On the Clinical Horizon

Virtual Reality and Cognitive Rehabilitation: A Brief Review of the Future

Virtual reality (VR) can be viewed as an advanced computer interface that allows the user to interact and become immersed within computer-generated simulated environments. Although media hype may have oversold VR's potential at this early stage in the technology's development, a uniquely suited match exists in VR's application to cognitive assessment and rehabilitation. VR offers the potential to develop human testing and training environments that allow for the precise control of complex stimulus presentations in which human cognitive and functional performance can be accurately assessed and rehabilitated. However, basic feasibility issues need to be addressed for this technology to be reasonably and efficiently applied to the cognitive rehabilitation (CR) of persons with acquired brain injury and neurological disorders. This article will present a brief introduction to the concepts of VR, as well as a rationale for the VR-CR connection. Basic theoretical and pragmatic issues for this application will be discussed and a review of relevant work that has been done, or is currently in progress, will be presented along with recommendations for future investigation in this area. Keywords: *acquired brain injury, cognitive rehabilitation, generalization, immersion, mental rotation, navigation, side effects, training, virtual reality*

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VIRTUAL REALITY (VR) technology has undergone a transition in the past few years that has taken it out of the realm of expensive toys and into that of functional technology. While many VR applications have emerged in the areas of entertainment, education, military training, physical rehabilitation, and medicine, only recently has the considerable potential of VR for the study and rehabilitation of human cognitive processes been recognized.[1-4]

Indeed, in a recent NIH report of the National Advisory Mental Health Council,[5] the impact of virtual reality environments on cognition was specifically cited, with the recommendation that "Research is needed to understand both the positive and negative effects of such participation on children's and adults' perceptual and cognitive skills. . . . "[5(p51)] One area where the potential for "positive effects" exists is in the application of VR technology for the cognitive assessment and rehabilitation of persons with acquired brain injury and neurologic disorders. In this regard, VR could serve to revolutionize the study of brain-behavior relationships, as well as produce treat-

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ment options unavailable with traditional methods.

The potential power of VR to create human testing and training environments that allow for precise control of complex stimulus presentations as well as provide accurate records of targeted responses is a cognitive psychologist's dream. However, the development of this application will require the merging of knowledge from a variety of disciplines, including (but not limited to) neuropsychology, educational theory and technology, human factors, medicine, and computer science. Basic questions pertaining to the structure of human cognitive processes, optimal levels of immersion to facilitate learning, transfer of training factors, motion sickness concerns, and computing parameters will need to be considered in an integrative fashion to properly advance these VR applications.

This article addresses the theoretical and pragmatic issues involved in applying VR technology in the area of cognitive rehabilitation (CR). It includes an introduction to the basic concepts of VR, a rationale for the VR–CR connection, a review of relevant literature regarding basic theoretical and pragmatic issues for this application, a review of works in progress, and a description of our ongoing work developing a mental rotation–spatial skills cognitive assessment and training system. References are provided in each section for further reading in each area reviewed.

VR: BACKGROUND AND DEFINITIONS

VR has been generally defined as " . . . a way for humans to visualize, manipulate, and interact with computers and extremely complex data."[6(p7)] While this general definition is useful, for the purposes of this article, VR can be viewed as an advanced form of computer interface that allows the user to "interact" with and become "immersed" in a computer-generated environment. A user experiences a "virtual reality" when computer-synthesized sensory stimuli simulate a real-world interactive experience. For example, a flight simulation system provides an interactive sensory illusion of a real flight.

Interaction is a key characteristic that distinguishes a VR experience from watching a movie. The believability of the experience (or "sense of immersion") can be heightened by employing specialized technology such as head-mounted displays, tracking systems, gesture-sensing gloves, or haptic displays.

A head-mounted display (HMD) is an image display system designed to be worn on the head (like a diving mask) that remains optically coupled to the user's eyes as he or she turns and moves. A tracking system[7] senses the position and orientation (pose) of the user's head (and HMD) and reports the information to a computer that produces the images for display in the HMD. In many cases full-color stereo image-pairs are produced. The combination of a HMD and tracking system allows the computer to generate images of any computer-modeled (virtual) scene that corresponds to what the user would see from his or her current pose if the scene were real. The user may walk and turn around to survey a virtual landscape, or inspect a virtual object by moving toward it and peering around its sides or back.

A tracking system can also be coupled to a person's hand or a glove that senses the articulation of the user's fingers. A tracked gesture-sensing glove allows the computer to sense when the user's hand intersects a virtual object. The position and articulation of the hand can be used to mimic direct manipulations such as grabbing, releasing, pushing, or rotating the objects in the virtual world.

Virtual objects cannot produce real forces, so the sense of touch, when needed, may be simulated by mechanical or robotic technologies, including electromechanical pin arrays that stimulate the fingertips and inflatable air chambers that press on the fingertips or palm of the hand. To simulate surfaces that are not penetrable, grounded force-producing systems such as robotic arms[8] may be employed.

High-fidelity VR systems may cost millions of dollars; however, low-cost commercial technology developed for the video game and desktop computing markets have cut component costs to the point where useful VR systems can be configured for under $10,000,[9,10] and as with most computing hardware, the costs are expected to continue to decrease over time. For a minimal cost, a desktop personal computer (PC) and display can be used with a head tracker to create the illusion of a window into a virtual world, however, the fixed display position and limited display area constrain a user's head motion and viewpoint to an extent that severely limits the mobility and interactions that are possible with this approach. More detailed information on VR definitions, equipment, options, and costs can be found elsewhere.[6]

THE VR-CR CONNECTION

Over the last 80 years, professionals in a variety of fields have developed techniques designed to reverse or arrest the cognitive decline and functional impairment that occur following brain trauma. Between the complexity of the subject matter and the nascent status of work in this area, considerable controversy exists as to the relative effectiveness of various CR approaches.[11-13] Our discussion here will not debate the merits of any CR approach but instead will focus on how VR may be a useful technology to administer a wide range of CR strategies.

CR approaches can differ based on a variety of conceptual criteria.[14] One criterion concerns the presumed "mechanism" whereby therapeutic change occurs. Therapeutic change may occur either through the reacquisition of cognitive abilities via repetitive, systematic, hierarchical *restorative* cognitive stimulation or by way of teaching alternative *compensatory* strategies that target actual task performance.

Another highly related conceptual dimension concerns the "content" of the treatment tasks. One may focus on the training of *component* cognitive processes, such as attention or memory, or emphasize *functional* skills training, such as practicing a standard set of steps in a work routine.

CR approaches can also be contrasted in terms of whether they are *person centered* or *environment centered.* Within this criterion, the decision for treatment direction is based on whether the person is capable of reacquiring either cognitive abilities or new functional skills, or whether the person's environment will need to be restructured to support independence. Most applications of CR are "multimodal"[12,15] and pragmatically offer a mixture of these various treatment orientations contingent on factors including (but not limited to) the client's neuropsychological profile of cognitive abilities, level of spared functional abilities, specific goals, and environmental support mechanisms. For example, the treatment direction for an elderly patient with dementia may focus more on compensatory, functional, and environment-centered goals, while a 20-year-old with mild head injury may be more suited to a restorative, component-based, person-centered approach. Available resources on the treatment delivery end can also be a factor in deciding a pragmatic CR direction.

Approaches for applying VR to CR

For the purposes of describing the application of VR to CR, existing approaches can be "collapsed" into two general opposite domains: *restorative approaches*, which focus on the systematic retraining of component cognitive processes (eg, attention, memory, and spatial skills) and *functional approaches*, which emphasize the stepwise training of observable behaviors, skills, and activities of daily living (ADLs).

These domains can be viewed as opposite ends of a continuum of methods, with many specific CR approaches falling somewhere between these poles. The restorative approach emphasizes a "drill-and-practice" method in which the person is hierarchically challenged to attend to, remember, and/or manipulate increasingly more difficult pieces of information contingent on success.[16] Hence, cognitive ability is expected to improve much the way a muscle gets stronger with increased exercise.

By contrast, functional approaches generally focus on training ADLs, such as remembering a sequence of events to prepare for work in the morning or a set of structured steps for completing day-to-day functional activities (eg, meal preparation, job tasks, or grooming routines). Functional methods may also include the use of a variety of compensatory aids, including memory notebook systems, electronic memory devices, alarms, calendars, and reminders posted in different positions around the house.[13]

Various weaknesses have been cited for both the restorative and functional methods. Criticism of restorative methods relates mainly to the weak generalizability or transfer of learning and thinking skills from the training environment to real-world challenges,[17,18] and research in this area tends to favor a functional skills training position. However, functional approaches have been criticized for an overemphasis on the brittle performance of overly learned functional behaviors, with a neglect of the underlying cognitive abilities required for the flexible problem solving needed to handle normally occurring variations in real-world circumstances.[14]

It is proposed that the application of VR technology to the rehabilitation of cognitive deficits could serve to limit the major weaknesses of both the restorative and functional approaches and actually produce a systematic treatment method that would integrate the best features from both methods. In essence, it may be possible for a VR application to provide systematic restorative training within the context of functionally relevant, ecologically valid simulated environments that optimize the degree of transfer of training or generalization of learning to the person's real-world environment. VR could also serve to provide a more controlled and systematic means for separately administering restorative or functional techniques when this direction is deemed appropriate. An analysis of VR's suitability in meeting the minimum criteria for both the restorative and the functional approaches, as well as examples of possible VR scenarios illustrating these potential applications for attention processes, memory, visual processing and higher reasoning, can be found in a previous paper.[4]

When discussing possible VR applications for CR, it is helpful to consider an important finding pertaining to preserved memory abilities following brain trauma. A number of studies have shown that in persons with neurologically based cognitive impairment, procedural, or skill, memory often remains relatively intact.[19,20] This type of memory process involves the capacity to learn rule-based or automatic procedures, including motor skills, certain kinds of rule-based puzzles, and sequences for running or operating things.[13]

Procedural memory can be viewed in contrast to declarative, or fact-based, memory, which is usually more impaired and less amenable to rehabilitative improvement. In addition, patients with neurologically based cognitive impairment often demonstrate an ability to perform procedural tasks without any recollection of the actual training sessions. This is commonly referred to as *im-*

plicit memory[21] and its presence is indicative of a preserved ability to process and retain new material without the person's conscious awareness of when or where the learning occurred.

These observations provide encouragement for the idea that VR, by way of its interactive and immersive features,[1] could provide training environments that foster cognitive improvement by exploiting the person's preserved procedural abilities. It is conjectured that cognitive processes could be amenable to restoration via procedures practiced repetitively within an environment that contains functional real-world demands. Whether the person can recall the actual training episodes is irrelevant as long as the learned process or skill is shown to generalize to functional situations. The real challenge would then be to somehow translate difficult declarative tasks into procedural learning activities that target the rehabilitation of complex higher reasoning abilities and possibly language deficits.

Advantages of applying VR to CR

A number of advantages for VR's applicability to learning and training (and hence rehabilitation) have been proposed by many authors investigating a range of applications.[1-4,22-24] These advantages are listed in the box, "Advantages of VR for CR Applications." It should be kept in mind that some of these advantages are also available using other methods, particularly traditional computer training, and hence the decision to select a VR approach should be weighed carefully using a realistic cost-benefit analysis. Also, while these proposed advantages offer considerable appeal, they do not guarantee that persons with cognitive impairments can learn in a virtual environment. Certainly VR has been shown to promote learning in unimpaired populations. These reports indicate

Advantages of VR for CR Applications

- Presentation of ecologically valid training scenarios and/or cognitive challenges that are difficult to present using other means (eg, dynamic three-dimensional visuospatial stimuli)
- Total control and consistency of stimulus delivery
- Presentation of hierarchical and repetitive stimulus challenges that can be varied from simple to complex, contingent on success
- Provision of "cueing" stimuli or visualization tactics (eg, selective emphasis) designed to help guide successful performance within an errorless learning paradigm
- Delivery of immediate performance feedback in a variety of forms
- Capacity to pause training for discussion or other means of instruction
- Option for self-guided exploration and independent training when deemed appropriate
- Modification of sensory presentation and response requirements based on the user's impairments (eg, movement, hearing, and visual disorders)
- Capacity for complete performance recording
- Availability of a more naturalistic/intuitive performance record for review and analysis by the user
- Design of safe learning environments that minimize risks due to errors
- Introduction of "gaming" factors into the learning situation to enhance motivation
- Ability to create low-cost functional training environments

VR training success in the areas of console operation,[25,26] building navigation,[27] operation of manufacturing equipment,[28] procedural skills for Hubble telescope repair,[29] military terrain knowledge,[30] and surgical procedures.[31] It can also be conjectured that these VR-learned functional activities utilize underlying cognitive processes, including attention, memory, visuospatial abilities, and executive functioning, that may have been positively affected by this mode of training.

The current status of this field, while provocative, is limited by the small number of studies that have been reported applying this technology to clinical populations. This is to be expected considering the expense of the technology and its relatively recent development. In spite of this, some work has emerged that can begin to provide the field with a basic foundation of knowledge. Although much of the work does not involve the use of fully immersive HMDs, studies reporting PC-based flat screen approaches are providing valuable information on issues necessary for the reasonable and measured development of this field. Non-HMD systems mainly allow the user to explore simulated three-dimensional (3-D) environments presented on a computer monitor with a lesser degree of the sense of immersion due to the absence of head-tracking capability and naturalistic visual and auditory inputs. An analogy sometimes used to compare HMD and non-HMD approaches is that it is like the difference between swimming in a large aquarium and looking in through the glass from the outside. Unfortunately, there are few reports examining the efficacy of HMD VR with cognitively impaired populations, although this is expected to change soon (see "Works in Progress").

Positive initial results have been reported for the Train to Travel program.[32] While still under development, this immersive VR system is primarily designed to teach persons with developmental disabilities how to use key bus routes on the Miami Valley Regional Transit System in Ohio. If this program succeeds, it would be useful as a demonstration that functional abilities could be efficiently and economically trained in a patient population with severe cognitive impairments.

Encouraging results using non-HMD VR have been reported in a group of students with cognitive impairments due to developmental disabilities.[22,23] Findings suggest the utility of low-cost PC-based flat screen-presented virtual environments for training functional activities (eg, supermarket shopping) in persons with severe cognitive impairments.

Although these results are promising, in light of the limited data on VR applications applied to clinical groups, the question of whether persons with cognitive impairments can learn in VR is still waiting to be fully answered. Also, it may be found that for some applications and populations, fully immersive systems may not be feasible or necessary. In light of this, the next section will focus on issues deemed important for the development of VR-CR applications, including both HMD and non-HMD reports, as well as relevant findings from both clinical and nonclinical populations.

THEORETICAL AND PRAGMATIC ISSUES

Before successful VR-CR applications for persons with cognitive impairments can be efficiently developed, a number of basic theoretical and pragmatic issues must be addressed. These include the concern over possible difficulties for these clinical groups in learning to navigate within this type of interface, the capacity for therapeutic gains within VR to transfer to real-world functional settings, and the degree to which potential side effects of VR exposure limit its applicability to these populations.

Navigation and interface issues

A full discussion of human factors issues pertaining to the benefits of immersion, interactivity, and navigational demands is beyond the scope of this article and is available elsewhere.[1,33,34] However, navigational concerns will be briefly addressed here, as they are considered to be of particular relevance to VR-CR applications.

VR has been characterized as an "intuitive interface" that allows a person to interact with a computer (and data) in a naturalistic fashion.[6] Wann and Mon-Williams[34] suggest that "the goal is to build (virtual) environments that minimize the learning required to operate within them, but maximize the information yield."[6(p845)] For persons with cognitive impairments to be in a position to benefit from VR-CR, they must be capable of learning how to navigate within the virtual environment. Many modes of VR navigation, while easily mastered by nonimpaired participants, could present problems for those with cognitive difficulties. Even if patients are capable of interacting in a VR system at a basic level, the extra nonautomatic cognitive effort required to navigate may serve as a distraction and limit or slow the rehabilitation process. In this regard, Psotka[1] hypothesized that facilitation of a "single egocenter" found in highly immersive interfaces serves to reduce "cognitive overhead" and thereby enhance information access and learning. Reduced motivation may also result when a person's first VR experience is characterized as "more work than it is worth." Thus far, reports on VR with patient populations using joysticks in both HMD[35] and non-HMD[22] systems have not revealed any major navigation learning difficulties, although interface concerns were not the empirical focus of these studies. Voice recognition technology may also be a useful approach for some types of navigation.[36] as it may provide for a more naturalistic interface on some training tasks and improve VR access for persons with motor impairments.

Also of critical importance is whether the means of navigation actually affect what aspects of the training environment are focused on and, consequently, what is learned. This was seen to be the case in a study that looked at what types of memory were enhanced in an unimpaired group during a four-room house navigation task.[37] This system used a non-HMD, joystick interface that allowed one subject to navigate the house (active condition), while a yoked subject was simply exposed to the same journey but had no control (passive condition). Differential memory performance between the two groups was observed, with the active group showing better spatial memory for the route and the passive group displaying superior object recall and recognition memory for the items viewed along the route. Perhaps a more intuitive method of navigation may have allowed the active group to perform as well on object memory via a more equal allocation of cognitive resources. Also, this navigation method may have taxed the subjects' divided attention capacity and thereby influenced the memory results found using this paradigm. This issue could be relevant for the design of VR training for persons with attention deficits. The development of more naturalistic interfaces could be of vital importance for the precise rehabilitative targeting of cognitive processes and could also have implications for the transfer of training issues discussed in the next section.

Generalization and transfer of training

A fundamental issue that has important implications regarding the feasibility of a VR approach applied to CR concerns the concept of transfer of training or *generalization*. In a classic review from the applied behavioral literature, Stokes and Baer[38] place strong emphasis on the need to plan and program for generalization when designing treatment interventions. Three types of generalization relevant to CR have been described[39]:

1. transfer of gains on the same materials on separate occasions
2. improvement on similar but not identical training tasks
3. transfer from the training environment to day-to-day functioning.

From this perspective, a VR application for the training of some hypothetical visuospatial ability would show good generalization if improvements were maintained across multiple VR sessions, seen on pencil-and-paper measures of the skill, and observed in a real-life task, such as assembling a piece of furniture or finding one's way home.

At this early stage of VR development, the primary emphasis has been on generalization from a VR environment to the actual real-world environment. In this regard, VR rests on strong theoretical ground. In a recent review,[15] five guiding principles for CR generalization are specified and include (1) issues of preprogramming; (2) identification of naturalistic reinforcements; (3) appropriate transfer measurement; and, particularly relevant to VR applications, (4) the use of sufficient examples or repetition with (5) stimuli common to both the training environment and the real world.

Based on these principles, VR would appear to be a powerful tool for implementing CR and promoting generalization. Support for this claim can first be seen in the related (and predecessor) field of aviation simulator research. In a recent report on theoretical issues concerning transfer of learning from aircraft simulators, Johnston[40] cites a transfer effectiveness ratio in aviation simulation research of .48. This ratio indicates that for every hour spent in aviation simulator training, one-half hour is saved in actual aircraft training.

Although it is theoretically and intuitively seductive to assume that by considering VR as "just another form of simulation" that generalization is guaranteed, research specific to VR environments must be examined. One early study reported that no evidence was seen for transfer from a VR "pick-and-place sequence task" to a real-world task.[41] However, some authors have noted problems with the criterion task used in this study—specifically, its simplicity[1] and its reliance on overlearned cognitive cues not specific to the VR training.[33]

In contrast, an encouraging literature is emerging that provides evidence of good generalization in nonclinical groups from virtual training environments to functional tasks. VR was shown to foster learning of console operations and this learning was shown to transfer to the actual console.[25,26] Spatial navigation training for a complex building was found to generalize by two different researchers.[26,27] In another study on navigation skills training,[30] soldiers used a self-guided virtual terrain environment to successfully learn the actual physical terrain that had been modeled. Self-guided VR training for machine operation has also been shown to promote generalization.[28] Results of a project conducted at Motorola University that is of particular practical interest indicated positive transfer from an HMD VR factory training program to the actual factory assembly line; the implications of this work for CR and vocational rehabilitation interests are obvious.

Finally, in the only study to examine generalization with clinical groups, evidence of positive learning transfer from a virtual training setting was found for a group of developmentally disabled students.[22] Students with significant cognitive impairments were trained on a PC-based, non-HMD virtual system to navigate through and select specific items in a virtual supermarket. In addition to demonstrating good transfer of learning, this study is noteworthy in that it suggests an efficacious approach to increasing the independence of persons with cognitive difficulties for whom a fully immersive HMD strategy may not be practical.

The above cited investigations represent essential "first steps" in determining whether VR training can generalize to functional activities. For persons whose cognitive abilities are challenged as a result of neurologic trauma, this line of research is especially important. The "generalization problem" has plagued the overall field of cognitive rehabilitation since its inception. It is essential that intuitive expectations of positive VR learning transfer be supported with quality research. This is vital for a VR approach to be taken seriously in this field.

Side effects of VR usage

For VR to become a feasible approach for CR, the potential for adverse side effects must be considered. A commonly reported VR side effect is a form of motion sickness that has been termed "cybersickness." Symptoms of cybersickness are reported to include nausea, vomiting, eye strain, disorientation, ataxia, and vertigo.[42] Cybersickness is believed to be related to sensory cue incongruity, which is thought to occur when there is a conflict between perceptions in different sense modalities (auditory, visual, vestibular, or proprioceptive) or when sensory cue information in the VR environment is incongruent with what is felt by the body or with what is expected based on the user's history of real-world sensory experience.[43]

The reported occurrence of cybersickness in virtual environments varies across studies depending on such factors as the type of VR program used, technical drivers (eg, vection, response lag, field of view), the length of exposure time, the person's prior experience using VR, active v passive movement, and gender.[44-48] In one study, 61% of 146 healthy subjects reported "symptoms of malaise" at some point during a 20-minute immersion and 10-minute postimmersion period.[47] While a paper on VR training for the Hubble telescope repair ground crew[29] suggested low incidence rates (5% to 40%) depending on the symptom, another recent study reported a 95% occurrence of some ill effects.[48] Also, the presence of maladaptive after-effects such as postural ataxia, eye-hand coordination difficulties, and flashbacks have been reported with VR exposure.[44,49,50] For those interested in more details on VR-related side effects and other relevant human factor concerns, a number of informative reviews are available.[1,33,34]

The side effect issue is of particular importance when considering the use of VR for persons with neurologic injury, some of whom display residual equilibrium, balance, and orientation difficulties. In the only report to date that addresses this issue, Pugnetti et al.[35] compared 11 neurologic injury patients with 41 noninjured subjects regarding self-reported prevalence of cybersickness. The authors tested subjects in an HMD VR system that was specifically designed for the diagnosis and rehabilitation of executive cognitive functioning. The results suggested a reduced occurrence of VR-related side effects (17%) compared to a past study using the same assessment questionnaire[46] and reported that the neurologically injured subjects appeared to be at no greater risk for developing cybersickness than the noninjured group.

Although these initial findings are encouraging, further work is necessary to specifically assess how factors such as type and severity of neurologic trauma, specific cognitive impairments, prior VR exposure, length of time within the VR environment, and characteristics of the specific VR program influence the occurrence of side effects. This is an essential step in determining the conditions where VR would be of practical value in the area of neuropsychological assessment and rehabilitation.

WORKS IN PROGRESS

The development of VR-CR applications is still in an embryonic phase. However, a number of works in progress should soon provide useful information as to the utility of this approach, as well as future directions for research. This section will briefly review some of the proposed and ongoing projects for this application.

One group of researchers has begun the work of developing a VR system specifically designed for cognitive assessment and rehabilitation.[3,35,51] Clearly at the forefront in this field by virtue of having an operationally proven HMD VR system in place, this research group initially focused on developing a system designed to address executive functions. Using a standard tool of neuropsychological assessment as a model (Wisconsin Card Sorting Test [WCST]), they created a virtual building that requires the person to utilize environmental clues in the selection of appropriate choices (doorways) in order to navigate through the building. The doorway choices can vary according to the categories of shape, color, and number of portholes, and the person is required to refer back to the previous doorway for clues as to the appropriate next choice. When the choice criterion changes, the user is then required to shift cognitive set, analyze clues, and devise a new choice strategy. The parameters of this system are fully adjustable so that training applications can follow initial standardized assessments.

In light of the large body of literature that exists on the WCST,[52] its choice as a model for this initial VR application is potentially quite useful. Research on clinical cases is reported to be under way using this system, and this laboratory is also developing programs to address attention, memory, visuomotor, and visuospatial cognitive functions. In addition, these researchers have recently reported findings pertaining to psychophysiologic variables (ongoing electroencephalogram [EEG] findings, heart rate, and auditory evoked potentials) that are recorded during participation in their VR system.[51] Research into VR effects on these variables as well as in brain imaging studies,[53,54] is likely to become an integral part of the development of VR-CR applications in addition to their value for the study of brain-behavior relationships.

A couple of research groups are currently developing VR applications aimed at attention/memory training.[37,55] These efforts will be particularly informative, as results using traditional methods for memory rehabilitation have been inconsistent at best.[56] One possible reason for the poor results in this area may be the difficulty maintaining a patient's motivation when confronting him or her with a repetitive series of memory training challenges, whether using word list exercises or real-life functional activities. VR training could potentially address this problem by providing environments that initially utilize gaming incentives, followed by the gradual fading in of functional environments, with an aim toward developing domain-specific memory.[57]

One group[55] has created a training scenario in which the user navigates an environment via a bicycle interface. The task requires the person to attend to and remember instructions to sequentially visit various objects in the environment. The authors present the interesting concept that the training will also improve physical fitness level which is hypothesized to improve brain activation as well as other variables relevant to rehabilitative concerns. This study is currently under way, with results expected shortly.

A second group,[37] whose findings of a spatial-content memory dissociation were presented above, are reported to be beginning testing on patient groups with their system (FD Rose, personal communication, March 21, 1997).

The area of unilateral visual neglect has also been targeted by one group[58] as an area that could derive benefit from a VR approach. This group has outlined a variety of ways that VR could serve to improve on traditional approaches for these types of attentional or representational impairments, commonly observed following strokes. They are reported to be starting pilot work using the "bicycle/memory" system cited above[55] in an effort to test a "general attention retraining" program with neglect patients.

We are currently developing an HMD VR system for the assessment and rehabilitation of a visuospatial cognitive function referred to as *mental rotation* (MR). The initial MR investigations began with the work of Shepard and Metzler,[59] who tachistoscopically presented pairs of two-dimensional perspective drawings to subjects and required them to make judgments as to whether the 3-D objects they portrayed were the same or different (Fig 1). A near-perfect linear relationship was found for the degree of rotational difference between the two objects and the reaction time to decide whether the objects were the same or different. Because strong linear relationships between hypothesized mental representations and behavioral performance are relatively rare, this cognitive variable has received much attention in the past 25 years.[60] Everyday life situations in which this imaginal visuospatial transformation ability comes into play are quite common and functionally relevant. These include automobile driving judgments, sports activities, moving furniture through narrow doorways, and many activities in which one needs to visualize the movement and ultimate location of physical items in 3-D space.

Our MR assessment and training system is designed to present, within a VR environment, a target stimulus that consists of a specific configuration of 3-D blocks (similar to those in Fig 1). After presentation of the target stimuli, the participant is presented with the same set of blocks, which must be rotated to the orientation of the target and then superimposed within it. The participant can manipulate the blocks in virtual space by grasping and moving a block-like "cyberprop" object that contains tracking devices and provides tactile feedback. The stimulus complexity of the target can be adjusted via changes in number of blocks and configuration, visual field of presentation, and the degree and type of rotation required. Response characteristics, such as the time needed to appropriately rotate the blocks and all movement sequences, can be recorded.

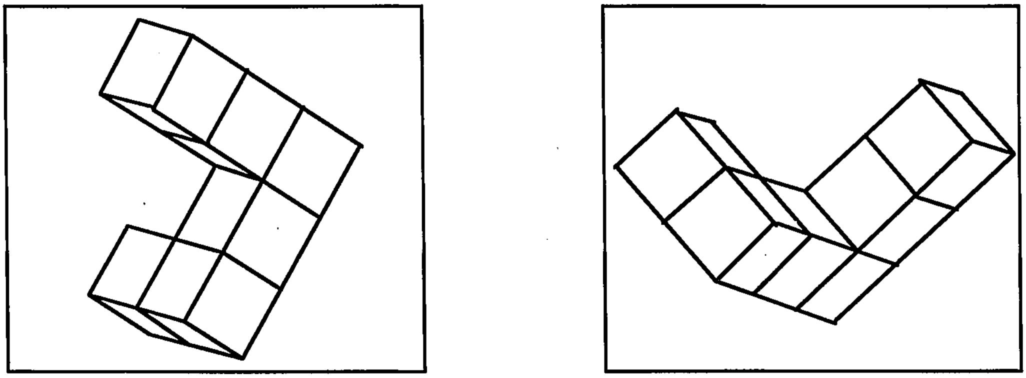

Fig 1. Sample mental rotation stimuli.

The system will allow for the hierarchical control of stimulus complexity and the capacity to record and measure all behavior in the VR setting, with an aim toward restorative cognitive rehabilitation. Immediate performance feedback (variable pitched sound or color changes) as to the effectiveness of the response approach can be programmed into the system in to help guide the participant in an "errorless learning" fashion.

To address functional assessment and rehabilitation goals in an ecologically valid manner, the block stimuli could then be replaced with images of real-life objects. This could be accomplished by expanding our interface device, allowing for more global movement and exploration of the virtual environment. Participants could be challenged to navigate within a simulated home or work environment in which common objects (eg, boxes, chairs, plants, file cabinets) could be moved to and placed at locations that vary contingent on shifting criteria (eg, positioning by size, shape, or function). The environment would contain obstacles such as low ceilings or narrow passageways that would require anticipatory MR judgments for successful performance. This format would test and train the planned movements needed to meet the requirements in the VR setting that are typically found in everyday visuospatial problem-solving situations.

It is expected that this system will improve the reliability and validity of MR assessment, as well as provide an efficient training and rehabilitation option for this aspect of cognition. The system will also be used to assess feasibility concerns for VR applications with groups not normally exposed to this type of simulation technology, such as the elderly. It is hoped that VR technology can provide these groups with assessment and treatment solutions that are not currently available using traditional methods. This system will also allow for investigations with nonclinical populations that could address MR-specific issues, including gender differences, visual field influences on learning, and localization studies using brain imaging.

CONCLUSIONS

The building of a foundation for the "reasoned" application of VR techniques in the area of CR will require investigation of a wide range of issues. At this early phase of VR technology, a number of obstacles impede the development of active research specifically testing persons with cognitive impairments. These obstacles include the relative lack of familiarity with this new technology and problems with funding acquisition for an untested and fairly expensive new treatment modality.

Although the obstacles can be seen as short-term difficulties (VR awareness is increasing, while system costs are decreasing), creative research approaches are needed to address initial feasibility questions and manifest VR's potential. Initial feasibility concerns for the use of VR for these purposes include differences in patient populations (eg, young head injury patients v senior citizens with early indications of Alzheimer's disease), the potential for VR-induced cybersickness in persons with various neurologic impairments, and whether persons with impaired cognition can initially learn how to navigate and interact within a VR environment. After these feasibility concerns are addressed, researchers will be better prepared to determine to what degree these patient groups can learn in VR, and whether VR-based learning generalizes or transfers to real-world situations.

A pragmatic approach for the basic study of VR–CR has been outlined in a previous paper.[4] It was suggested in that paper that the CR researcher seek out already existing VR systems developed for other purposes and, using clinical populations, creatively build a relevant VR-CR experimental design around the capabilities of the system. After enlisting the cooperation of the system's owner for temporary access, the researcher's development and funding requirements could be substantially reduced. This "second-hand" tactic would allow for the economic study of basic VR-CR research questions (eg, side effects assessment, navigation issues, and learning and generalization concerns).

One hypothetical example given involved utilizing the Motorola "virtual factory" system[28] and suggested that a clinical group be trained in procedural tasks of starting up and operating a subset of the factory line's equipment during three temporally spaced VR training periods. Participants could then have their performance tested on the actual criterion tasks with the appropriate subset of real equipment. This approach could serve to economically investigate navigation and generalization issues and allow for assessment of side effects.

Another tactic for the pragmatic VR-CR researcher focuses on the need to design a VR system that can test multiple questions with the same cognitive variable. For example, the Mental Rotation Spatial Skills system described above was conceptualized to address a range of VR-related questions (eg, learning, generalization, and side effects), factored with clinical treatment issues (use and feasibility with different clinical populations), and to allow for the unique study of specific MR issues in nonclinical groups (eg, gender differences, visual field presentation-learning effects, brain imaging, and psychophysiologic correlates). These considerations were definite "selling points" in getting acceptance and resources for the development of this system.

In closing, VR technology offers a unique set of advantages for the delivery of rehabilitative strategies to persons with cognitive impairments. As this new technology becomes more accessible, basic feasibility issues will begin to be addressed. This reasonable and cautious initial assessment of the basic issues is necessary to prevent "hype-inflated" expectations of VR's potential from overshadowing its realistic benefits. The "what if" questions in our theoretical musings will have to be replaced with the "what is" answers derived from a rational and objective study of the issues.

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