CYBERPSYCHOLOGY & BEHAVIOR
Volume 8, Number 3, 2005

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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CYBERPSYCHOLOGY & BEHAVIOR
Volume 8, Number 3, 2005

Commentary on Rose, F.D., Brooks, B.M., & Rizzo, A.A., Virtual Reality in Brain Damage Rehabilitation: Review

THE AUTHORS HAVE MADE a strong case for the use of virtual environments (VE, or virtual reality) in interventions at all levels of the rehabilitative process. We would prefer the use of a term other than "virtual reality," since computer-generated reality is a distant objective. It follows from the authors' comments that a particularly valuable feature of VEs is precisely their un-reality. A patient may benefit from the exploration of a world without clutter, and without the distracting or restricting presence of other actors. Navigating abnormally quickly may be beneficial, since it increases the speed at which spatial cues are encountered[1]; augmentation may draw attention to significant cues, and their gradual removal can require participants to make progressively greater use of their own memorial and navigational skills.

As the authors point out, the traditional assumption that brain damage is irremediable has been replaced by a more optimistic assumption that training can be restorative. Their emphasis is therefore on rehabilitative uses of VEs rather than "assistive" smart technologies, which may have the effect of replacing (and therefore undermining) a participant's own cognitive skills—a form of debilitation. Stanton et al.[2] notably found that successive VE exploration-test sessions progressively improved the rate and accuracy with which disabled children acquired spatial information, suggestive of an improvement in spatial functioning per se. The flexibility of VEs potentially allows progressive migration into proximal zones of cognitive development, as Vygotskii proposed[3,4]; indeed, a virtual assessment task (cf. the authors' discussion of the WCST) might be broadened into a rehabilitation package if the scaffolding of learning can be achieved. Improvement in spatial skills in a group of children with cerebral palsy was achieved in a recent study[5] by using Luria-Vygotskii training methodologies to allow children with poor starting performance levels to interface effectively with VEs.

The time–space dimension and event chronology is arguably a neglected area of rehabilitation. In recent work, young adults with disabilities created images of events in their lives, which were assembled into virtual time lines.[6] This technique may potentially improve upon the use of two-dimensional (2-D) time lines[7] in remedial and mainstream history teaching. Older individuals' reminiscence of events, including in childhood, has been used in the past as a strategy to slow cognitive deterioration, and VE may be useful in this aspect of rehabilitation.[8]

The authors argue that autonomous activity in a VE can enhance spatial learning where a task can be performed via motoric coding. Clearly, active-passive differences may depend on a number of factors,[9] and for Andrews et al.[10] a disbenefit of using a VE actively is added distraction. But interactional demands may also be crucial. Interestingly, the movements required to operate manual VE input devices closely resemble the directional sequential movements used in the secondary tasks used conventionally to compete for working memory capacity.[11] In a recent study by Sandamas and Foreman (unpublished data), accuracy in placing room objects on a map after passively observing VE exploration was significantly reduced by having to perform secondary complex motor tasks, but not simple motor tasks or a semantic task. Any benefit of active control of virtual displacements may be attenuated by the devotion of spatial working memory capacity to the operation of an interface device. A rider to this is that it cannot be assumed that all brain activity detected during desk-top VE-functional brain imaging studies is equivalent to that occurring in the brain in real-world equivalent tasks.

The use of VEs extends the differential diagnostic potential of existing testing methods. A recent study[12] compared two similar allocentric tasks (a virtual tray of objects task [VTOT], and a virtual flag location task [VFLT]) with a judgment of line orientation (JLOT) task, in closed head injury (CHI) patients and others with Parkinson's disease (PD). CHI patients were impaired on all three tasks used, but a non-demented PD group in the relatively early stages of PD was impaired only on the VTOT task. The latter involves considerable 3-D object manipulation, so that the result is consistent with several previous reports of selective spatial PD deficits.[13–15] PD patients were notably unimpaired on the VFLT (requiring larger-scale [virtual] cognitive spatial "mapping"). Motor impairments in patient groups often precludes real-world testing on tasks of this kind.

Problems faced by advocates of applied VE technology are cost and availability. Where VEs are created to assess or rehabilitate, particularly where these are required to represent an existing real equivalent environment,[16,17] considerable technician time may be required to produce and update the virtual models. Moreover, software packages can become unavailable, and 3-D construction formats become obsolete. Although companies are beginning to offer tailored environments in the health, treatment, and rehabilitation sphere,[18] a pressing future need is to find strategies to engage the optimal use of computer technologies. Some 60% of helpful technology lays idle on shelves because potential users are unwilling or incapable of using it effectively—indeed, ever switching it on! Technology has to be seen to be accessible and effective; this is a so-far neglected human factors aspect of VE use.

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As a physiotherapist working in the field of stroke rehabilitation, I recognize that there are some areas which could be enhanced by the use of virtual reality (VR), especially given the fact that resources are limited, but at the same time certain outcomes may be improved with more intensive input.

INTERACTION

VR has the advantage of being able to bring to a patient an environment that might otherwise be inaccessible. This opens up an array of possibilities for interaction in circumstances more compatible with the realities of everyday life, which is more meaningful to the patient and of more practical value. It is the interactive aspect of a task that promotes aspects of learning.

RE-LEARNING A SKILL

The re-learning of a skill requires not only an understanding of a task but also the ability to follow through all aspects of the task from beginning to end. VR can help in this scenario by enabling the patient to practice all, or parts, of the task in a meaningful setting. Whatever the task may be, it is only fully re-established at a normal level when it can be performed on an automatic basis without the need for conscious thought or monitoring, for example, putting on an item of clothing, or on a more physical note, preparing to get up into standing from sitting. Whereas many patients may never achieve this level of normality, there are those who do have the potential to do so, and VR could help them achieve this. For those less fortunate, they may be helped at least to some degree by being able to repeatedly practice a task in a virtual setting.

MULTI-SKILLING

In everyday circumstances, we are often required to perform more than one activity or skill at a time, for example, talking on the phone whilst writing down information. This may provide another opening for VR in that it could be used to simulate a set of dual circumstances that the patient may typically encounter during their day. This could enable improvement in a domestic setting or possibly assist a patient who is looking to return to work. It would be an advantage if the VR program could be tailored to the needs of the individual patient.

OVERCOMING NEGLECT

Where there is adequate physical recovery for a patient to use a limb functionally, for example, using the upper limb for simple tasks, yet the patient neglects to do so as a consequence of neurological impairment, then there may be a place for VR to improve the patient's focus on using the limb. This could start with double-handed activities and progress to one-handed activities, for example, drinking from a glass using two hands, progressing to using one hand only.

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The worldwide prevalence of acquired neurodevelopmental handicap is probably very substantial but practically inestimable. Increasing numbers of children are born prematurely, or suffer fetal insult by trauma or toxicity, sustain birth-related insults, inflicted or accidental brain injury, cancer, burns or infections, as well as a range of secondary insults from cardiac and renal disorders, nutritional, sensory, or emotional deprivation. These developing brains are all at significant risk of aberrant development, including extensive changes in myelination, with consequent delays, deficits, and late degenerative disorder.[1–4] As the children enter adulthood, with insufficient knowledge, abilities, and skills with which to survive independently, their quality of life will be poor.

Rehabilitation has the potential to change that ominous prognosis by effecting significant and beneficial long-term changes in the developing nervous system. Unfortunately, rehabilitation services for children are notable for their absence.[5–7] This should be of substantial concern to health, education, and social services, and to governments generally, but nothing changes. The absence of rehabilitation has little to do with our state of knowledge,[8–12] or economic wealth.[13] It may be as Skinner[14] suggested, that scientists get the facts but governments make the decisions based upon perceived wisdom and common sense. In this case, the prevalent but insupportable unscientific wisdom is that children achieve a better recovery from brain injury than do adults, implying no need for rehabilitation, especially in the long term.[15,16]

Developmental plasticity has its limits, but even damaged brains can benefit from appropriate intervention. The goal of enhanced cerebral recovery and development remains a challenge.

CAN VIRTUAL REALITY MEET THAT CHALLENGE?

VR provides unique opportunities for a child to engage in an enriched, stimulating, and rewarding environment, based upon necessary real-world experiences but individually tailored to his needs.[14,17] That increases the probability of beneficial functional and structural changes in the brain.[11,18] VR has the potential to facilitate recovery, improve myelination, increase cerebral reserve, and thereby improve post-insult development. The child has better foundations for the acquisition of skills necessary to achieve better long-term outcome. Participation in VR rehabilitation environments, especially when combined with appropriate educational support, may protect against the long-term risk of neurodegenerative disorders.

Potential applications include targeting both the "how" and "what" functions of the brain. Children are provided with environments and tasks not otherwise available because of their age and disabilities. Thus, immersion as a team member in a game, or enhanced physical exercise[19] may improve arousal, activation, effort, learning, and memory. Similarly, learning to explore environments, solve problems, find routes, or manipulate tools and objects, or specific training for a neurological impairment in vision, perception, or balance may help develop specific functions or skills in a variety of areas. One may readily think of many individual children for whom there has been no ready solution to rehabilitation problems. The immobile child who never has the opportunity to explore his home, run a race, or play football, for example. The potential applications are as inestimable as the long-term benefits, but as equally exciting. The results of intervention should be evaluated at all levels, from neurobiology to psychology and quality of life.

Recent changes to classification of disability,[20] with new terms of Activity and Participation, seem tailor made for pediatrics, such that Development should be the fourth factor. To effect significant change, the inherent plasticity of the developing nervous system must be understood, the potential developed, and the opportunities afforded by VR grasped.

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TWENTY YEARS AGO, I wrote an article titled "Automated Assessment" for a book titled *New Developments in Clinical Psychology*,[1] and outlined the potential for using computers for neuropsychological assessment, reviewing some fledgling studies that had taken place. The new desktop PC's had just become affordable (not to myself as a Ph.D. student), and researchers were starting to program serious neuropsychological tests such as the Wisconsin Card Sorting Test on the new Apple II computer.[2] An exciting future was ahead, leading to the development of such neuropsychological procedures.

Although the technology for virtual reality (VR) applications in clinical neuropsychology has, for practical purposes, been around since the mid 1990s, they are still in approximately this position—a bright future, but with much work to be done in developing applications that are adopted widely in clinical settings. What are the principles that should guide such endeavour?

USE VR CREATIVITY

VR offers the opportunity to create applications that were not possible previously, but also to make them exciting and relevant. So, whilst is it possible to administer the WCST using conventional cards, converting the task into one that has similar cognitive demands, but has a more game-like quality, involving delivering frisbees, sodas, popsicles, and beach balls to bathers[3] is likely to be more motivating than the more traditional method. The paper by Rose et al.[4] demonstrates convincingly that this field attracts and stimulates creative approaches.

USE CHEAP AND STABLE TECHNOLOGY

To move beyond experimental projects, the technology has to be widely available and hence commercially viable. It takes substantial time and resources to develop, standardize, and validate neuropsychological applications, so the technology has to be stable. Hence, it is likely that neuropsychological procedures that are commercially successful (and hence ultimately useful for people with brain injury) will use the PC and their existing monitor, perhaps aided by a joystick and no more. Head-mounted displays may prove essential for certain applications, made practical if cheap stable technology is available.

CAPITALIZE ON THE TECHNOLOGY

The advent of computing technology led people to believe that "automated" applications would take over what are called "pen and pencil" tests. This did not happen. Instead, it became apparent that computers had niche applications, able to do some things that could not be done using conventional procedures. The challenge in the main is to create new opportunities, as well as replicating past techniques in a different format. So, for example, VR in neuropsychology has proved useful for assessing spatial memory, where large-scale spatial domains can be created and the inconvenience, space, and time needed to do this in the real world is overcome. Already route finding assessment techniques have been shown to be valid in patients with brain damage.[5] Similarly, the assessment of executive functioning in patients has been hampered in the past by the lack of ecological validity of the tests used, and the ability to realistically test organizational, sequencing, and planning skills of patients using a standardized format may only be possible using VR.[6] Finally, a range of rehabilitation techniques can be developed that simulate real world activities without risk to the patient.[7]

CONCLUSION

The paper by Rose, et al.[4] has reviewed many promising developments in this field; the challenge is to find ways of following the three principles outlined above.

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As a physician who has spent 15 years working within a Stroke Rehabilitation service and who has had the opportunity to contribute to research utilizing virtual reality (VR), I do perceive significant opportunities in this clinical area with regard to assessment and rehabilitation.

I am constantly struck by the fact that the psychological impact of stroke, though less immediately apparent than the physical impact, is as disabling. Problems often do not become apparent to sufferers until they are exposed to the requirements of everyday life. It is then that the problems of attention and memory impairment can come sharply into focus: roles are changed within relationships, former activities of work or pastimes cannot be achieved to the previous level, accepted activities (such as driving, working out home accounts, and shopping) now become a challenge. These difficulties have been confirmed in a recent study of stroke sufferers carried out by the Centre for Health Services Studies at the University of Kent.[1] These impairments associated with stroke frequently lead to secondary complications, including depression, frustration, anger, and breakdown in personal relationships. VR would appear to have potential both in the assessment and rehabilitation of such problems.

ASSESSMENT

VR may have the following benefits over current assessment tools for analyzing the types of psychological impairment suffered by individual stroke victims.

- Assessment can be carried out in a more life-like setting, even though the individual is unable to physically operate in the setting,
- VR may be able to provide a more comprehensive assessment of the various components of psychological impairment within one test than can be achieved by current approaches.
- VR can be used for specific assessments that may be relevant for statutory or work reasons (e.g., driving, legal competency).
- VR can provide the opportunity to analyze the process by which patients carry out tasks as well as the outcome of the task undertaken. Most current assessments provide information on outcome only. The ability to monitor the process of carrying out tasks may provide particularly useful insights into psychological impairments.

REHABILITATION

There is increasing evidence that rehabilitation is most effective when it can be carried out in the patient's everyday environment. It is only then that the subtle impact of psychological impairments, such as attention, perception, and memory impairment, come sharply into focus. While hospital-based therapy input can enhance physical recovery, full rehabilitation can only happen in the everyday environment.

- VR may help bridge the gap between home and hospital in various ways. It provides the opportunity to work on psychological impairments of perception, attention, and memory function associated with stroke using "life" settings while a subject remains physically confined.
- VR may be used for specific retraining tasks, that is, specific work tasks, driving tasks, and home activities (e.g., shopping, cooking).
- VR may be helpful in rehabilitation when associated communication impairments exist. It may be possible to improve non-verbal contact with the stroke patient using visual clues and everyday virtual environments
- VR may provide opportunities to enhance the mood of patients by providing animation by participation in activities in a virtual sense that they cannot perform in reality during the recovery period (i.e., they may be able to participate in virtual cooking, virtual golf, or virtual driving). Such stimulation might help break the long periods of physical and mental inactivity associated with recovery.

The potential for the use of VR in stroke rehabilitation may also apply to other conditions where brain impairment occurs (i.e., dementias and possibly pre-dementia states associated with cerebrovascular disease).

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THE AUTHORS have extensively reviewed the literature concerning virtual reality (VR) and cognitive rehabilitation published from the mid-nineties, giving a realistic summary of what has been done so far and hints as to what remains to be done to effectively impact recovery after brain damage. Because a relatively small number of patients have so far been tested and/or retrained using VR, only general statements can be drawn as to specificity, feasibility, and efficacy of VR applications. The number of well-conducted studies however is slowly growing, and the same holds for the interest raised among experts and non-experts. But in spite of the prevalence of brain-damaged individuals in the technologically advanced regions of the world, the general impression is that VR applications devoted to rehabilitation are still but a very small proportion of VR-based products developed for non-recreative purposes. This does not necessarily mean failure, but probably stems from a degree of persistent immaturity of the area, which is preventing its widespread diffusion as a means of dealing with all the impairments listed in the article. A disparity between highly developed countries may also exist, and we acknowledge there may be differences between the United States and Europe, notably so our country, due to historical, cultural, and economical reasons.

A brief commentary is probably not the place to discuss a multifaceted issue such as this, but we think it very important to draw the VR community's attention to it again, as we cannot capitalize any more on the effect of novelty and unrealistic expectations. We think that, if VR technology were to continue its slow but firm ascent, it should become more and more familiar to everybody in the field of rehabilitation, not only via excellent readings such as Roses et al.'s paper, but also by direct confrontation with its applications. In other words, it is probably time to think more seriously about diffusion issues in parallel to the scientific development of ideas and academic research. As a matter of fact, the EC community has already included these issues into its funded programs with variable results. We feel that acceptance and acknowledgment of the merits of VR research from the outside should be sought with more determination, along with honest analysis and declaration of problems and pittfalls. Solutions are probably at hand, but not frequently sought. We might dream of a scenario in which centers and researchers of excellence in the field could be joined in an effort to optimize for free diffusion over the Internet their most valid and tested applications, and let clinicians and therapists all over the world develop their own experience with them. We know of a few European and U.S. projects that have already provided this opportunity with some success. This could allow both the diffusion of the main scientific message and the build-up of experience by independent users, and arguably also of a large database of clinical cases to be used for a more rapid and valid appraisal of efficacy and applicability issues.

We do know of relatively dated but brilliant applications developed by single research centers all over the world that have now been dismissed simply because funding always requires new ideas and projects. We are not dreaming of resuscitating dead stuff, but suggesting that survival of VR as a valuable tool in rehabilitation requires more continuity; too much unapprochable novelty generates refusal, and confuses potential users of otherwise serious and effective applications. To put it differently, we must not be caught by the type of explosive development that VR for entertainment is undergoing; we must behave quite differently in spite of economic pressure. Personally, we find it quite discouraging to be able to freely download videogames from the Internet, and yet see almost no fully optimized fruit of cognitive VR research.

The efforts of getting adequate funding and coordination, and solving technological difficulties for such a project should not be an excuse for not trying.

Finally, we would like to comment on another issue that the review highlighted: that of functional brain imaging studies as a means of getting insight into the immediate effects of VR on the healthy and damaged brain and—even more importantly—its ability to document long-lasting effects. In the recent past, we proposed that VR should be regarded as a tool to assess integrative functions of the brain and hence in some way complementary to more traditional tools derived from neurobehavioral and cognitive science. Of course, VR is more specific for vision-based cognition, and less so for motor or other sensory functions. In line with the above reasoning, it is hoped that the combined use of VR and neuroimaging will definitely clarify the role VR has to play among diagnostic and research tools. This will hopefully lead to a greater acceptance of VR by professionals involved in rehabilitation.

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