Virtual reality in rehabilitation following traumatic brain injury

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ABSTRACT

The potential use of virtual reality (VR) in neurological rehabilitation has frequently been discussed. This paper relates current thinking on the subject to the clinically defined concepts of impairment, disability and handicap. It is concluded that VR has a contribution to make to reducing all three, as well as in the initial assessment of the consequences of traumatic brain injury.

Keywords: traumatic brain injury, assessment, impairment, disability, handicap

1. THE TECHNOLOGY OF VIRTUAL REALITY

> "Imagine a wrap-around television with three dimensional programmes, including three dimensional sound, and solid objects that you can pick up and manipulate, even feel with your fingers and your hands. Imagine immersing yourself in an artificial world and actively exploring it. Imagine that you are the creator as well as the consumer of your artificial experience, with the power to use a gesture or word to remold the world you see and hear and feel." (Rheingold, 1991)

More prosaically VR might be described as a computer technology which allows us to create detailed three dimensional representations of particular real life or imaginary situations, which can be examined and manipulated and within which one can move around.

The visual, auditory and tactile aspects of the computer generated virtual environment are delivered to the subject through visual display units and speakers within the helmet (head mounted display) and through heat and pressure emitting devices in "data gloves" or a "body suit" which looks a bit like a space suit. It was with good reason that Stewart (1992) described someone fully attired for VR as resembling "a mime in scuba gear"! These sensory experiences, in turn, are dependent upon the subject's movements within the environment which are relayed back to the computer from the helmet sensor, the hand held joy stick or other control device and the data gloves or body suit. For example, if a subject in a virtual room looks to the left or right, or up or down, the computer will detect these movements through the helmet sensor and alter accordingly the visual images relayed to the subject via the helmet display units. Similarly, if the subject touches an object in a VR environment the computer will detect this and deliver the sensation of tactile pressure through the pressure devices in the gloves.

Its most vital characteristics are "presence" , the feeling of being immersed in the computer generated world, - and that it is interactive. Within the virtual world created by the computer every response the "user" makes has a consequence to which he/she must adapt in terms both of mental processing and behaviour. What VR allows us to do is to temporarily isolate a person from his/her normal sensory environment and substitute for it an artificial computer generated environment built to the precise specifications of the programmer.

This sort of VR is at the forefront of research. Some aspects of it, for example the data gloves, require considerable further development (Durlach and Mavor, 1995). Financially it is at the very top end of the VR market, costing well in excess of £150,000. Consequently, its applications to real world problems are somewhat limited at present. However, VR technology is available at more affordable prices. A good quality immersive system based on the head mounted display but without the data gloves or body suit can be purchased for £65,000.

In addition to the immersive variety so far described VR also comes in a so-called "non-immersive" form which is very much cheaper still. Here the visual aspects of the computer generated VR environment are presented not through helmet mounted displays but on a conventional computer monitor or projected onto a screen. The subject controls his/her movement within the environment by means of a joy stick or other control device. In non-immersive VR it is as if the

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subject is looking at the immersive VR environment, previously described, through a window (the computer monitor or screen). Of course as the size of this window is increased, from a conventional computer monitor, to a slide projection screen, to a series of screens which surround the subject (Browning, Cruz-Neira, Sandin et al, 1993), so the subject's sense of immersion can be increased. Although never conveying the sense of complete immersion in the environment associated with the more expensive immersive systems, non-immersive VR is, in other respects, comparable.

Clearly the potential uses of VR extend far beyond the computer games so often associated with it (see Durlach and Mavor, chapter 12). Already VR has been applied to the training of surgeons, pilots and drivers where training in a computer generated virtual world avoids the danger, expense and problems of monitoring and control associated with training in the real life situation. Similarly VR has been used by engineers, architects and designers to visualise real life structures (eg oil rigs, buildings, machinery) prior to actually building them, and by scientists to visualise systems difficult to illustrate in other ways (eg molecular interactions, effects of reduced gravity in various situations etc).

One area with very considerable potential for VR applications is the area of neurological rehabilitation (Rose and Johnson, 1994; Rose et al 1996; Rizzo and Buckwalter, 1995; Pugnetti et al, 1995). However, if those involved in the development of VR are to be of help to the clinicians and therapists working in this area of rehabilitation it is important that they familiarise themselves with the clinicians' terminology and the detail of the problems they seek to address.

2. TRAUMATIC BRAIN INJURY – THE SILENT EPIDEMIC

Traumatic brain damage has been labelled "the silent epidemic" (Klein, 1982). Frankowski, Annegers and Whitman (1985), in a review of seven major reports on the incidence of traumatic brain injury in the United States, arrived at an average incidence figure of approximately 250 per 100,000 of the population. This figure is in good agreement with statistics from Australia and the United Kingdom. Road accidents are the biggest single cause, accounting for between a third and a half of all such injuries. Other major causes are assaults and falls. Males are twice as likely to suffer a traumatic brain injury as females. Since the peak incidence falls in the 15 - 24 age range, the consequent problems are likely to be very long term and to become even longer term as medical science becomes ever more successful in increasing survival rates. The need for effective rehabilitative strategies is obvious. Moreover, these strategies must take account of practical considerations such as increasing pressure on staff time and the predominant age group within this category of patients. It is also crucial that there is clear agreement about the precise aims of whatever rehabilitative strategies are adopted.

The consequences of damage to the brain are usually described in terms of three concepts, impairments, disabilities and handicaps. These are defined as follows:

An impairment is:

> " - - - any loss or abnormality of psychological, physiological or anatomical structure or function." (World Health Organisation, 1980, p.27)

Disability refers to the effects of an impairment on a person's ability to perform an activity in a normal manner. The definition of this term is:

> " - - - 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." (World Health Organisation, 1980, p.29)

The final term, handicap, is defined as:

> " - - - a disadvantage for a given individual, resulting from an impairment or a disability, that limits or prevents the fulfilment of a role that is normal (depending on age, sex and social and cultural factors) for the individual." (World Health Organisation, 1980, p.29)

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 context of that particular person's previous abilities, expectations and aspirations.

Whilst the model is not universally accepted (Johnston, 1996) the terms "impairment", "disability", and "handicap" define a progression of consequences of traumatic brain injury which link the initial injury with eventual outcome and, most importantly, identify targets for rehabilitation strategies.

VR has a potential role in rehabilitation of all three consequences of brain damage. However, it is important to recognise the differing levels of objectives in the three cases. For example, with an impairment the primary objective of VR rehabilitation may be to bring about clearly defined changes in brain structure or function; with a disability the objective in using VR may be to directly facilitate the learning process; and with a handicap the objective may be to use VR in a prosthetic manner.

However, before any rehabilitation can begin the patient's condition must carefully assessed. VR has a valuable role here also.

3. VIRTUAL REALITY IN ASSESSMENT OF REHABILITATION NEEDS

The first step in any successful rehabilitation programme is the accurate and comprehensive assessment of the patient's current abilities. Whilst the methodology for assessing sensory and motor capacities is well developed there is a continuing debate about how best to assess cognitive functions such as attention, memory and reasoning and how what is measured under these headings relates to practical skills in real life settings. This is the issue of the "ecological validity" of measures. The 1970s and 1980s saw a reaction against laboratory based measures of cognitive function which had been developed within the mainstream of experimental psychology. Increasingly these were seen as too narrow and artificial to give an accurate guide to cognitive function in real life situations and, in consequence, several tests of "everyday" cognitive function have been developed. However, in their turn these so-called "ecologically valid" measures have been criticised for a lack of rigorous control of the test situation (Banaji and Crowder, 1989).

Andrews et al (1995) have suggested that a possible solution to the problem lies in measuring cognitive function within a VR environment. VR allows the measurement of cognitive function to be made in the context of interaction with a realistic everyday environment without sacrificing the opportunity to maintain strict control over every aspect of the test situation. For example, a distractible patient's ability to carry out simple procedures in a kitchen can be tested without there being any danger. Since it is under the control of the computer programmer, by definition, VR allows precise and detailed analysis of the environment within which cognitive function is assessed and to which the subject's responses are being measured. Moreover, since interaction with a VR environment can be made contingent on a wide range of motor responses it is possible to measure cognitive function in an everyday situation in people whose motor disabilities restricts movement in the real world. Similarly, particular aspects of the sensory array which are presented to the patient can be artificially enhanced to help overcome partial sensory loss (Middleton, 1992).

In other words VR allows us to place a neurological patient in a variety of precisely controlled simulated environments which are entirely safe and which are intentionally programmed in order to avoid, as far as possible, the patient being at a disadvantage as a consequence of sensory or motor impairments. Having created this "level playing field" we can simply observe how the patient behaves - how active, how interested, how distractible -as well as seeking to investigate particular cognitive functions.

The work referred to above (Andrews et al, 1995) was concerned with using VR to measure memory. VR is also currently being used to develop measures of spatial memory and of contralateral neglect although results have not yet been published.

In providing ecologically valid measures of cognitive function VR will provide a valuable resource for those involved in cognitive rehabilitation. However, VR has the potential to contribute to a more fundamental type of assessment of traumatic brain injury. Frequently, clinicians are confronted with patients whose level of responsiveness is so reduced that it is difficult to arrive at any reasonable estimate of their residual abilities. An extreme instance is patients who are in a persistent vegetative state (PVS). In 1993 the High Court granted permission to those caring for Hillsborough victim, Tony Bland, to remove his nasogastric feeding tube and thus allow him to die. Since then there has been a great deal of debate about the ethical and legal problems raised by PVS patients (Jennett, 1993; Andrews, 1993) and understandable public concern about the adequacy of the methods available to assess the true cognitive function of such patients. As Murphy (1995) has observed, neither brain scanning (CT/MRI) nor electroencephalography (EEG) can reliably predict or detect PVS and the label is ultimately applied to patients on the basis of "clinical judgement". The concern of both the general public and the clinicians is that the failure to show "consistent psychologically meaningful responses" (Jennett, 1993) to a sensory stimulus, which is characteristic of PVS, might be overcome if only the right stimulus or stimulus combinations could be found.

Fully immersive VR (the headset, body suit and data gloves), in combination with suitable input/output devices to interface between the patient's behavioural and physiological responses (Knapp and Lusted, 1992), could be of great help here. VR would allow the patient to be exposed to a sensory world of a complexity which it is impossible to deliver in any other way. Sensory stimuli could be delivered singly, or in combination, without context or in meaningful and familiar contexts (the patient's own home or workplace could easily be recreated), and over prolonged periods of time. Moreover, responses to stimulation could be sought, not only in overt behaviour, but in subtle movements and a range of physiological responses. Certainly VR has the potential to improve on existing assessments of sensory responsiveness (Freeman, 1993) in maximising the chance of identifying the right combination of stimuli and minimising the chance of missing a meaningful response. Of course, if this application of VR were to be successfully developed it could also be used to deliver sensory stimulation for therapeutic purposes (Wilson and McMillan, 1993).

4. VIRTUAL REALITY IN REHABILITATION OF IMPAIRMENT

As will be apparent from the definitions given above, the term impairment is used to refer primarily to compromised anatomy and physiology and its immediate functional consequences. Can VR be used to reduce impairments? Although as yet there is little direct evidence that it can, a case can certainly be made that it should.

A primary effect of most forms of neurological insult is a reduction in cerebral arousal - activation. This combines with other common neuropsychological impairments, for example in attention, memory and motivation, to result in significantly reduced levels of interaction between the patient and his/her environment whether at home or on the ward. Coexisting sensory and motor impairments, such as hemiplegia, typically restrict interaction still further.

Clinicians agree that this is undesirable and that environmental interaction is vital to the rehabilitation process. Moreover their clinical judgement is supported by an extensive scientific literature. Neuroplasticity, the brain's capacity to modify its structure and function in response to experience gained from interaction with the environment is no longer in doubt (Rose and Johnson, 1996). Animal studies have shown that increased levels of environmental interaction result in a more highly developed and more efficient brain (Renner and Rosenzweig, 1987). Brain changes attributable to increased interaction include a greater amount of cerebral cortex (the part of the brain primarily associated with cognitive function), more profuse connections between cortical neurons, increased activity in glial cells and a higher metabolic rate within the cerebral cortex. Increased environmental interaction has also been shown to enhance functional recovery following many types of brain damage in animals and, in particular following damage to the cerebral cortex (Rose, 1988; Will and Kelche, 1992).

Conventional therapies in neurological rehabilitation, such as physiotherapy, occupational therapy and speech therapy, involve increased levels of interaction, of course. However, research has shown that, for example, stroke patients typically spend only 30 to 60 minutes per day in formal therapy (Tinson, 1989). Consequently, there are lengthy periods in the patient's day when levels of environmental interaction are quite low.

Here, again, VR can be of help to the therapist. VR provides a powerful means of increasing levels of environmental interaction. Importantly it is generally a compelling experience, and largely inescapable, unlike more conventional computer based cognitive rehabilitation programmes (Bradley, Welch and Skilbeck, 1993). Moreover, as noted above, since interaction with a VR environment can be made contingent upon whatever motor capacity the patient has, and also take account of sensory impairments, this technology is eminently well suited to this therapeutic interaction.

The therapeutic role of environmental interaction in the brain damaged rat is not yet fully understood. Moreover, there is always a question mark over the extent to which data derived from rats can be extrapolated to humans. Nevertheless, it is possible that interaction with a virtual environment might have direct effects on the brains of neurological patients, increasing their efficiency and, consequently, maximising their functional output. The possibility of success, given that VR is a non-invasive and low risk strategy, would certainly indicate further investigation.

Indeed the argument may be even more compelling than that. Just as the animal studies indicate that environmental enrichment causes thickening of the cerebral cortex of the brain, so they also show that the opposite of enrichment, environmental impoverishment, causes cortical thinning (i.e. actually damages the brain). Often, in discussing traumatic brain damage a distinction is drawn between different injuries. The first injury is due to the impact between brain and windscreen, road, or whatever. The second injury, which is to an extent avoidable, involves further damage to the brain as a result of complications arising from the first injury, for example, a sudden drop in blood pressure which damages brain tissue by starving it of oxygen, or the swelling of the brain which damages brain tissue by crushing it. The third injury, degenerative damage, occurs as nerve pathways severed by the initial impact degenerate causing secondary damage elsewhere in the brain. However, if as a result of brain damage patients become less interactive (their environments effectively become impoverished) this may represent yet another injury, the fourth injury. VR therapy, then, may be the means not only of enhancing function but also preventing further damage.

As this particular application of VR to rehabilitation is developed it will be necessary to investigate the effects of exposure to VR on both nervous system structure and function and on behaviour in order to establish whether interaction with a virtual environment in neurologically impaired humans can be equated with changes associated with interaction with the real environment in brain lesioned animals. Already there have been reports of psychophysiological changes during interaction with a VR environment (Pugnetti, et al, 1994) and Decety, et al (1994) have carried out PET scans following exposure to VR. However, as yet nervous system changes accompanying interaction with VR environments is a largely unexplored area.

5. VIRTUAL REALITY IN THE REHABILITATION OF DISABILITY

The remedy for a failure to perform a normal activity in a normal manner (i.e. a disability) would most obviously seem to lie in the training process. As noted above, VR has proved to be a valuable training aid where training in real life situations would be impractical because, for example, it would be dangerous or unduly expensive. In the specific context of neurological rehabilitation VR also has great potential where training in real life situations, although not totally impractical, is made difficult because of the patient's sensory, motor and cognitive disabilities. Because the virtual training situation has been constructed in every last detail to the computer programmer's specification, certain aspects or categories of sensory stimuli can be accentuated to offset partial sensory impairment. The salience of stimuli and the links between them can also be emphasised to offset some of the effects of cognitive impairments. Once again movement within the training situation can be precisely geared to whatever motor abilities the patient has. There are also other benefits. In terms of staff resources it is clearly less time consuming to train a patient in a controlled and danger free VR environment than in a real life environment which is much less predictable and possibly fraught with danger for both the patient and other people.

A variation on the VR theme which has particular value in a training context is known as "augmented reality". By placing half silvered optical surfaces within the head mounted display, positioned in front of each eye, it is possible for the subject to retain a view of the real world but to have superimposed upon it virtual images. For example, a trainee surgeon could have a virtual image of the vascular system superimposed upon the area of the real body to guide his/her incision. In a neurological rehabilitation context, for example, linguistic labels could be superimposed upon real objects in the environments of patients suffering from object agnosia.

VR is currently being developed as a training aid in several neurological rehabilitation contexts. Emmett (1994), using the knowledge that despite their difficulty in walking Parkinson's patients do step over objects placed in their paths, presented visual obstacles via a head mounted display to achieve normal gait. VR has also been used to develop everyday living skills for children with severe learning disabilities (Brown and Wilson, 1995; Brown, Stewart and Wilson, 1995). This system consists of three programmes, a virtual house which includes an interactive kitchen, a virtual city for developing traffic sense, and a virtual supermarket to train subjects to choose and pay for goods. Currently, it is being used in ten special schools. A somewhat similar endeavour is Mowafty and Pollack's (1995) "Train to Travel". This project was devised to enable people with cognitive impairments to use public transport. Following training on basic skills, including recognition of landmarks, the students are immersed in a simulation of an actual fixed bus route for as many rides as they need. This form of training eliminates the need for a teacher to accompany them on real trips, which can take up to fifteen hours to reach the same level of competence. In addition to these published examples (not an exhaustive list) there are ongoing attempts to use VR in training patients to overcome impairments in attention, incidental and spatial memory, visuospatial function and to correct contralateral neglect.

The arguments for applying VR specifically to the training of patients with traumatic brain injuries have been rehearsed on several occasions (see, for example, Rizzo and Buckwalter, 1995: Rose et al, 1996). Without doubt VR embodies many of the characteristics of an ideal training medium (Darrow, 1995) and, in this respect, has significant advantages over traditional computer based cognitive rehabilitation formats (Bradley et al, 1993). However, as yet there appear to be no published empirical evidence of the efficacy of its use in this context (Darrow, 1995). It is to be hoped that this situation will have been remedied before the next European Conference on Disability, Virtual Reality and Associated Technologies.

Of course central to any claims of success for these training procedures is the demonstration that what is learned in VR transfers to real life situations. Whilst some have made such claims (Standen and Cromby, 1995; Wilson, 1993) others have not found any significant transfer (Foreman et al - personal communication; Kozac et al, 1993). For a fuller review of evidence on transfer from the virtual to the real world, see Rizzo and Buckwalter (1995). Certainly further systematic research is needed on this transfer of training issue.

6. VIRTUAL REALITY IN THE REHABILITATION OF HANDICAP

The term handicap refers to the disadvantage for a given individual resulting from impairment or disability. Alternatively handicap might be described a pattern of difficulty experienced by a person as a consequence of the juxtaposition of a particular pattern of impairments and disabilities, on the one hand, and, on the other, that person's lifestyle and aspirations. If everything possible is already being done to reduce impairments and disabilities and if life style and aspirations are not to be compromised more than necessary, the use of prosthetic devices is indicated. Examples include, at the simplest level, notebooks to help overcome memory problems and, at a more technological level, devices for utilising the eye movements of paralysed patients to operate keyboards. VR also has a potential contribution to make here. Indeed the addition of VR to the existing technologies employed in prosthetics promises to revolutionise the lives of the disabled. However, progress depends upon progress not only in VR technology but also in the development of input devices which interface between whatever response repertoire the patient has (Knapp and Lusted, 1992) and the virtual world, and developments in robotics which allow the patient's actions in the virtual world to be translated into actions in the real world.

Of all the uses of VR in neurological rehabilitation this is the one which perhaps requires most development. But it is also one of the most exciting. Ultimately one can imagine a situation in which the disabled might be able to carry out tasks in their real world environments by operating within a linked virtual version of it. Recent work by Simsarian and Fahl (1995) investigates this possibility. Lasko-Harvill (1993) has claimed that: "In VR the distinction between people with and without disabilities disappears." Exaggeration for the sake of emphasis, perhaps. However, the combined resources of VR and robotics promises to empower the disabled to an extent undreamt of even a few years ago. However, there are others at this conference much better qualified to review work on the role of VR in prosthetics.

7. VIRTUAL REALITY AND CLINICAL ACCEPTANCE

Remarkable as it is VR is a technology which does seem to attract rather more than its fair share of hyperbole. Discussing developments in medicine, nanotechnology and VR, Fruchterman asserts that: "We are on the threshold of the Age of Magic - - - ." (Fruchterman, 1992, p.15) Still more expansive is a quotation from John Perry Barlow:

> "I - - am in cyberspace, a universe churned up from computer code, then fed into my eyes by a set of goggles through whose twin video screens I see this new world. All that remains of my corporeal self is a glowing, golden hand floating before me like Macbeth's dagger. I point my finger and drift down its length to the bookshelf on the office wall -"
>
> Barlow (quoted by Marcus, 1992)

If those who advocate the use of VR in rehabilitation are to be taken seriously by clinicians it is perhaps advisable to curb the temptation to wax lyrical in this way. The realities of day to day life on a traumatic brain injury rehabilitation unit do not sit happily with such, as yet, unsupported promise. We should continue to be mindful of the observation made in the National Academy of Sciences report (Durlach and Mavor, 1995), that so far for VR the "excitement to accomplishment ratio" remains high.

Clinicians will have other concerns as well. For example they may see cost and technical complexity as a barrier to the development of VR therapy. There is also, as with all new treatments, an ethical question. As medical interventions go a VR based therapy is unlikely to be particularly contentious. It is non - invasive and must be seen as a low risk strategy. However, there is evidence that exposure to VR, particularly immersive VR, can have side effects. These include visual disturbances and motion sickness.

Mon-Williams et al (1993) reported that normal healthy subjects experienced transient reduced binocular vision after wearing a head mounted display for just ten minutes. They argued that this was due to compromised visual experience resulting from the generation of 3-D visual space from 2-D images. However, subsequent research (Rushton et al, 1994) found that 'new-generation' head-sets, such as the Visette 2000 HMD, did not lead to changes in binocular function even after thirty minutes use. Nor did these authors find any significant changes across a range of visual performance measures. Nonetheless, Rushton et al (1994) caution that these findings do not apply to stereoscopic displays, and evaluations of this type of display still need to be carried out. Related to the question of visual symptoms is that of nausea following use of a head mounted display. In immersive VR environments the display devices utilise a number of oculomotor systems. The incongruity between visual and vestibular motion cues can produce sickness symptoms. This so-called "simulator sickness" produces similar symptoms to motion sickness, including disorientation, sweating, nausea, headache, and general discomfort. Regan (1995) found that 61% of subjects (n=150) reported symptoms at some stage during a 20 minute immersion and 10 minute post-immersion period. However, Kolasinki (1995) has found considerable variability in the extent to which subjects in VR do suffer from this condition. No significant side effects have been reported with non immersive VR.

If VR is to be used clinically it is important that its effects on bodily systems be thoroughly investigated (Eberhart and Kizakevich, 1993) but, on the basis of research so far, side effects do not appear to represent a serious barrier to the use of VR in neurological rehabilitation. However, it is important to remain vigilant. For example, Middleton (1992) warns that immersion in VR can be quite disorienting for the hearing impaired or deaf and great caution seems advisable at this stage in using VR with patients displaying psychiatric symptoms. As we develop VR as a therapy it is probable that we will discover still more exclusion criteria. Certainly they should not deter us - any more than cost and technical complexity should deter us - from seeking to exploit the very considerable potential for VR in brain damage rehabilitation.

Although a relatively young technology the very great potential of VR to improve the lives of those with traumatic brain injury, and other types of brain damage, is not in dispute. However, in order to fulfil this potential we must invest great effort in research, development and evaluation. To this end we need to forge sound working relationships with our clinical colleagues and take their perspective and their aims as our starting point. We have just entered the second half of the "Decade of the Brain" (Goldstein, 1990). It is not unrealistic to hope that by the end of the decade VR therapy will be part of the clinician's armoury in tackling the problems of traumatic brain injury.

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