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Virtual Reality in Brain Damage Rehabilitation: Review

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ABSTRACT

Given the high incidence of brain injury in the population, brain damage rehabilitation is still a relatively undeveloped field. Virtual reality (VR) has the potential to assist current rehabilitation techniques in addressing the impairments, disabilities, and handicaps associated with brain damage. The main focus of much of the exploratory research performed to date has been to investigate the use of VR in the assessment of cognitive abilities, but there is now a trend for more studies to encompass rehabilitation training strategies. This review describes studies that have used VR in the assessment and rehabilitation of specific disabilities resulting from brain injury, including executive dysfunction, memory impairments, spatial ability impairments, attention deficits, and unilateral visual neglect. In addition, it describes studies that have used VR to try to offset some of the handicaps that people experience after brain injury. Finally, a table is included which, although not an exhaustive list of everything that has been published, includes many more studies that are relevant to the use of VR in the assessment and rehabilitation of brain damage. The review concludes that the use of VR in brain damage rehabilitation is expanding dramatically and will become an integral part of cognitive assessment and rehabilitation in the future.

INTRODUCTION

Brain damage has often been referred to as the "silent epidemic." Its high levels of incidence are not in doubt. Frankowski et al.[1] reviewed seven major reports of the incidence of traumatic brain injury (TBI) and reported an average incidence of 250 cases per 100,000 of the population in the United States. By 1998, the estimated incidence of this type of brain damage had been revised downwards to 100 cases per 100,000 of the population.[2] Unfortunately, according to the Minutes of Evidence of a Select Committee on Health, Session 2000–2001, there is a lack of reliable up-to-date data in the United Kingdom on the incidence of TBI. However, from figures published in 1991,[3] the current estimate for the incidence of people admitted to hospital with TBI in the United Kingdom is approximately 270–310 per 100,000.[4] Figures for stroke cases in Western Europe indicate an incidence of 250 per 100,000, with an even higher incidence in Eastern European countries.[5] The incidence of brain damage due to neurodegenerative diseases increases with age, with the prevalence of dementia ranging from 1% at age 65 to 30% at age 85 years and older.[6] These estimates suggest that over three and a half million people aged 65 years of age and older are currently suffering from dementia in the European Union. With an increasing ageing population in the western world, the size of the problem is increasing. The implications for society in economic, social,

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and human terms are clear to see. Goldstein [7] reported that more people receive medical care in the United States for disorders of the brain and nervous system than for any other health problem, and it has been estimated that the direct medical costs just for TBI treatment in the United States are $48.3 billion per year.[2]

Given the epidemic-like proportions of the problem of brain damage, it is of interest that this particular epidemic has been so "silent" in not eliciting the acknowledgment afforded to many other large-scale health issues. The explanation is multifaceted. Firstly, brain damage is not a single medical condition. Even the simplest classification would recognize developmental, traumatic, vascular, and degenerative brain damage, and within each of these classifications, there are numerous ways in which conditions might be sub-classified, all with different profiles. Brain damage, therefore, is very different from an influenza epidemic in which there is a single cause and a clearly defined set of symptoms. The relatively low public awareness of brain damage also reflects the state of development of neuroscience. Whilst neurology has a long history, the origins of the more broadly based discipline of neuroscience, which has provided so much of our understanding of the nature of brain damage, are relatively recent. In this regard, it is of interest to note that as recently as the 1960s the brain was widely believed to be "hard-wired" by the time a person was born and that structural damage thereafter was permanent and its consequences "incurable." Such a view of the brain was not conducive to the development of active treatments for brain damage, still less to the development of rehabilitation strategies. This did not change until we began to understand the concept of neuroplasticity. It was not until the 1980s that the study of brain damage rehabilitation began to emerge as a specialist area of neuroscience, known as restorative neurology[8] or neurological rehabilitation.[9]

BRAIN DAMAGE REHABILITATION

Unsurprisingly, in view of its short history, brain damage rehabilitation is not underpinned by a clearly defined and agreed theoretical base. Nevertheless, those working in this field have established principles that define a vision of what rehabilitation should seek to achieve and provide a framework for multidisciplinary working towards objectives.[10] Crucial to the rehabilitation approach is to move away from the strict medical model of brain damage and to adopt a more holistic view of the person with brain damage. Helpful in making this transition is to view the rehabilitation process in terms of the concepts of impairment, disability, and handicap:

- *Impairment:* "any loss or abnormality of psychological, physiological or anatomical structure or function."[11]
- *Disability:* "any restriction or lack (resulting from an impairment) of ability to perform an activity in the manner or within the range considered normal for a human being."[11]
- *Handicap:* "a disadvantage for a given individual, resulting from an impairment or disability, that limits or prevents the fulfilment of a role that is normal (depending on age, sex, and social and cultural factors) for that individual."[11]

Importantly these terms define a progression of consequences of brain damage that has been described by Rose and Johnson[12]:

> The term "impairment" simply labels the effect of the injury on the brain and its function. The term "disability" assesses the impairment due to the brain injury in terms of its effects on what would be considered a normal profile of activities for a fit person. Finally, the term "handicap" places the disability within the personal context of that particular person's previous abilities, expectations and aspirations.[12]

The progression identified by these terms also identifies a continuum along which the positions of rehabilitation interventions can be clearly seen. We would argue that the use of virtual environments has potential for supporting rehabilitation at several points on this continuum.

POTENTIAL USES OF VIRTUAL REALITY IN BRAIN DAMAGE REHABILITATION

We have argued elsewhere that virtual reality (VR) has potential in addressing impairments, disabilities, and handicaps.[13] The main discussions in the literature so far have centered on the ways in which VR might be developed to address impairments and disabilities.

Damage to the brain, in reducing a person's ability to interact with the physical environment, often leads to a type of "environmental impoverishment." There is widespread agreement among clinicians that this sort of reduction in environmental interaction is counterproductive in terms of rehabilitation objectives. There is also an extensive animal research literature which suggests that, if this reduction in interaction can be reversed by a process of "environmental enrichment" (effectively enforced interaction with the brain-damaged animal's physical environment), the functional consequences of the brain damage are often reduced. Helping patients with brain damage, despite probable reductions in levels of cerebral arousal—activation, and the restrictions imposed by reductions in sensory, motor, attention, and other cognitive functions—presents serious logistical problems for staff. Frequently, staffing levels prevent these problems being adequately addressed. VR allows for the possibility of developing specific and appropriate opportunities for environmental interaction, tailored for the individual patient. Most importantly, the technology of VR allows us to deliver these opportunities for environmental interaction directly to the patient via a head-mounted-display (HMD) or screen rather than having to rely on the intensive rehabilitation staff input which is needed to help patients to interact with the real environment.

These arguments, and the underpinning neuroscience literature on which they are based, have been extensively reviewed.[14] Since then, there has been evidence of something of resurgence in animal research on the effects of environmental enrichment on both the undamaged and the damaged brain.[15–17] Interestingly, we are also beginning to develop ways of measuring brain activity using fMRI during interaction with virtual environments, which will allow us to establish whether exposure to virtual environments can directly influence the damaged brain.[18,19] This is an extremely exciting area of research and one that holds the promise of conclusively demonstrating the potential of VR in directly addressing the functional impairments caused by brain damage.

The emphasis of the present review, however, is the role of VR in addressing disabilities. An obvious potential use of VR is for retraining the performance of cognitive functions which, as a result of brain damage, can no longer be perfomed, "in a manner or within the range considered normal" (WHO definition of disability, 1998). Virtual environments are already used extensively for training,[20] and their potential for training people with brain damage has been discussed before.[21–27]

CURRENT USES OF VIRTUAL REALITY IN BRAIN DAMAGE REHABILITATION

The use of VR in brain damage rehabilitation is a relatively unexploited resource at the present time, but it has the potential to expand in the same way as the use of VR in vocational training has expanded in recent years. A few years ago, the use of VR in vocational training was a rarity, confined to large-scale and expensive virtual environments such as the flight simulator.[28] Now, virtual environments have a useful role to play in numerous vocational training programs where real-life training is dangerous, expensive, or difficult to monitor and control. The many diverse occupations that currently make use of the immersive and interactive properties of VR include drivers,[29] divers,[30] parachutists,[31] fire-fighters,[32] soldiers,[33] Royal Navy submarine training,[34] and surgeons.[35]

The obvious advantage of using VR in cognitive rehabilitation is its potential to simulate many real-life or imaginary situations, thereby providing the opportunity for more ecologically valid and dynamic assessment and training. It also has the capacity to provide absolute consistency of the environment with the potential for infinite repetitions of the same assessment or training task. It has the flexibility to enable sensory presentations, task complexity, response requirements, and the nature and pattern of feedback to be easily modified according to a user's impairments. In addition, unlike many conventional assessment and training methods, VR-based assessment and training provides precise performance measurements and exact replays of task performance.

The main focus of much of the exploratory research that has been performed to date has investigated the use of VR in the assessment of cognitive abilities, but there is now a trend for more studies to encompass rehabilitation training strategies. Where possible, the studies are reviewed under headings of the principal neuropsychological impairment that they address. However, some studies address issues which span several impairments, and these are reviewed under the heading "General."

EXECUTIVE DYSFUNCTION

The term "executive dysfunction" refers to impairments in the sequencing and organization of behavior and includes problems with planning, strategy formation, and mental flexibility. Damage to the prefrontal cortex has been strongly linked to executive dysfunction, and standardized neuropsychological tests have been devised to assess whether patients with damage to this area are susceptible to impairments. However, these tests have been criticized as lacking ecological validity, as some patients have been found to perform in the normal range on neuropsychological tests, but demonstrate impaired behavior in everyday life.[36] The use of VR has the potential to present some of these neuropsychological tests in a more ecologically valid way.

One of the earliest studies to devise a VR-based equivalent of a neuropsychological test of executive dysfunction was conducted by Pugnetti et al.[37] They used an immersive VR system to portray a VR equivalent of the Wisconsin Card Sorting Task (WCST).[38] The task was to reach the exit of a virtual building. The virtual environment comprised 32 rooms of variable shapes, each with a number of rooms that lead to dead-end corridors, the next room, or, in the case of the final room only, the exit. The strategy was to match either the shape or the color of the door which lead to the next room, and the criterion was changed every seven consecutive correct selections.

In a later study, they compared the performance of patients with neurological impairments and non-impaired control participants on the WCST and their VR-based version.[39] They found that controls performed better than patients in both tests. There was a modest correlation between the two tests, but they demonstrated different learning curves. In the WCST, there was an almost linear increase in the number of errors up to the fourth or fifth set, whereas in the VR test, errors decreased sharply from the first to the second and third categories. A clearly significant difference between patients and controls only emerged after the fourth category in the WCST, whereas this difference was apparent in the first category in the VR test. The authors suggested that "this finding depends on the more complex (and complete) cognitive demands of the VE setting at the beginning of the test when perceptuomotor, visuospatial (orientation), memory, and conceptual aspects of the task need to be fully integrated into an efficient routine." The detection of these early "integrative" difficulties may be particularly relevant for the task of predicting real world capabilities from test results.

A more recent study has also incorporated the elements of the WCST into a task which involves delivering frisbees, sodas, popsicles, and beach balls to bathers who sit under umbrellas in a virtual environment of a beach scene.[40] Similar to the WCST, the matching criterion switches from color to object to number. In the study, non-impaired participants performed both the WCST and the VR-based test with the order of performance on the tests counterbalanced across participants. The VR-based test was found to be more difficult than the WCST, but most performance scores from the two tests were significantly correlated. There were also order effects, indicating that participants had learned from their experiences in the first test. The authors concluded that their test measures the same cognitive functions as the WCST and may prove to be more ecologically valid.

The multiple errands task is another neuropsychological test for which a virtual environment has been devised and tested on five patients with executive dysfunction and five matched controls.[41] Despite the patients not differing from normative values on the standard executive dysfunction measure, the Behavioural Assessment of the Dysexecutive Syndrome battery,[42] they were impaired relative to controls on the real and virtual versions of the multiple errands task. In addition, there was a significant correlation between performance in the real and virtual tasks. The authors concluded that virtual environments may provide a more discriminating method of assessing planning impairments than currently available standardized tests. Such concordance between real and virtual task performance (along with the TBI/control discrimination) suggests that the VR method would have a pragmatic advantage for its use, since it is much easier to administer than the real world testing while offering more systematic stimulus control and response measurement.

Another common symptom of executive dysfunction is rule breaking. A recent study by Morris et al. used the virtual environment of a bungalow to assess strategy formation and rule breaking of 35 patients who had undergone prefrontal lobe surgery and 35 age- and IQ-matched controls during a furniture removal task.[43] All the patients and controls were able to navigate around the virtual bungalow and perform the task, but the patients showed less efficient strategies and increased rule breaks compared to the controls.

MEMORY IMPAIRMENTS

An important feature of cognitive assessment is determining whether a patient has memory impairments. However, assessing memory in the sterile setting of a rehabilitation ward is necessarily restrictive and may not be an accurate reflection of a patient's real-world abilities. Some exploratory studies have used VR to try to assess patients' memory in a more ecologically valid and controlled way than would otherwise be possible.

One of the first studies that assessed memory in non-impaired participants within a virtual environment was performed by Andrews et al.[44] They compared incidental memory for objects presented on a computer monitor in the following five conditions: during participants' interaction with a four-room virtual environment; in four static displays without any context; in the same four static displays in which participants were required to move the cursor over each object in turn; in four static pictures of the virtual rooms; and in the same four static pictures of the virtual rooms in which participants were required to move the cursor over each object in turn.

Subsequent recognition memory performance was found to be significantly lower in the condition where participants encountered the objects in the virtual environment than in any of the other conditions. The researchers concluded that participants were distracted by their interaction with the virtual environment and that incidental memory is particularly susceptible to distraction. They also pointed out that the interactive condition is more representative of patients' real-world memory ability than any of the other conditions, as real-life does not occur as a series of static displays.

A recent study by Mathias et al.[45] found that participants with TBI performed as well as controls in an object memory task using an HMD office scenario. This scenario required participants to scan the environment from a fixed sitting position and later recall 16 objects that were arrayed in positions around the office. This equivalence in performance may suggest that the absence of distracting navigational demands along with naturalistic head-turning used for scanning produced a test where participants with TBI could perform as well as controls. Since impaired performance by participants with TBI relative to controls was found on word list memory tests for these groups, this task may actually reflect spared visual memory ability when attentional demands are constrained during a visual object memory assessment

A further study assessed object and spatial memory of non-impaired participants using a yoked-control design in which active participants navigated around a four-room virtual environment searching for a non-existent umbrella, whilst passive participants watched their progress on a second monitor in an adjoining cubicle[46] In subsequent tests, there was no significant difference between active and passive participants' free recall or recognition of the virtual objects, but active participants recalled the spatial layout of the virtual environment better than passive participants. The superior performance of active participants in the spatial layout recall test indicates that their memory was enhanced for aspects of the environment which were directly involved in their navigation. The authors surmised that navigation of the virtual environment may have been responsible for active participants encoding the spatial layout of the virtual environment in a motoric form, which resulted in their superior recall.

A study using the same basic procedure was performed with vascular brain injury patients and control participants.[47] Results of this study showed that controls scored higher than patients in spatial and object recognition tests. However, active patients and controls again scored higher than passive patients and controls in a spatial layout test. In an object recognition test, passive controls scored higher than active controls, whereas there was no significant difference between active and passive patients. Again, the superior performance of active patients and controls in the spatial layout test was attributed to navigation of the virtual environment, resulting in the spatial layout being encoded motorically, thereby activating an alternative memory source. Similar results were found when the same study was performed with multiple sclerosis patients.[48]

The results of these studies are in line with those of a previous study which found that active non-impaired participants exhibited better spatial acquisition of a virtual environment than passive participants, as measured by a route-finding test.[49] However, they differed from two studies which found that non-impaired active participants were no better than passive participants in estimating the direction in which objects they had previously encountered in a virtual environment were located.[50,51] The difference between these studies may be attributable to the different tests of spatial memory used. The main difference between those studies that showed enhanced spatial memory for active participants and those that did not was that only the former used spatial memory tasks which were facilitated by retracing the original route through the virtual environment. It is therefore possible that motoric memory traces created during encoding were responsible for the enhanced spatial memory of the active participants. The results of these studies are believed to have implications for future strategy in memory rehabilitation. It may be possible to promote learning in people with memory impairments within a virtual environment by using motoric encoding to tap into spared procedural memory.

One study sought to do this by training a patient with amnesia (M.T.) in route finding around a hospital rehabilitation unit using a PC-based virtual environment of the real unit.[52] M.T. had been in the unit for 2 months prior to her training, but was still unable to find her own way around the unit. Prior to training, she was unable to perform 10 simple routes around the unit, all involving locations that she visited regularly. She was trained in the virtual environment on two of these routes and tested at weekly intervals on all 10 routes by a clinical psychologist who was unaware which routes she was learning in the virtual environment. After 3 weeks, she was able to perform the two routes she had been learning in the virtual environment, but she was still unable to perform the remaining eight routes. For her next course of training, she learned one of the remaining eight routes in the virtual environment and one in the real unit. After 2 more weeks, she was able to perform the additional route she had been learning in the virtual environment, plus the original two routes, but not the route she had been learning in the real unit. Unfortunately, she was still explicitly unaware that she knew how to perform any of the routes.

The authors offered three possible reasons for the counterintuitive finding that M.T. learned the route trained in the virtual environment quicker than she learned the route trained in the real unit. First, she performed the route very quickly in the virtual environment and was therefore able to practice it many more times than she was able to practice the route trained in the real unit during the 15-min training session.

Second, she was able to practice the route in the virtual environment without distractions. In the real unit, she was continually being distracted by other patients and by open doors along the route. Third, one of the strategies used to train M.T. was the backwards training method. This involved M.T. moving backwards a short distance from her destination and immediately retracing her steps to her destination. The distance she moved backwards was gradually increased until it encompassed the whole route. This training method was particularly successful in the virtual environment but less successful in the real unit where she was liable to back into other patients and wheelchairs.

This study showed that the use of VR in rehabilitation is not only useful as an assessment tool, but also has the potential to offer a useful training method and that training in a virtual environment does transfer to improved real world performance. In addition, it showed that VR is particularly suited to assessing and training spatial memory. In an innovative study, Morris et al.[19] used a PC-based virtual environment to investigate the brain correlates of egocentric memory (spatial knowledge relative to the observer) and allocentric memory (spatial knowledge relative to cues independent of the observer). They conducted functional magnetic resonance imaging (fMRI) of 11 control participants and two patients with anoxic hippocampal damage whilst they were performing egocentric and allocentric memory tasks in a virtual arena. Results from the control participants showed a network of brain activation associated with spatial processing in both the allocentric and egocentric memory tasks, but bilateral posterior hippocampal activation only during the allocentric memory task. The two patients with anoxic hippocampal damage showed a similar network of brain activation associated with spatial processing but no hippocampal activation in the allocentric memory task. The use of VR combined with fMRI in this study enabled the network of brain activation involved in a dynamic and interactive task to be identified and directly demonstrated the neuronal effects of brain damage. This combination of VR and fMRI provides considerable scope in the future to advance our knowledge of the brain correlates of other memory tasks.

One of the most disabling forms of memory impairment is the inability to remember to perform actions in the future (prospective memory failure).[53] Impaired prospective memory is more likely than any other form of memory impairment to interfere with independent living as sufferers may forget to switch off the stove, to light the gas, or to take medication. A realistic assessment of a patient's prospective memory ability should therefore be a major focus of any cognitive rehabilitation program.

Unfortunately, it is not currently possible to perform a comprehensive assessment of prospective memory ability in a rehabilitation setting because no standardized test is yet available. The most relevant test is the Rivermead Behavioural Memory Test (RBMT),[54] which was developed as a method of identifying everyday memory problems. However, only two, or possibly three, items in the RBMT relate to prospective memory ability, an insufficient number on which to base a realistic assessment.

VR offers the potential to assess, and possibly train, prospective memory ability in a pseudo–real-world situation. An exploratory study has assessed the performance of stroke patients and age-matched control participants on three prospective memory tasks (remembering to put "Fragile" labels on five glass items; remembering to allow removal men access every 5 min; and remembering to close the kitchen door to keep the cat in) whilst performing a furniture removal task in a virtual environment of a four-room bungalow.[55] Stroke patients were severely impaired at remembering to label glass items and to close the kitchen door compared to age-matched controls, but they were only marginally impaired at remembering to allow removal men access every 5 min.

Using the same procedure and virtual environment, Morris et al.[43] compared the prospective memory ability of frontal lobe patients and controls. They found that frontal lobe patients were most impaired at remembering to allow removal men access every 5 min compared to controls. They were also impaired at remembering to label glass items, but they did not show any significant impairment at remembering to close the kitchen door. The results of these two studies indicate that this VR-based prospective memory task is not only capable of discriminating between patients and controls, but it may also be capable of discriminating between the prospective memory abilities of patients suffering from different forms of brain damage.

SPATIAL ABILITY IMPAIRMENTS

Although spatial ability is obviously closely associated with spatial memory, there are additional neuropsychological features involved. According to Michael et al.[56] there are three dimensions of spatial abilities—spatial relations and orientation; visualization; and kinesthetic imagery (ability to determine the spatial position of an object in relation to oneself)—all of which are necessary prerequisites of independent living. According to Rizzo et al.[57] "Virtual environment technology may provide unique assets for targeting spatial abilities with its capacity for creating, presenting, and manipulating dynamic 3-D objects and environments in a consistent manner and for the precise measurement of human interactive performance with these stimuli."

A number of studies have investigated the use of screen-based virtual environments to assess and train spatial ability.[57] For example, place-learning abilities in a virtual environment were found to correlate with TBI patients' opinions of their own wayfinding problems.[58] VR has also proved useful in encouraging the development of spatial skills of children whose physical disabilities restrict their mobility.[59–61]

Recent research has used immersive audio virtual environments that provide auditory cues to supplement the environment information used by people with visual impairments.[62,63] The preliminary results of a study which used this technology to design a computer game for blind children showed that the children were able to navigate and interact with the virtual environment using the auditory cues.[64] The children were subsequently able to represent the spatial layout of the environment using Lego bricks, indicating that the auditory cues had helped them to build up their own cognitive maps of the virtual environment.

ATTENTION DEFICITS

Problems with attention are obviously common in children with attention deficit hyperactivity disorder (ADHD), but they have also been cited as the major disability after TBI[65] and are common in age-related dementias. Considering that attention is a necessary prerequisite of virtually all cognitive functions, it is surprising that relatively few studies have explored the possibilities offered by VR in assessing and training attention deficits. For example, VR offers the potential for attention to be directed towards a specific scenario without any distractions, but to introduce distractions as and when required.

Rizzo et al. have recognized the potential for VR in the assessment and training of attention deficits.[66,67] They have developed an HMD-based virtual classroom for the study, assessment, and possible rehabilitation of attention processes. A clinical trial of a vigilance task in the virtual classroom has been performed in which eight ADHD male children and 10 non-diagnosed children were required to hit a response button whenever they saw the letter "X" preceded by the letter "A" on the virtual blackboard. Each child completed two 10-min trials, one without distractions and one with audio and/or visual distractions, including classroom noise, movement of other pupils, and activity outside the window. Results indicated that the ADHD children had slower reaction times, made more errors, and had higher overall body movement than the control children. In addition, the ADHD children were more negatively impacted by distraction than the control children.

The virtual classroom has considerable potential for diagnosing, and potentially training, children with ADHD. Similar virtual environments could be devised for people with TBI and age-related dementias who have attention deficits.

UNILATERAL VISUAL NEGLECT

An unusual form of impairment after brain damage that may benefit from the use of VR is unilateral visual neglect, the inability of patients with damage to their left or right cerebral hemisphere, often caused by a stroke, to respond to stimuli presented on the side opposite the lesion. Unilateral visual neglect is an attentional or representational deficit, not a visual field deficit. Potential applications for the use of VR in the rehabilitation of visual neglect were first proposed by Rushton et al.[68] Since then, researchers at the Kaiser Rehabilitation Center have developed a VR-based tracking and cueing system, incorporating a head-mounted display, to assess and rehabilitate patients with left hemineglect.[69] The research is reported in its initial stage, but five patients with left hemineglect had been briefly tested and the equipment showed that all these patients had a greater maximal angle to the right than to the left. Another study demonstrated that a head-mounted display-based eye tracking system used in a virtual environment was a feasible way to assess and potentially to rehabilitate unilateral visual neglect.[70,71] They found that patients with left unilateral visual neglect only scanned and identified objects to the right side of the virtual environment, whereas control participants scanned and identified objects in the entire scene.

GENERAL

The majority of the above studies have been directed towards rehabilitation associated with specific impairments resulting from brain injury. However, many studies have used VR to try to offset some of the handicaps that people experience after brain injury.

From a person who has suffered a brain injury's viewpoint, one of the most disruptive handicaps that they may experience on recovery is not being allowed to drive. Similarly, older adults, who may even be in the early stages of dementia, are loath to forego the independence offered by driving their own automobiles. Clinicians are often given the task of deciding whether or not their patients should be allowed to continue to drive, but their decisions are necessarily subjective and criteria may vary from one clinician to another.

A PC-based VR driving simulator, incorporating an HMD, with steering wheel, brake, and accelerator, was tested on 17 adults with TBI and 17 non-impaired adults, matched for gender, age, and intelligence.[72] Performance measures included speed, steering, braking, merging with traffic, and changing lanes. Results from the study discriminated between the two participant groups with the non-impaired adults performing better than the adults with TBI on most of the performance measures. This form of driving simulator would be a valuable addition to a brain injury rehabilitation ward where patients could initially practice driving on a straight, deserted road and gradually increase the complexity of the driving scenario.[73] Given the importance that many patients attach to being able to continue driving, they would be motivated to use the simulator, which would not only improve their driving ability, but also help to relieve some of the monotony associated with hours spent in a rehabilitation unit between therapy sessions.

Street crossing is another skill that could aid independent living and might be practiced safely in a rehabilitation unit. A virtual street-crossing environment has been devised and tested on 95 schoolchildren from two schools—a suburban school and an urban school.[74] Learning in the virtual environment was found to transfer to improved real-world street crossing of children from the suburban school, but not children from the urban school. An initial study has also been performed to train two autistic children on street crossing in a virtual environment using an HMD.[75] The two children adapted well to the HMD and were able to track moving automobiles and select objects.

A train to travel HMD-based virtual environment for people with learning disabilities has also been devised, one component of which is a virtual bus ride.[76] The simulated route consisted of two interconnecting bus journeys, one beginning at a stop near the student's home and the other ending at the place of employment, allowing the student to learn skills necessary to transfer from one bus to another.

The students and their teachers found the virtual bus route exciting and fun, and students appeared to learn from training in the virtual environment because they were able to control the pace and content of delivery.

A user group of 15 people with learning disabilities and a facilitator have collaborated to develop a virtual city.[77] The user group suggested what they wanted in the virtual city, what they wanted to learn, and how it should be designed. The virtual city featured a house, a supermarket, a café, and a transport system. Evaluation of the project was concerned as much with the design of the virtual environments and their usability, as with monitoring skill learning.[78] The virtual city was found to provide interesting and motivating learning environments that were accessible to people with learning disabilities. In addition, users were able to learn some basic tasks, and there was some evidence of transfer of training of tasks performed in the virtual city to real world tasks.

Other functional activities involved in independent living, such as food preparation skills, have also been trained in virtual environments. For example, 30 patients with TBI were assessed on their ability to perform 30 steps required to prepare soup from a can in a virtual kitchen using an HMD.[79] Auditory and visual cues were used to promote learning. The TBI patients adapted well to the HMD, and test-retest reliability measures were encouraging.

A screen-based virtual kitchen was used to train 24 catering students with learning disabilities on fish, meat, fruit, and vegetable preparation tasks, hazard recognition, and fire drills.[24] In the food preparation tasks, virtual training was found to be as beneficial as real training and more beneficial than workbook training on subsequent real-world performance. However, training on hazard detection in the virtual kitchen was not found to improve real-world performance more than workbook training. One of the reasons the authors offered for these divergent results was that only the food preparation tasks involved learning a number of procedural steps which benefited from virtual training.

VR-based rehabilitation therapy may have even more wide-ranging beneficial effects. A recent study used background music to enhance the VR-based rehabilitation of a patient with an early form of Alzheimer's disease who was experiencing memory problems.[80] Three 15-min rehabilitation sessions each week for 12 weeks comprised three virtual experiences, which alternated with three auditory experiences, with the same cycle being repeated every 2 weeks. In the virtual experiences, the patient wore an HMD, and was immersed in one of three virtual environments, allowing her to re-experience her childhood, participate in a tournament, or walk the streets of a modern city. The patient's ability to orient herself and recall previously completed routes was tested during these sessions. After treatment, the patient reported improvements in her memory for names, her ability to use the correct word during conversation, and her sleep patterns. In addition, her performance in various neuropsychological tests, including the Wechsler Memory Scale,[81] an information retention test,[82] and the Stroop Test,[83] appeared to have improved, but these improvements were not significant. Although this case is only exploratory and there were no significant results, it does indicate that there may be potential uses for VR in less conventional rehabilitation therapy.

It is also possible that impaired memory may be improved by physical exercise. VR has been used to increase the motivation of people with TBI to exercise during their rehabilitation. Pedaling on an exercise bicycle enabled patients to navigate around three flat-screen VR environments to visit various virtual objects and locations.[84] The authors hypothesized that improvements in fitness engendered by the VR-based exercise would enhance brain activation and thereby improve cognitive processes. In support of their hypothesis, participants who were trained using the VR-based exercise bicycle performed better than control participants on visual and verbal learning tasks.

Because of confines of space, we have not been able to mention all the relevant research that has been performed. However, Table 1 follows, which, although not an exhaustive list of everything that has been published, includes many more papers that are relevant to the use of VR in the assessment and rehabilitation of brain damage. Where similar material has been presented in written articles or book chapters and presentations, we have only included the written version. Unfortunately, space dictates that many informative studies concerning the rehabilitation of people with learning disabilities and physical impairments cannot be included.

Although the use of VR in brain injury rehabilitation is still a relatively unexploited resource at the present time, the studies discussed here indicate that it is expanding dramatically. There is little doubt that the use of VR will become an integral part of cognitive assessment and rehabilitation in the future.

TABLE 1. BIBLIOGRAPHY OF VR REHABILITATION STUDIES

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