Department of Rehabilitation, Hong Kong; convenience sample recruited in a healthcare setting Participants: Subjects 18–55 years of age with ABI sustained ≥3 months prior. Not clear how many with TBI, but age indicates than not many had stroke.	System: Study-designed; non-immersive, PC-based VR program using everyday activities for training prospective memory Intervention: 10 sessions, 2 times/week, 30–45 minutes in duration Control: Reading and table games activities Main outcome measures: • Both groups were assessed for between-group differences on the prospective memory tests. • The VR group was assessed for immediate and delayed recall of prospective memory tasks, event-based, time-based, and ongoing tasks.	• Improvements were seen in both VR-based and real-life groups for: • Prospective memory outcome measures • Related cognitive attributes such as frontal lobe functions and semantic fluency.

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Table 1. (Continued)

Topic, reference (year), country	Study characteristics	Interventions and outcome measures	Outcomes
Ability to function independently			
Yip and Man[19] (2009), Hong Kong	Objectives: Effect on cognitive function (prospective memory, ability to function independently) Design: Case study Setting: Department of Rehabilitation, Hong Kong Participant: Adult male, 30 months since onset. Memory was the main cognitive deficit,	System: Study-designed; 3-D, non-immersive VR program developed using Virtools software. The tasks included traveling by bus and grocery shopping. Intervention: 10 sessions of 35–40 minutes in duration, 3 times/week Main outcome measures: • Built-in training parameters recorded by the computer: Distance traveled, time taken to accomplish all tasks, and the occurrence of inappropriate behaviors • Behavioral checklist of community living skills in the real environment (six tasks) • Self-efficacy questionnaire (11 items) • A brief interview regarding the usability of the program	• The subject showed an improvement in skills acquisition and memory performance. • An improvement in performing the tasks when tested again in the real environment (score increased by 16 percent). • Distance traveled and time taken to perform the task decreased. • Dangerous road crossing behavior did not improve. • Self-efficacy score worsened. • The program was well received. The subject was motivated to repeat the training process. Note that this intervention had much better results with 3 stroke subjects participating in the study.
Emotions: Road rage and risky driving			
Cox et al.[25] (2010), United States	Objectives: Effect on emotions (road rage, risky driving) Design: RCT $n=11$ Setting: As above Participants: As above	System: Commercial, Ford T driving simulator Intervention: 4–6 sessions, of 60–90 minutes in duration. Control: No training Main outcome measures: Questionnaires on road rage and risky driving behavior	• The VR driving simulator was well received and considered realistic and effective, with no reported simulation sickness. • Participants demonstrated a reduction in road rage ($P=0.01$) and risky driving ($P=0.04$) at post-assessment.

3D, three-dimensional; ABC, Activities-specific Balance Confidence Scale; AMIPB, Adult Memory and Information Processing Battery; BBS, Berg Balance Scale; BBT, Box and Block Test; COP, center of pressure; Emory UE Test, Emory Test of Upper Extremity Function; FM Test, Fugl–Meyer Test of Motor Recovery; LEFS, Lower Extremity Functional Scale; MAND, McCarron Assessment of Neuromuscular Dysfunction; NFI, Neurobehavioral Functioning Inventory; PASAT, Paced Auditory Serial Addition Task; PC, personal computer; RCT, randomized controlled trial; TBI, traumatic brain injury; VE, virtual environments; VR, virtual reality; WAIS-R, Wechsler Intelligence Scale.

with a selection of games selected for training balance, weight bearing, strength training, aerobics, and yoga games.[16] The cost of the Nintendo ''Wii Fit'' is about $130.[32]

Motor functions: Study-designed systems. Study-designed systems included a variety of combinations of software and hardware. Betker et al.[14,15] used a flexible pressure-sensitive mat with a grid of piezoresistive sensors, Federal Students AID (FSA) software, and center of pressure–controlled exercise videogames for investigating sitting and standing balance. The pressure data from the mat were sent for display on a personal computer containing the FSA software. The games used (''Under Pressure'' and ''Memory Match'') had adjustable difficulty levels.

The system used by Holden et al.[20] for arm and hand training consisted of a computer, specially developed software, and a motion-tracking device. The prerecorded arm movements of a ''teacher'' and the arm movements of the patient were simultaneously displayed on the computer screen using the motion-tracking device. The patient was asked to mimic the teacher's trajectory, learning by imitation. The difference between the teacher's and the patient's trajectories provided the augmented feedback. The task (game) involved pouring from a cup, with the subjects holding a real cup and trying to imitate the virtual teacher's motions.

The system used by Mumford et al.[21,22] for upper-limb rehabilitation consisted of a personal computer, proprietary software, a large computer screen placed horizontally and covered with safety glass, a camera tracking system, and a user interface that includes augmented feedback and automated recording of performance data. Participants moved an object over the screen to cued locations while receiving augmented movement feedback to reinforce speed, trajectory, and placement.

The system used by Ustinova et al.[23,24] for arm–postural coordination training consisted of WorldViz (Santa Barbara, CA) Vizard software, integrated with a six-camera system for motion capture and a custom-made (developed by the authors) three-dimensional immersive videogame (''Octopus''). The participants use large arm movement to control their avatar and trying to ''pop'' the maximum number of bubbles blown by the octopus.

Cognitive functions. The systems used for investigating cognitive functions were generally commercial or semi-commercial. Caglio et al.[12,13] used ''Midtown Madness 2,'' a driving game, developed by Rockstar San Diego (Carlsbad, CA) and published by Microsoft Game Studios (Redmond, WA), to train spatial and verbal memory. It is a free roam racing game, which features a range of vehicles that can be driven around London and San Francisco. This inexpensive game may be used on the Xbox® (Microsoft) or on a computer.

Grealy et al.[29] used a semi-commercial bike driving simulator to investigate memory. The system consisted of commercially available immersive VR environments and a study-built gyroscope-mounted exercise bike. Driving through VR environments of a Caribbean island, a town, a countryside, and snowy mountains with ski runs was designed to train attention, information processing and learning.

Gamito et al.[17] used an online three-dimensional platform developed using a commercial tool, the Unity 2.5 game engine (Unity Technologies, San Francisco, CA), for memory and attention training. The patient interacted with the VR head-mounted display, mouse, and laptop keyboard. The VR scenario consisted of a small town with several buildings, a minimarket, and an apartment. The participant was able to move around and to grab objects.[17]

Yip and Man[19,27] developed a three-dimensional, non-immersive–type VR community skills training program using everyday activities to train prospective memory and ability to function independently. The program was developed using commercially available 3DVIA Virtools software (Dassault Systèmes, Vélizy-Villacoublay, France), which enables users to created virtual environments. Activities in the game included traveling by bus and grocery shopping in a convenience store.[19,27] The previously mentioned study of Cox et al.[25] used the Ford T driving simulator to investigate emotions, specifically, the effect on road rage and risky driving.

Outcomes

Generally, each study uses a different VR system for the intervention. Therefore, it is difficult to determine the correlation between the complexity of the system and outcomes and whether the most expensive systems result in better outcomes. The details of outcomes generated by individual VR systems are presented in Table 1. The summary analysis of outcomes is presented below.

Motor functions. Compared with pretraining, improvements in subjects' balance were seen in several case studies. The subject was able to maintain a standing position without hand support for up to 20 seconds, compared with inability to perform exercise before training, increase the duration of training sessions threefold, maintain concentration on standing balance exercises,[15] and sit without falling for 20-second intervals.[14] The Berg Balance Scale and the symmetry of weight distribution during standing improved.[16] Improvements were seen on measures of static and dynamic balance and reduced gait deviations.[18] In small pilot RCTs, improvements on the Balance and Mobility Scale were either similar in the VR and conventional exercise groups[26] or were small and statistically/clinically insignificant.[28] In a semi-experimental study with four subjects, three subjects demonstrated qualitative improvement in upper limb function, especially with end-point trajectories performed during the virtual and real-world tests.[20] The trajectories were smoother, straighter, and more accurate, compared with baseline. For two subjects, these changes were fairly large. For one subject, changes were slight, and one subject showed no change. Clinical test scores also improved (Fugl–Meyer Test of Motor Recovery in two subjects, Emory test of Upper Extremity Function in three subjects). Subjects with TBI were able to learn a movement in the virtual environment and generalize this ability to real-world performance of similar tasks.[20] In other studies, participants demonstrated some improvements in VR system-rated measures (accuracy, speed, and efficiency of movement)[20–22] and mixed improvement in speed and some measures of movement skill.[21] Improvements were also seen on standardized tests for general upper-limb function (Box and Block Test, Neurobehavioral Functioning Inventory).[22] In two studies, arm–postural coordination improved after a single session.[23,24] Unfortunately, there was no follow-up to assess duration of these improvement. Driving performance improved significantly in the VR group, but not in controls with no training.[25]

Cognitive functions. In case studies, following VR-based interventions, participants appeared to show a better performance on tests for spatial memory but no improvements in verbal memory. Improvement appeared to be sustained after a 1-year no-contact follow-up period.[12,13] There was a significant increase in working memory and attention levels; the percentage of correct responses increased, and the average time for task conclusion decreased.[17] Results were confirmed by a comparative study, where there was a significant improvement in attention, and in visual learning tasks, but not in memory functions, as measured by the logical memory and the complex figure test in the VR group compared with (no training) controls.[29] In another case study,[19] the subject showed an improvement in skills acquisition and memory performance, as measured by decreased distance traveled and time taken to perform the task. The improvements in performing the tasks in the VR environment translated to an improved score when tested again in the real environment (the score increased by 16 percent). However, dangerous road crossing behavior and the ability to function independently (self-efficacy score) did not improve.[19] In a pilot RCT performed by the same team, improvements were seen in prospective memory outcome measures, such as semantic fluency.[27] VR retraining in a driving simulator was able to affect emotions; participants demonstrated a significant reduction in road rage and risky driving at postassessment.[25]

Attitude. Attitudes of participants in VR interventions to improve motor functions were more positive than for traditional therapy. The VR participants demonstrated greater enthusiasm, expressing enjoyment and improved confidence. Comments indicated that if the VR were more available, it would be used.[28] Attitudes of participants in VR interventions to improve cognitive functions were also positive. The training for everyday tasks such as traveling by bus and grocery shopping in a convenience store was well received, with the subject motivated to repeat the training process.[19] In another study, the VR driving simulator was well received by subjects and was considered realistic and effective, with no reported simulation sickness.[25]

Discussion

At present, the evidence that the use of VR in rehabilitation of TBI improves motor or cognitive functionality is limited, primarily because it is provided by case studies and very small RCTs. However, before–after comparisons consistently show improvements in motor functions such as balance (four case studies and two small RCTs) and upper extremity functions (five studies) and for various cognitive function measures (four case studies and one pilot RCT). The studies that compared VR therapy with a traditional therapy showed no difference in improvements between the two. When a new therapy becomes available, it is usually compared with a ''gold standard'' and should be proved to be ''as good as'' or better than a traditional one. This improvement has not been demonstrated by studies included in this review. However, neither did the VR studies show poorer outcomes than the traditional therapies, and there were indications that improvements may be evident when more research becomes available.

The VR therapy has some advantages over traditional therapies. The main advantage of using VR in TBI rehabilitation is its potential to simulate many real-life or imaginary situations, while providing a safe and consistent environment with the potential for infinite repetitions of the same assessment or training task and, unlike many conventional assessment and training methods, providing precise performance measurements and exact replays of task performance. In addition, VR has the flexibility to modify sensory presentations, task complexity, response requirements, and the nature and pattern of feedback to the user's impairments.[33]

An additional advantage of VR therapy is that it can be developed for home-based therapy. With therapies that could take years to complete, the development of the program that could be performed by patients at home, with a minimal input from therapist and carers, should be a goal of every therapy.

Saposnik et al.[34] listed the most important limitations to conventional post-stroke rehabilitation, which may be summarized as follows: (1) limited availability depending on geography; (2) dependent on transportation to special facilities; (3) time-consuming; (4) labor and resource-intensive; (5) dependent on patient compliance; (6) initial benefits often underappreciated by stroke survivors; and (7) dependent on health insurance and/or out-of-pocket expenses after the initial phase of treatment. These limitations are also relevant to post-TBI rehabilitation. The development of VR therapy as home-based, or based in local, nonspecialized clinics, would take care of limitations related to availability of specialized facilities, transportations to specialized facilities, and related costs.

Patient compliance may also improve with the use of VR therapy. The patient's attitude toward VR therapy was more positive than for traditional therapy. The VR participants demonstrated greater enthusiasm, expressing enjoyment and improved confidence. Comments indicated that if the VR were more available, it would be used,[28] with the subject motivated to repeat the training process.[19]

Commercial gaming consoles and off-the-shelf videogames are being increasingly used in clinical practice. A recent audit of urban stroke rehabilitation facilities in Australia showed that 61 percent of these facilities had purchased a Nintendo Wii system.[35] Videogame therapy is being successfully used with older people who were not raised playing videogames. Although stroke can occur at any age, 72 percent of people who suffer a stroke are older than 65 years.[36] In contrast, 45 percent of TBI victims are normal adults 20–64 years of age, 41 percent are children and adolescents (0–19 years of age), and only 14 percent are older adults ($>$65 years of age).[2]

The attitude of younger people toward videogames is more positive. Industry statistics show that 58 percent of Americans play videogames, and the average age of gameplayers is 30 years, with 32 percent of players 18–35 years of age and 36 percent above 36 years of age.[37] The population of TBI victims is much younger and more likely to have prior exposure to videogames. Assuming that a more enthusiastic attitude toward therapy leads to increased compliance, using videogames for therapy should increase patient compliance enormously.

However, one of the issues with the use of commercial games and consoles such as the Nintendo Wii and Xbox

Kinect® (Microsoft) is that these applications have been not designed as medical devices or with a primary focus of a rehabilitation tool. Many of these applications are too difficult to use as a therapy tool by people with disabilities and cannot be accessed or altered to improve usability. To function as therapy tools, the games should allow the user to interact in a way that is appropriate for his or her level of impairment and must be easily changed to increase the level of challenge as the user improves. They should also avoid giving negative feedback, which may discourage participation.[38]

Future direction for therapeutic research and practice

The research centers that investigate the use of VR for therapy should develop online games or videogames that produce positive outcomes in post-TBI therapy and make them available for therapy centers and for home-based use.

In their article entitled ''Games for rehabilitation: The voice of the players,'' Flynn and Lange[39] surveyed over 150 disabled players of videogames from nine countries throughout the world. Their findings are relevant to the use of videogames for TBI therapies. All of the participants indicated that they believe videogames have a place in rehabilitation. However, responders said they would appreciate if the gaming industry introduced some changes to game design to make them more user-friendly to players with a disability, including offering a variety of gameplay speeds, adding levels of difficulty/adaptive levels, and possibly introducing some kind of a ''cheat code'' or switch that would allow players to skip certain difficult parts of the game.[39]

Conclusions

The use of VR has the potential to provide alternative, possibly more available and affordable rehabilitation therapy of TBI in settings where access to therapy is limited by geographical or financial constraints.

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