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A SWOT Analysis of the Field of Virtual Reality Rehabilitation and Therapy

Abstract

The use of virtual-reality technology in the areas of rehabilitation and therapy continues to grow, with encouraging results being reported for applications that address human physical, cognitive, and psychological functioning. This article presents a SWOT (Strengths, Weaknesses, Opportunities, and Threats) analysis for the field of VR rehabilitation and therapy. The SWOT analysis is a commonly employed framework in the business world for analyzing the factors that influence a company's competitive position in the marketplace with an eye to the future. However, the SWOT framework can also be usefully applied outside of the pure business domain. A quick check on the Internet will turn up SWOT analyses for urban-renewal projects, career planning, website design, youth sports programs, and evaluation of academic research centers, and it becomes obvious that it can be usefully applied to assess and guide any organized human endeavor designed to accomplish a mission. It is hoped that this structured examination of the factors relevant to the current and future status of VR rehabilitation will provide a good overview of the key issues and concerns that are relevant for understanding and advancing this vital application area.

1 Introduction

Virtual reality (VR) has now emerged as a promising tool in many domains of therapy and rehabilitation (Weiss & Jessel, 1998; Glantz, Rizzo, & Graap, 2003; Zimand et al. 2003; Rizzo, Schultheis, Kerns, & Mateer, 2004). Continuing advances in VR technology, along with concomitant system-cost reductions, have supported the development of more usable, useful, and accessible VR systems that can uniquely target a wide range of physical, psychological, and cognitive rehabilitation concerns and research questions. What makes VR application development in the therapy and rehabilitation sciences so distinctively important is that it represents more than a simple linear extension of existing computer technology for human use. VR offers the potential to create systematic human testing, training, and treatment environments that allow for the precise control of complex, immersive, dynamic 3D stimulus presentations, within which sophisticated interaction, behavioral tracking, and performance recording is possible. Much like an aircraft simulator serves to test and train piloting ability, virtual environments (VEs) can be developed to present simulations that assess and rehabilitate human functional performance under a range of stimulus conditions that are not easily deliverable and controllable in the real world. When combining these assets within the context of functionally

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relevant, ecologically enhanced VEs, a fundamental advancement could emerge in how human functioning can be addressed in many rehabilitation disciplines.

But we know that already. What we don't know is: What place will VR occupy in the future of rehabilitation?

Depending on who you ask, you're likely to hear a variety of responses to that question that might include such words as: "Visionary!" "too expensive," "just what the field needs," "but how will that impact the therapist's role?" "sounds like the Holodeck," "need better interfaces," "hmm . . . interesting possibilities," "can they really do that?" and so forth. In essence, the view that one takes of VR and its potential to add value over existing rehabilitation tools and methods is often influenced by such factors as one's faith in technology, economic concerns, frustration with the existing limitations of traditional tools, fear of technology, popular-media influences, pragmatic awareness of current hardware limitations, curiosity, and healthy skepticism.

For those working in the "trenches" trying to employ VR in a meaningful way for rehabilitation purposes (or for those just getting their feet wet), a more systematic strategy for evaluating the state of the field could be of value for informing one's judgment, decision making, and guesses as to what's possible now and what lies ahead in the future. Without applying a structured framework to aid one's thinking about the current status and future of VR and rehabilitation, it is quite easy to regularly oscillate between flights of wishful thinking and bouts of abject discouragement, depending on the daily ebb and flow of provocative data and system crashes. Perhaps our susceptibility to this sort of bipolar "second-guessing" of VR could be reduced if one is armed with a comprehensive yet intuitive method for organizing the myriad factors that will serve both to enable and to limit how well we can successfully translate our virtual-reality rehabilitation vision into actual reality! Such a strategy may also help us to identify realistic goals and establish priorities regarding which clients are the most appropriate candidates for VR and which technologies are best suited to creating applications to meet their needs. Although a high capacity to live with ambiguity is a requirement for those who explore novel emerging approaches in any discipline, a focused approach for guiding our expectations could make that process more manageable and productive in the long run.

In view of these issues, this paper will present a SWOT analysis for the field of VR and the rehabilitation sciences (see Figure 1). SWOT is actually an acronym that stands for strengths, weaknesses, opportunities, and threats, and is a commonly employed framework in the business world for analyzing the factors that influence a company's competitive position in the marketplace with an eye to the future. A classic success story for the value of a SWOT analysis is Dell Computer Corporation's use of the framework to make the strategic decision to implement mass customization, just-in-time manufacturing, and direct Internet sales (Collett, 1999). However, the SWOT framework can also be usefully applied outside of the pure business domain. A quick check on the Internet will turn up SWOT analyses for urban-renewal projects, career planning, website design, youth sports programs, evaluation of academic research centers, and it becomes obvious that it can be usefully applied to guide any organized human endeavor designed to accomplish a mission.

Generally, a SWOT analysis serves to uncover the optimal match between the internal strengths and weaknesses of a given entity and the environmental trends (opportunities and threats) that the entity must face in the marketplace.

- A **strength** can be viewed as a resource, a unique approach, or capacity that allows an entity to achieve its defined goals (e.g., VR can allow for precise control of stimulus delivery within a realistic training or rehabilitation simulation).
- A **weakness** is a limitation, fault, or defect in the entity that impedes progress toward defined goals (e.g., the limited field of view and resolution in a head-mounted display can limit usability and perceptual realism).
- An **opportunity** pertains to internal or external forces in the entity's operating environment, such as a trend that increases demand for what the entity can provide or allows the entity to provide it more effectively (e.g., tremendous growth in the interactive digital gaming area has driven development of

Strengths	**Weaknesses**
● Enhanced Ecological Validity ● Stimulus Control and Consistency ● Real-Time Performance Feedback ● Cuing Stimuli to Support "Error-Free Learning" ● Self-Guided Exploration and Independent Practice ● Interface Modification Contingent on User's Impairments ● Complete Naturalistic Performance Record ● Safe Testing and Training Environment ● Gaming Factors to Enhance Motivation ● Low-Cost Environments That Can be Duplicated and Distributed	● The Interface Challenge 1: Interaction Methods ● The Interface Challenge 2: Wires and Displays ● Immature Engineering Process ● Platform Compatibility ● Front-End Flexibility ● Back-End Data Extraction, Management, Analysis, Visualization ● Side Effects
Opportunities	**Threats**
● Emerging Tech 1: Processing Power and Graphics/Video Integration ● Emerging Tech 2: Devices and Wires ● Emerging Tech 3: Real-Time Data Analysis and Intelligence ● Gaming-Industry Drivers ● VR Rehabilitation with Widespread Intuitive Appeal to the Public ● Academic and Professional Acceptance ● Close-Knit VR Rehabilitation Scientific and Clinical Community ● Integration of VR with Physiological Monitoring and Brain Imaging ● Telerehabilitation	● Too Few Cost/Benefit Proofs Could Impact VR Rehabilitation Adoption ● Aftereffects Lawsuit Potential ● Ethical Challenges ● The Perception That VR Will Eliminate the Need for the Clinician ● Limited Awareness/Unrealistic Expectations

Figure 1. *Summary of a SWOT analysis for VR rehabilitation and therapy.*

the high-quality, yet low-cost graphics cards needed to make VR deliverable on a basic PC).

- A **threat** can be any unfavorable situation in the entity's environment that impedes its strategy by presenting a barrier or constraint that limits achievement of goals (e.g., clinical administrators' and financial officers' belief that VR equipment is too expensive to incorporate into mainstream practice).

What has typically been found to be effective, based on SWOT input, is a strategy that takes advantage of the entity's **opportunities** by employing its **strengths** and by proactively addressing **threats** by correcting or compensating for **weaknesses.** This paper will begin by briefly reviewing the oft-discussed topics relating to VR strengths and weaknesses, with illustrations from existing work in the fields of rehabilitation and therapy. Due to space limitations, the examples provided are not meant as an exhaustive listing. The more challenging analysis of opportunities and threats requires an examination of scientific, technological, medical, marketing, and attitudinal trends that may well be open to varied interpretations by readers depending on their experiences and resources. This structured examination of the factors relevant to the current status and future of VR rehabilitation will be unlikely to produce a final answer that readers will consensually agree upon. But we do hope to stir the visionary pot enough to stimulate some creative pondering of these issues that will linger on a bit as you consider this vital and meaningful VR application area!

In the following discussion, the term *rehabilitation* is defined broadly as a general descriptor to refer to both the *assessment* and *treatment* of impairments in human physical, cognitive, or psychological functioning. *Impairment* will refer to either: (1) a loss of existing ability due to injury, a disease process, mental disorder, or in some cases, the aging process; or (2) a failure to display age-based normative abilities due to a specified developmental or learning disability.

2 VR Rehabilitation Strengths

2.1 Enhanced Ecological Validity

Traditional clinical rehabilitation methods have been criticized as limited in the area of *ecological* validity, that is, the degree of relevance or similarity that a test or training system has relative to the "real" world, and in its value for predicting or improving "everyday" functioning (Neisser, 1978). Adherents of this view challenge the usefulness of analog tasks for addressing the complex integrated functioning that is required for successful performance in the real world. A primary strength that VR offers rehabilitation is in the creation of simulated realistic environments in which performance can be tested and trained in a systematic fashion. By designing virtual environments that not only "look like" the real world, but actually incorporate challenges that require real-world functional behaviors, the ecological validity of rehabilitation methods could be enhanced. As well, within a VE, the experimental control required for rigorous scientific analysis and replication can still be maintained within simulated contexts that embody the complex challenges found in naturalistic settings. Thus, VR-derived results could have greater predictive validity and clinical relevance for the challenges that patients face in the real world.

A number of examples illustrate efforts to enhance the ecological validity of assessment and rehabilitation by designing VEs that are replicas of relevant archetypical functional environments. This has included the creation of virtual cities (Brown, Kerr, & Bayon, 1998; Costas, Carvalho, & de Aragon, 2000), supermarkets (Cromby, Standen, Newman, & Tasker, 1996); homes (Pugnetti et al., 1998; Rose, Attree, Brooks, & Andrews, 2001); kitchens (Christiansen et al., 1998; Davies et al., 2002), school environments (Stanton, Foreman, & Wilson, 1998; Rizzo, Bowerly, et al., 2002), workspaces/offices (McGeorge et al., 2001; Schultheis & Rizzo, 2002); rehabilitation wards (Brooks et al., 1999), and even a virtual beach (Elkind, Rubin, Rosenthal, Skoff, & Prather, 2001). While these environments vary in their level of pictorial or graphic realism, this factor may be secondary in importance, relative to the actual activities that are carried out in the environment, for determining their value from an ecological validity standpoint. Since humans oftentimes display a high capacity to "suspend disbelief" and respond as if the scenario were real, it could be conjectured that the "ecological value" of a VR task may be well supported in spite of limited graphic realism and less immersion (such as in flat-screen systems). In essence, as long as the VR scenario resembles the real world, possesses design elements that replicate key real-life challenges, and the system responds well to user interaction, then ecological validity would likely be enhanced beyond existing analog approaches. Evidence to support this view can be drawn from clinical VR applications that address anxiety disorders. While a number of the successful VR scenarios designed for exposure-based therapy of specific phobias would never be mistaken for the real world, clients within these VEs still manifest physiological responses and report subjective units of discomfort levels that suggest they are responding as if they are in the presence of the feared stimuli (Wiederhold & Wiederhold, 1998). As well, the extinction of the fear response that occurs in the VE is often seen to generalize to the non-VR world, and thus provides evidence for the ecological validity of this form of treatment (Glantz et al., 2003).

2.2 Stimulus Control and Consistency That Supports Repetitive and Hierarchical Delivery

One of the cardinal strengths of any advanced form of simulation technology involves the capacity for systematic delivery and control of stimuli. In fact, one could conjecture that the basic foundation of all human research and clinical methodology requires the systematic delivery and control of environmental stimuli and the subsequent capture and analysis of targeted behaviors. In this regard, an ideal match appears to exist between the stimulus-delivery assets of VR simulation approaches and rehabilitation requirements. Much as a tank simulator can provide combat testing and training, VEs can be developed to present simulations that assess and rehabilitate human physical, cognitive, and psychological processes under a range of stimulus conditions that are not easily controllable in the real world. This "Ultimate Skinner Box" asset can be seen to provide value across the spectrum of rehabilitation approaches, from analysis at an analog level targeting component cognitive processes (e.g., selective attention performance contingent on varying levels of stimulus-intensity exposure), to the complex orchestration of more molar functional behaviors (e.g., planning, initiating, and physically performing the steps required to prepare a meal in a chaotic setting). Although traditional flat-screen computer-based testing and training tools also offer these assets, it is our view that the added value for using VR resides in the capacity for systematic stimulus delivery embedded within immersive simulations of functional real-world environments.

This strength can also be seen to allow for the *hierarchical* delivery of stimulus challenges across a range of difficulty levels. In this way, an individual's rehabilitation can be customized to begin at a stimulus challenge level most attainable and comfortable for that person, with gradual progression of difficulty level based on performance gains. For example, on the analog level, Yang and Kim (2002) created a motion training system in which subjects started with a simple 1D translation task and later moved to more complex 6-degrees-of-freedom motion tasks. With such hierarchical stimulus challenges, subjects displayed performance improvements equivalent to real-world training. For more complex integrated behavior, the assessment of driving skills following traumatic brain injury is one example where individuals may begin at a simplistic level (i.e., straight, nonpopulated roads) and gradually move along to more challenging situations (i.e., crowded highways) (Schultheis & Mourant, 2001). Such stimulus-control assets provide the opportunity to identify, modify, and train individual performance strategies at various hierarchical levels of challenge within a VE. As well, the successful execution of many everyday activities requires the integration of a variety of cognitive and motor functions, and subsequent component evaluation of these complex behaviors is often challenging to clinicians and researchers. With this powerful capacity for stimulus control within a VE, the impact of specific patient assets and limitations may be better isolated, assessed, and rehabilitated. A good illustrative example of this can be seen in Rizzo, Bowerly, et al. (2002), with a VR classroom that was designed to systematically present distractions while children diagnosed with attention deficit hyperactivity disorder attempted to focus on a vigilance task within the classroom. Substantial degradations in attention performance and increases in motor hyperactivity were seen in these children (compared to normal controls) when stimulus distractions typically found in real classrooms were systematically introduced.

2.3 Real-time Performance Feedback

Performance feedback as to the status and outcome of a response is generally accepted to be necessary for most forms of learning or skill acquisition and is equally essential to the learning process that underlies rehabilitation (Sohlberg & Mateer, 2001). While feedback can be presented in a VE to signal performance status in a form that wouldn't naturally occur in the real world (e.g., a soft tone occurring after a correct response), more relevant or naturalistic sounds can also be creatively applied to support response calibration and enhance the perceived realism of the scenario. For example, in an Internet-delivered VR application designed to help children with learning disabilities practice escape from a house fire (Strickland, 2001), the sound of a smoke-detector alarm raises in volume as the child gets near to the fire's location. As the child successfully navigates to safety, the alarm fades contingent on her choosing the correct escape route.

The potential value of virtual-performance feedback for rehabilitation applications can be seen from applications designed to support physical therapy in adults following a stroke (Deutsch, Latonio, Burdea, & Boian, 2001; Jack et al., 2001). These applications use various glove and ankle interface devices that translate the user's movements into a visible and somewhat relevant activity that is presented graphically on a flat-screen display. For example, in one application, as the user performs a prescribed hand exercise designed to enhance fractionation (independence of finger motion), the image of a hand appears on the display, playing a piano keyboard, reflecting the actual hand movements of the client. In a similar application, the appropriate hand movement moves a "wiper" that serves to reveal an interesting picture along with a display of a graphic rendering of a performance meter representing range of movement. These features serve not only as mechanisms for providing feedback regarding the ongoing status of targeted movement, but also could serve as motivators. Results from this lab with stroke patients, presented in a series of seven case studies, reported positive results for rehabilitating hand performance across range, speed, fractionation, and strength measures (Jack et al.). In one noteworthy case, functional improvement was reported in a patient who was able to button his shirt independently for the first time post-stroke following two weeks of training with the VR hand interface. As well, by making the repetitive and often boring work of physical therapy exercise more interesting and compelling, patients reported enhanced enjoyment leading to increased motivation.

2.4 Cuing Stimuli to Support "Error-Free Learning"

The capacity for dynamic stimulus delivery and control within a VE also allows for the presentation of cuing stimuli that could be used for "error-free" learning approaches in rehabilitation-training scenarios. This asset underscores the idea that in some cases it may *not* be desirable for VR to simply mimic reality with all its incumbent limitations. Instead, stimulus features that are not easily deliverable in the real world can be presented in a VE to help guide and train successful performance. In this special case of stimulus delivery, cues are given to the patient *prior* to a response in order to help guide successful error-free performance. Error-free training, in contrast to trial-and-error learning, has been shown to be successful in a number of investigations with such diverse subjects as pigeons to persons with developmental disabilities, schizophrenia, as well as a variety of CNS disorders (see Wilson & Evans, 1996, for review). This asset can also be harnessed to provide immediate performance feedback to users contingent on the status of their efforts. Such automated delivery of feedback stimuli can appear in graded (degree) or absolute (correct/incorrect) forms and can be presented via any—or multiple—sensory modalities (though mainly audio, visual, tactile are used), depending on the goals of the application and the needs and sensory capabilities of the user. For example, Brooks et al. (1999) reported success with a severely amnestic stroke patient using an error-free VR training approach for wayfinding in a rehabilitation-ward VE that produced positive transfer to the real ward. Harrison, Derwent, Enticknap, Rose, & Attree (2002) also reported mixed results with the use of cuing stimuli in a VR system designed to train maneuverability and route finding in novice motorized-wheelchair users.

2.5 Self-Guided Exploration and Independent Practice

Independent self-assessment and "home-based" skills practice by clients are common components of most forms of rehabilitation. Generally, it is accepted that having clients do "homework" will promote generalization of skills learned in treatment proper to everyday behavior. The widespread increase in access to personal computing over the last decade has also encouraged the autonomous use of computerized self-help software by clients. As such, it is likely that the independent use of VR will also become more common as access to systems and software expands in the future. Notwithstanding the potential for shoddy VR applications to reach the marketplace with little evidence to support their efficacy or value, the option for independent VR use (when guided by an appropriate professional) can be viewed as a strength for a number of reasons. When compared with existing flat-screen computerized testing and training formats, VR is distinguished by its capacity to provide higher levels of both immersion and interactivity between the user and the VE. These unique features are seen to enhance the suspension of disbelief required to generate a sense of presence within the VE. When this psychological state of presence occurs, it is conjectured to create a user experience that may influence task performance (Sadowski & Stanney, 2002). This user experience may produce behaviors that are *different* from what typically occurs in persons undergoing traditional testing and training, due to the user's attention being more occupied "within" the VE. As well, the user experience may be less self-conscious due to the perceived removal of the test administrator from the immediate personal and attentional space. This experience could provide a unique qualitative window into how people perform tasks when operating in a more independent and autonomous fashion. For example, if clients were allowed to freely interact within a functional VE (i.e., office, mall, home, etc.) that contained very subtle test challenges, the recording, and later observation, of more naturalistic client behaviors would be possible. This could include observing how individualized compensatory or problem-solving strategies are spontaneously employed when challenged with a complex situation. As well, this may also be of value for monitoring decision making and risk taking in the assessment of potentially hazardous real-world skills in a VE, such as driving an automobile.

2.6 Interface Modification Contingent on User's Impairments to Support Access to Rehabilitation

Limitations still exist in fostering truly naturalistic VR interaction with current 3D user-interaction methods (Bowman, Kruijff, LaViola, & Poupyrev, 2001). However, for certain populations with sensorimotor impairments, existing 3D UI tools can still support access to rehabilitation in VR beyond what is possible with traditional non-VR methods. Oftentimes in rehabilitation, permanent impairments in one domain of functioning may interfere with the testing and training of another set of functions that potentially could benefit from treatment. For example, one of the current challenges in cognitive rehabilitation concerns the effective adaptation of testing and training methods by clients with significant sensory and/or motor impairments. When such adaptations are attempted, the question often arises as to how much a client's performance reflects centrally based cognitive dysfunction versus artifacts due to more peripheral sensorimotor impairments. VR offers two ways in which this challenge may be addressed in the testing and training of cognitive and everyday functional abilities in persons with sensorimotor impairments.

One approach places emphasis on the design of adapted human-computer interface devices in a VE to promote usability and access. The thoughtful integration of adapted interface devices between the person and VR system could assist those with motor impairments to navigate and interact in rehabilitative VR applications (beyond what might be possible in the real world). Such interface adaptations may support actuation by way of alternative or augmented movement, speech, expired air, and tracked eye movement, and by way of neurofeedback-trained biosignal activity (Barrett, McCrindle, Cook, & Booy, 2002). These devices, while admittedly "unnatural," allow patients to interact beyond what their physical impairments allow. One basic example involves the use of a gaming joystick to navigate in a VE that was found effective for teaching wayfinding within a VE modeled after an amnestic client's rehabilitation unit (Brooks et al., 1999). These authors partially attributed the observed positive training effects to the patient's capability for quicker traversing of the VE using a joystick compared to what her ambulatory impairments would allow in the real environment. This strategy, by minimizing the impact of peripheral impairments on performance, allowed for centrally based performance components to be more efficiently trained.

A second approach to this challenge has been to tailor the sensory modality components of the VE around the needs of the persons' impairments. The few efforts in this area have mainly attempted to build simulated structures for persons with visual impairments by the use of enhanced 3D sound (Lumbreras & Sanchez, 2000) and haptic stimuli (Connor, Wing, Humphreys, Bracewell, & Harvey, 2002; Lahav & Mioduser, 2002). For example, Lumbreras and Sanchez, aiming to design computer games for blind children, created a 3D audio VR system referred to as "AudioDOOM." In this application, blind children use a joystick to navigate the mazelike game environment exclusively on the basis of 3D audio cues (i.e., footstep sounds, doors that "creak" open, echoes, etc.) while chasing "monsters" around the environment. Following varied periods of time in the audio VE, the children are then given Legos to construct their impression of the structure of the layout. The resulting Lego constructions are often noteworthy in their striking resemblance to the actual structure of the audio-based layout of the maze. Children using this system (who never actually have seen the physical visual world) often appear to be able use the 3D sound cues to create a spatial-cognitive map of the space and then accurately represent this space with physical objects (i.e., Legos, clay, sand). Examples of some of these constructions are available on the Internet (http://www.dcc.uchile.cl/~mlumbrer/audiodoom/audiodoom.html). While tested mainly with children, it is possible to conceive of such 3D audio-based environments as providing platforms for assessment and rehabilitation of persons with visual impairments at any age.

2.7 Complete Naturalistic Performance Record

The review of a client's performance in any rehabilitation activity typically involves examination of numeric data and subsequent translation of that information into graphic representations in the form of tables and graphs. Sometimes videotaping of the actual event is used for a more naturalistic review and for behavior-rating purposes. These methods, while of some value, are typically quite labor-intensive to produce and sometimes deliver a less than intuitive method for visualizing and understanding a complex performance record. These challenges are compounded when the goal of the review is to provide feedback and insight to clients whose cognitive impairments may preclude a useful understanding of traditional forms of data presentation. VR offers the capability to capture and review a complete digital record of performance in a virtual environment from many perspectives. For example, performance in a VE can be later observed from the perspective of the user, from the view of a third party or position within the VE, and from what is sometimes termed a "God's-eye view," from above the scene, with options to adjust the position and scale of the view. This can allow a client or therapist to observe the performance from multiple perspectives and repeatedly review the performance. Options for this review also include the modulation of presentation, as in allowing the client to slow down the rate of activity and observe each behavioral step in the sequence in slow motion.

2.8 Safe Testing and Training Environment, which Minimizes Risks due to Errors

As alluded to in the VR driving example presented above, when developing certain functionally based assessment and rehabilitation approaches, one must consider the possibility of safety risks that may occur during activities designed to test and train abilities in the real world. Driving would probably represent one of the more risk-laden activities that a client with cognitive and/or physical impairments would undertake in order to achieve functional independence. However, even simple functional activities can lead to potential injury when working with persons having CNS-based impairments. Such potential risks can be seen in the relatively "safe" environment of a kitchen (i.e., burns, falls, getting cut with a knife) as well as in more naturally dangerous situations such as street crossing, the operation of mechanical/industrial equipment, and driving a motor vehicle. Additionally, the risk for client/therapist injury and subsequent liability concerns may actually limit the functional targets that are addressed in the rehabilitation process. These "overlooked" targets may actually put the client at risk later on as they make their initial independent efforts in the real world without having such targets addressed thoroughly in rehabilitation.

Thus far, this asset has served as a driving force for VR-system design and research with clinical and "at-risk" normal populations. Such applications include: street crossing, with unimpaired children (McComas, MacKay, & Pivak, 2002), with populations with learning and developmental disabilities (Strickland, 2001; Brown et al., 1998), and with adult traumatic-brain-injury groups with neglect (Naveh, Katz, & Weiss, 2000); kitchen safety (Rose, Brooks, & Attree, 2000); escape from a burning house, with autistic children (Strickland, 2001); preventing falls, with at risk elderly (Jaffe, 1998); use of public transportation (Mowafty & Pollack, 1995), and driving, with a range of clinical populations (Rizzo, Reinach, McGehee, & Dawson, 1997; Liu, Miyazaki, & Watson, 1999; Schultheis & Mourant, 2001). In addition to the goal of promoting safe performance in the real world, some researchers have reported positive results for building a more rational awareness of limitations using a VR approach. For example, Davis & Wachtel (2000), have reported a number of instances where older adults, poststroke, had decided *not* to continue making a return to driving a primary immediate goal after they had spent time in a challenging VR driving system.

2.9 Gaming Factors to Enhance Motivation

Plato is reputed to have said, "You can discover more about a person in an hour of play than in a year of conversation" (cited in Moncur & Moncur, 2002). This ancient quote has particular relevance for VR rehabilitation applications. Observing and/or quantifying a person's approach or strategy when participating in a structured game-based activity may provide insight into functioning similar to what is acquired with traditional (yet less meaningful) standard performance assessments. The capacity for a person to become engaged in a gaming task and become less focused on the fact that they are being "tested" may provide a purer gauge of naturalistic ability. As well, another more compelling clinical direction may involve leveraging gaming features and incentives for the challenging task of enhancing motivation levels in clients participating in rehabilitation. In fact, one possible factor in the mixed outcomes found in rehabilitation research may be in part due to the inability to maintain the clients' motivation and engagement when confronting them with a repetitive series of training challenges, whether they be cognitive or physical activities. Hence, the integration of gaming features in VR-based rehabilitation systems to enhance client motivation is viewed as a useful direction to explore.

Thus far, the integration of gaming features into a VE has been reported to enhance motivation in adult clients undergoing physical and occupational therapy following a stroke (Jack et al., 2001; Kizony, Katz &, Weiss, 2003). As well, Strickland (2001) reports that children with autism were observed to become very engaged in the VR safety-training applications she has developed that incorporate gaming features. Further anecdotal observations suggest that children diagnosed with attention deficit hyperactivity disorder often have a fascination for the type of stimulus environments that occur with computer/video games (Greenhill, 1998). Parents are often puzzled when they observe their children focusing on video games intently, while teacher reports indicate inattention in the classroom. Additionally, in the first author's clinical experience, it was observed that some of the young adult traumatic-brain-injury clients, who had difficulty maintaining concentration on traditional cognitive rehabilitation tasks, would easily spend hours at a time playing the computer game SimCity. These observations suggest that designers of rehabilitation tasks can benefit from examining the formulas that commercial game developers use in the creation of interactive computer games. These formulas govern the flow and variation in stimulus pacing that provide linkage to a progressive reward and goal structure. When delivered within a highly interactive graphics-rich environment, users are observed to become extremely engaged in this sort of game play. Neuroscience research in the area of rapid serial visual presentation (RSVP) may provide some scientific insight into the human attraction to these fast-paced-stimulus environments. In this regard, Biederman (2002) suggests that a gradient of opiate-like receptors in the portions of the cortex involved in visual, auditory, and somatosensory perception and recognition drives humans to prefer experiences that are novel, fast, immersive, and readily interpreted. This may partly underlie the enhanced motivation that is observed for the types of activities that are presented in interactive gaming environments. While many reasons may contribute to the allure of current interactive computer gaming, a proper discussion of these issues is beyond the scope of this article. However, the potential value of gaming applications in general education and training is increasingly being recognized. An excellent presentation of these topics can be found in Prensky (2001), along with an extensive gaming bibliography that is available at the Digiplay Initiative (2002).

2.10 Low-Cost Functional Environments That Can be Duplicated and Distributed

Rather than relying on costly physical mock-ups of rehabilitation environments, VR offers the capacity to produce and distribute identical "standard" environments. Within such digital rehabilitation scenarios, normative data can be accumulated for performance comparisons needed for diagnostics and for training purposes. While the initial cost to produce an environment may be high, this financial outlay could be dissipated with cost sharing by professionals adopting the environment. In view of this, the future evolution of VR in rehabilitation will likely be driven by three key elements. First, continuing advances in the underlying enabling technologies necessary for VR delivery, along with concomitant hardware-cost reductions, will allow VR to become more available and usable by independent clinicians and researchers. Second, this potential for increased access and the impact of market forces will result in further development of new VR applications that target a broader range of clinical and research targets. And finally, continued research aimed at determining reliability, validity, and utility will help establish certain VR applications as mainstream rehabilitation tools. Contingent upon the occurrence of these events, it will be possible that future rehabilitation professionals will be able to purchase a VR system that provides them with a suite of environments (i.e., home, classroom, office, community, etc.) within which a variety of testing and training tasks will be available. This has already occurred in the area of VR anxiety-disorder applications, with no fewer than three companies marketing systems in this manner. Internet access to libraries of downloadable VR scenarios will become a likely form of distribution. Data-mining, scoring, and report-writing features will also become available similar to what currently exists with many standardized computer-administered paper-and-pencil tests. As well, highly flexible "front-end" interface programs will allow clinicians and researchers to modify stimulus delivery/response capture parameters within some VEs and tailor system characteristics to more specifically meet their targeted purposes. This level of availability could provide professionals with unparalleled options for using and evolving standard VR applications in the service of their clients and for scientific aims.

3 VR Rehabilitation Weaknesses

3.1 The Interface Challenge 1: Interaction Methods

Enhanced ecological validity has already been raised as an important strength for VR-based rehabilitation. However, before this vision can be fully reached, conceptual and technological advances need to occur in the area of 3D user-interface devices and techniques. From a human-computer interaction perspective, a primary concern involves how to design more effective, efficient, and easily learnable methods for human interaction with such complex systems. Current methods are still limited in the degree to which they allow users to naturalistically interact with the assessment and rehabilitation challenges presented in a VE. Rehabilitation developers are often constrained to use existing hardware that often falls short of the aim to foster natural interaction. This is a significant problem, since in order for persons with cognitive and/or physical impairments to be in a position to benefit from VR applications, they should ideally be able to easily learn how to navigate and interact within a VE in a manner similar to how they do it in the real world. Many modes of VR interaction (i.e., wands, joysticks, 3D mice, etc.), while easily mastered by unimpaired users, could present problems for those with cognitive or physical impairments. A case can be made that, short of fostering truly realistic naturalistic interaction, perhaps interaction methods based on “magic” that give the user “suprahuman” interaction abilities are a viable option (Bowman et al., 2001). However, these methods would need to be highly learnable, and for some rehabilitation applications, devices might also have to be custom-made to suit the special needs and impairments of patients. This would require extensive usability testing even before the clinical efficacy of the scenario could begin to be evaluated. Even if patients are capable of using a less natural interaction method at a basic level, the extra nonautomatic cognitive effort required to interact/navigate could serve as a distraction and limit the assessment and rehabilitation processes. In this regard, Psotka (1995) hypothesizes that facilitation of a “single egocenter” found in highly immersive interfaces would serve to reduce “cognitive overhead” and thereby enhance information access and learning.

This is representative of the larger general problem of designing usable interfaces for all VR applications. Despite some recent progress in interaction modeling (Bowman et al., 2001), finding the best interface method for a given application usually requires costly and time-consuming usability testing. Other major obstacles for designing usable interfaces for VR-based rehabilitation include the rapid changes in hardware capabilities, device availability, cost, and the lack of a mature methodology in interaction design. The situation is often compared to the case of 2D desktop interfaces, where a mature interface methodology has emerged over the last 30 years using devices that are standardized/fixed (mouse, keyboard, monitor) (Preece, Rogers, & Sharp, 2002). With the absence of such an established design methodology, we are still limited to a trial-and-error exploratory approach to VR interaction design. Such a method adds another layer of challenges for rehabilitation professionals who have little familiarity with usability testing. Additionally, managed-health-care dollars are scarce for supporting this type of essential, though less sexy, usability research with clinical populations. This is an area that needs the most attention in the current state of affairs for VR rehabilitation, and better multidisciplinary collaboration in application development may be a key element for future success.

3.2 The Interface Challenge 2: Wires and Displays

Many devices that are required to operate a VR system or to track user behavior require wires and various connectors that are a source of distraction and inconvenience. Wires constrain interaction, both mentally and physically, and complex motion can result in the user getting tangled in wires and cables that limit usability and could create safety hazards. Similarly, after all the years of advancements in the field of VR, an inexpensive technology for head-mounted display (HMD) systems with near-human vision quality has yet to arrive. HMDs are still cumbersome, mostly tethered, and provide only limited resolution and field of view. Provision of stereoscopy within an HMD is still problematic, due to the conflict between flat displays and human eye accommodation and convergence factors that sometimes results in user eyestrain, headaches, and other side effects. Fully immersive projection displays (i.e., CAVE, Powerwalls, Immersadesks) may offer better visual characteristics, yet remain a very expensive option that reduces pragmatic availability for rehabilitation uses. 3D sound display technology has seen much progress in the last 20 years and control of the azimuth (left and right) of sound stimuli has become quite effective (Duda, 2004). However, the 3D sound quality produced from the general-purpose sound cards is at its best with the use of a headphone instead from a set of speakers (not tethered). This is because the head-related transfer functions used in the sound cards are usually sampled with microphones located in the two ears of a human head model. This in turn makes the use of multichannel speakers difficult because the synthesized sound is based on two channels (two-speaker configurations can be used with less accurate effect). Moreover, it is still difficult to produce sound effects in terms of the elevation and range. Even though inexpensive wireless headphones are available, the fact that headphones (or earphones) must be used at all in addition to the HMD is sometimes a nuisance for users.

Progress has also been relatively slow in display technology for addressing other sensory modalities such as touch and olfaction. For example, force-feedback haptic devices require a large mechanical structure, and this poses many challenges in terms of usability, distraction, and costs. The available commercial products in this area also mainly target only proprioceptive sensation with limited degrees of freedom using expensive exoskeletal devices (Cybergrasp, 2004). "Phantom-type" devices (Massie & Salisbury, 1994), while showing some value for surgical simulation (MacFarlane, Rosen, Hannaford, Pellegrini, & Sinanan, 1999), have such constrained functionality that it is tough to justify the costs in view of the limited rehabilitative targets that they can address. However, researchers with the resources for such force-feedback equipment have reported successful implementation with clinical groups using the Reach-In system (Broeren, Björkdahl, Pascher, & Rydmark, 2002) and with custom-built devices for hand and ankle rehabilitation (Burdea, Popescu, Hentz, & Colbert, 2000). For tactile sense simulation, the research has primarily focused on techniques to recreate the texture of virtual surfaces using special devices and materials such as the piezo-electric elements (Hirota & Hirose, 1995; Allison, Okamura, Dennerlein, & Howe, 1998; Burdea, 1996; Ikei & Stiratori, 2002). These systems typically are applied to a relatively small skin area such as the fingertip and find very low utility in actual system deployment. Proposals to use small vibratory devices for tactile feedback applied to a larger skin area have been made in several application contexts (Tan & Pentland, 1997; Jang, Yang, & Kim, 2002), but results on their utility and usability are still preliminary. In general, most precision haptic/tactile devices are still too costly to find their way into mainstream rehabilitation, and the troubling thought is that there does not seem to be a visible breakthrough in these areas in the near future. This is unfortunate since better touch simulation is especially desirable for motor rehabilitation and for creating applications for patients with visual and auditory impairments (Lahav & Mioduser, 2002).

Tracking devices and sensors are one of the fundamental technologies for any VR system, yet still present considerable usability, cost, and accuracy limitations. Even though wireless tracking methods have become available, they are still expensive and not accurate enough. Magnetic trackers, perhaps the most popular type, either require a specially made magnetic-field-free operating room or a cumbersome calibration process to achieve a reasonable accuracy. Inertial trackers are prone to drift and error accumulation after some extended period of use. Ultrasonic and optical methods have line-of-sight and occlusion problems. Accurate marker-based tracking systems are very expensive, low in usability (e.g., users must wear special suits), and thus are finding use mainly for animation production and motion capture, and not for everyday use as is often required in rehabilitation. Real-time marker-less vision-based tracking is still in early stages of development for 6DF applications (Wren, Azarbayejani, Darrell, & Pentland, 1997; Cohen, Li, & Lee, 2002), but may provide useful options in the future. In essence, significant advances are still needed to produce low-cost and accurate tracking technology required for more effective VR rehabilitation systems.

3.3 Immature Engineering Process for VR-Based Rehabilitation Systems

While often touted as the media of the next generation, virtual reality still has not caught up with the mainstream of content development, let alone for VR-based rehabilitation applications. One of the major obstacles is the lack of models, methodologies, and tools for VR system/content development. Building, testing, and maintaining a VR-based rehabilitation application is undoubtedly a very complex process. Developers must integrate disparate bodies of knowledge in both engineering and rehabilitation that include such subareas as tracking, displays, interaction, computer graphics, simulation, human factors, biokinesiology, cognitive psychology, and so forth. What makes VR rehabilitation-application development so difficult is that, on top of having to tackle traditional computational and logical challenges, one must also address usability concerns specific to the application, its task components, and the characteristics of the clinical user group. The requirements for a VR application designed to treat fear of flying in an otherwise healthy adult phobic will naturally differ substantially from one to teach a Down's Syndrome teenager how to navigate a supermarket.

The system science for VR has not yet reached maturity to efficiently address these challenges (Seo & Kim, 2002). Recent object-oriented VR development tools provide only abstractions for the system functionalities (i.e., device handling, displays, etc.). Unlike ordinary programming tasks, VR execution and development environments are different, not just in the temporal sense, but also in the physical sense. Many VR systems have usability problems simply because developers find it costly and tiring to switch back and forth between the development (e.g., desktop) and execution environments (e.g., immersive setup with HMD, glove, trackers, etc.), and fail to fully test and configure the system for usability. Such issues make system optimization and cost estimation for building a VR application very difficult. Therefore, the perceived cost of a VR application becomes quite high, and in most cases, wrongly so, because with the knowledge and application of system science, a cost-effective solution should be found. Consequently, the inability to predict overall development cost remains a major weakness for VR to be proliferated to many different fields. In comparison to game development, VR-based rehabilitation systems tend to be "one-offs" rather than marketed for a mass audience. Such a nature is more of a reason to have a model for cost estimation and for development. That is, game development may justify a large investment due to its large market, while a one-of-a-kind VR system usually cannot afford to do so and requires a more targeted, systematic approach.

3.4 Platform Compatibility

In order for VR to come into mainstream rehabilitation practice, one basic computational device needs to be easily configurable to run a variety of applications in a manner akin to the ease of installing and running both MS Word and Adobe Acrobat on the same machine. However, most virtual-reality applications are not interoperable. This is primarily due to the relatively short history of active VR-based application development. In the early days (late 80s to mid-90s), most VR applications were developed using Silicon Graphics (SGI) graphics workstations that ran the IRIX operating system (a variant of the UNIX operating system). SGI was also instrumental in developing many useful tools for VR application development, including the Performer, OpenGL, and Inventor (SGI, 2004a). However, due to their high cost and the PC graphics-card revolution, many developers now have switched to the PC platform. This created initial problems in that there were few good development tools equivalent to those available on the SGI workstations and it took years for VR engine API vendors to come up with relatively stable and bug-free versions of their software for PCs. For example, the Windows version of the very popular Performer became available only in 2003 (SGI, 2004b). Consequently, many interesting and useful early SGI-based VR applications need to be substantially modified in order to be ported to the MS Windows environment, arguably the most popular operating system in use today. The transition from special-purpose graphics workstations to clustered PCs for CAVE-type systems (which usually require a form of a multiprocessing system) has only recently begun as the major graphics-card vendors started to offer the "Gen-Lock" feature, which can connect graphics cards installed on different PCs to work together in synchrony. Thus, the current situation is such that, although we are starting to truly converge toward using PC/Windows as the main development platform, there are still many legacy applications that are written for other hardware platforms and operating systems. Similarly, while many developers are making a case for the use of the LINUX operating system, very few clinical settings are willing to adopt this OS as they are already beholden to the Microsoft juggernaut!

However, it is not just the problem of different operating systems and computing hardware, but more importantly, the fact that applications are not written in a flexible and reconfigurable manner. VR systems use many different devices and software, including graphics/video-processing cards, trackers, buttoned devices, cameras, 3D sound hardware, voice-recognition software, mono/stereo displays, and so forth. Applications that have been developed for one particular configuration of devices often fail to run (under the same computing operating environment) if the proper devices (and their drivers) are not available. In many situations, it is difficult to duplicate the exact same operating environment and as such, applications need to be able to accommodate (through software control) similar devices (e.g., between different graphics cards, trackers, driver versions, display types). For rehabilitation applications, the situation should exist where a number of different device configurations can still work with similar effects (e.g., using wired trackers or wireless vision-based trackers, using tactile devices or without), without requiring the constant scrutiny of a programmer on site. Surely, this presents a problem in effectively maintaining VR systems, which again illustrates the critical need for an engineering-science approach to the whole lifecycle of VR application development.

3.5 Front-End Flexibility

Rehabilitation therapists and professionals are often not programmers. Consequently, in order to maximize the usability and subsequent usefulness of a VR rehabilitation program, great care needs to be placed on building an intuitive front-end interface. We will go as far as saying that the rule of thumb should be that the menus, options, and so forth for adjusting stimulus parameters should be no more complex than that found in MS Powerpoint! Unfortunately that is often not the case with much of the clinical VR software that is being used in rehabilitation. Oftentimes a program is hard-coded so that the clinician can use it only in a "one-size-fits-all" manner, or else any adjustments require actually going into the program files and changing lines of code. As simple as code modifications are to a programmer, requiring nonprogrammer clinicians to do this is often a "deal-breaker." To avoid this requires the application of user-centered design strategies, whereby the "user" in this case is the clinician. While the few commercial VR rehab/therapy developers are now addressing this problem (i.e., Virtually Better, Digital Mediaworks, Psychology Software Tools, etc.), many university-based VR packages build these functions in as an afterthought. Sadly, many innovative scenarios do not get applied and tested to their full potential after a clinician with little computer-science tech support gets frustrated following a challenging first start or subsequently when adjustments cannot be made easily in the program to suit the needs of a particular patient.

3.6 Back-End Data Extraction, Management, Analysis, Visualization

As with the front-end problem mentioned above, non-computer-savvy professionals need VR software that spits out performance data automatically and in an intuitive form. While this may add cost to the initial development and consequently is often not well attended to in clinical applications, it is an absolute requirement for a VR rehabilitation application to be adequately used and evaluated. Most VR rehabilitation applications that record complex performances often produce very large files of raw data that then require *another* program to unravel the metrics that a clinician is interested in. While those files of raw output of course have value, the next step needed to make an application have real usable clinical utility is to also deliver basic summary scores, comparison statistics with accumulated normative data, and intuitive representations of the findings in standard graphical and even 3D formats. It is our view that both the front-end and back-end weaknesses seen in much of the VR rehab software to date is the product of developers with limited resources rushing to simply produce a proof of concept, collect some quick clinical data, and then apply for more grant money to fix usability problems later. As we all know from other application areas, this is usually a more costly approach and, even worse, may lead to the program being abandoned in the early stages of testing out of frustration by the clinical professionals using the application.

3.7 Side Effects

In order for VR to become a safe and useful tool for any application, the potential for adverse side effects needs to be considered and addressed. This is a significant concern as the occurrence of side effects could limit the applicability of VEs for certain clinical populations. Two general categories of VE-related side effects have been reported: cybersickness and aftereffects. *Cybersickness* is a form of motion sickness with symptoms reported to include nausea, vomiting, eyestrain, disorientation, ataxia, and vertigo (Kennedy, Berbaum, & Drexler, 1994). Cybersickness is believed to be related to sensory-cue incongruity. This is thought to occur when there is a conflict between perceptions in different sense modalities (auditory, visual, vestibular, proprioceptive) or when sensory-cue information in the VE environment is incongruent with what is felt by the body or with what is expected based on the user's history of real-world sensorimotor experience (Reason, 1970). *Aftereffects* may include such symptoms as disturbed locomotion, changes in postural control, perceptual-motor disturbances, past pointing, flashbacks, drowsiness, fatigue, and generally lowered arousal (Rolland, Biocca, Barlow, & Kancherla, 1995; DiZio & Lackner, 1992; Kennedy & Stanney, 1996). The appearance of aftereffects may be due to the user adapting to the sensorimotor requirements of the VE, which in most cases is an imperfect replica of the non-VE world. Upon leaving the VE, there is a lag in the readaptation to the demands of the non-VE environment, and the occurrence of aftereffects may reflect these shifts in sensorimotor response recalibration. The reported occurrence of side effects in virtual environments in unimpaired populations varies across studies, depending upon such factors as the type of VE program used, technical drivers (i.e., vection, response lag, field of view, etc.), the length of exposure time, the person's prior experience using VEs, active versus passive movement, gender, and the method of measurement used to assess occurrence (Hettinger, 1992; Regan & Price, 1994; Kolasinski, 1995). In a review of this area, Stanney and colleagues (1998) target four primary issues in the study of VE-related side effects that may be of particular value for guiding feasibility assessments with different clinical populations. These include: "(1) How can prolonged exposure to VE systems be obtained? (2) How can aftereffects be characterized? (3) How should they be measured and managed? (4) What is their relationship to task performance?" (p. 6). These questions are particularly relevant to developers of clinical VEs, as these systems are primarily designed to be used by persons with some sort of defined diagnosis or impairment. It is possible that clinical users may have increased vulnerability and a higher susceptibility to VE-related side effects, and ethical clinical vigilance to these issues is essential. Particular concern may be necessary for neurologically impaired populations, some of whom display residual equilibrium, balance, perception, and orientation difficulties. It has also been suggested that subjects with unstable binocular vision (which sometimes can occur following strokes, TBI, and other CNS conditions) may be more susceptible to postexposure visual aftereffects (Wann & Mon-Williams, 1996). These issues should be investigated further in order to determine what effective methods exist to reduce side effects that could limit the feasibility of VEs for applications with clinical populations. An extended discussion of clinical data in this area can be found in Rizzo, Schultheis, & Rothbaum (2002).

4 VR Rehabilitation Opportunities

4.1 Emerging Advances in VR Technology 1: Processing Power and Graphics/Video Integration

Providing visual realism is undoubtedly an important component in developing an effective VR rehabilitation environment. Although it is still difficult to exactly quantify what constitutes a minimum level of realism, the continuing revolution in consumer-level computer-graphic technology has helped the cause of VR for many applications, including the rehabilitation domain. The level of possible detail in visual realism can be indirectly measured by the capabilities of the polygon and texture-processing power of the graphics hardware. This figure, the number of polygons that can be rendered in a scene in real time, has increased almost exponentially during the past several years. For example, the original PlayStation, released in 1995, rendered 300,000 polygons per second, while Sega's Dreamcast, released in 1999, was capable of 3 million polygons per second. The PlayStation 2 renders 66 million polygons per second, while the Xbox set a new standard, rendering up to 300 million polygons per second (Xbox, 2004). Thus, the images on today's $200 game consoles rival or surpass those available on the previous decade's $50,000 computers (Laird, 2001).

Textures and images have been used effectively to enhance visual realism and the graphics-processing capabilities on the PC level have also increased dramatically over the past few years, with this trend expected to continue in the future. The days of up to 128 MB of dedicated onboard texture memory (128 × 128-sized texture is about 64 KBs, and 128 MB texture memory can hold 2000 of these) are already looming and what we once called the graphics card or VGA controllers are now becoming a separate dedicated computing unit for graphics. Such graphics processing units (GPUs) are now programmable and thus pixel-and texel-specific computations can be customized for enhanced realism and real-time performance (Fernando & Kilgard, 2003). This makes image-based rendering, such as view morphing and environment maps (in addition to using traditional textured 3D polygons) an attractive approach for enhancing pictorial realism. Many other dedicated computational modules on today's graphics board will continue to make real-time shadows and realistic light effects (such as ray casting) possible. These light effects are very important for constructing images tuned to the human visual system. Stereoscopic support, multichannel outputs, and multiboard synchronization are becoming standard or popular features. With the popularity of PC-based games, PC architectures and data bus systems are being redesigned and customized for the exchange of a large amount of model and image data between the CPU, memory, and the graphics subsystem. One of the promising trends in interactive graphics is the resurgence of computer vision techniques, an excellent alternative to using wired sensors to track user behavior. Computer vision requires considerable image processing, and the ever increasing power of CPUs and GPUs is also making vision-based techniques more viable.

4.2 Emerging Advances in VR Technology 2: Devices and Wires

While the issue of cumbersome displays with limited capabilities and the design of usable interfaces remain a challenge for VR-application developers (and researchers), two recent developments are very promising. The first concerns the emerging advances in display technology driven by general consumer markets. For example, autostereoscopy makes stereo viewing possible without the need to wear any special equipment (i.e., polarized or active shutter-type glasses), a feature that can enhance the overall usability of VR systems. The Sharp Corporation has recently unveiled an autostereoscopic notebook computer based on an LCD parallax barrier technology that is only $500 more than the ordinary notebook computer. Moreover, such technology can be combined with digital light projection (DLP) technologies to be applied to larger projection display systems. Digital television and new types of display systems such as plasma TV, LCD, and DLP will eventually make advanced digital imagery ubiquitous in homes, with hopefully some "spillover" into clinical applications.

Another positive development is the strong trend toward wireless technology. In the context of VR, there are two visible thrusts in this direction. One is the already mentioned resurgence of computer vision techniques for tracking user motion and for monitoring and inferring user state and intention. Computer vision techniques generally suffer from long computation time due to the inherent nature of image processing (having to make a calculation for each pixel). Dedicated hardware and faster/cheaper CPUs are practically making this limitation disappear. For example, Sony has recently introduced a camera-based interface for the PlayStation 2 called the EyeToy for under $50 (EyeToy, 2004). Canesta Inc. has developed a new solid-state chip that can sense 3D objects and process such data in real time (the technology has been applied to implementing a virtual keyboard by tracking human fingers) (Canesta, 2004). Cheap vision processing will one day enable wireless whole-body tracking (Wren et al., 1997; Cohen et al., 2002) that will have significant impact on the feasibility of physical therapy VR applications. Real-time vision processing will also enhance mixed/augmented reality systems applied to rehabilitation. Augmented reality systems would work quite well for certain rehabilitation applications by allowing the user's own body parts to be seen when interacting with overlaid virtual objects. This would be of value for many areas, but especially for physical therapy, where this approach could be leveraged to enhance the sense of proprioception and promote hand-eye coordination. The second thrust with the wireless-technology trend is the advent of ubiquitous computing. Ubiquitous computing advocates the distribution of processing and sensor elements around everyday living environments so that various objects in the environment can monitor and respond to us to provide intelligent service (Weiser & Brown, 1996). While such a society is still a long time in coming, efforts in wireless communication are already making an impact on wireless-sensor technology. In fact, using wireless technology such as Bluetooth, Radio Frequency ID (RFID) tags, ad hoc networks, and so forth, it is already possible to unwire various current sensors used in the VR context. Advances in this domain, if fueled by widespread adoption with consumer technology, could result in low-cost tracking sensors that would have significant impact on the usability of VR in general, as well as for rehabilitation applications.

4.3 Emerging Advances in VR Technology 3: Real-Time Data Analysis and Intelligence

One of the strengths observed for VR rehabilitation is the capability for sensing 3D behavioral-action data and then presenting feedback regarding ongoing progress for enhancing learning, perhaps via an errorless-learning paradigm. Such useful feedback is possible with the emergence of real-time motion analysis coupled with direct acquisition of motion data (Baek, Lee, & Kim, 2003). Traditional motion analysis used to be an off-line and sometimes manual process because the raw data is usually in video form and such video data processing is very time consuming and difficult. For example, a typical golf-swing motion analysis used to require a golf professional to manually segment out (using a mouse) the relevant features in the video (e.g., golf club, shoulder line, etc.), and only then would the computer algorithm be able to track motion and produce automatic analysis data. Today, various motion sensors that can directly collect specific motion profiles are making their way into the motion and sports science arena. This could serve as a starting point for designing VR applications in motor rehabilitation that integrate gaming features to enhance motivation! Going one step further from simply analyzing patient data, AI techniques could be applied to make intelligent rehabilitation suggestions and perhaps even guide the pacing of stimulus challenges within the VE, contingent on the patient's motor performance.

For rehabilitation domains with a social context, virtual humans, realistic both in appearance and behavior, will be very important. Realistic (in terms of appearance and motion) virtual synthetic humans are already commonplace in PC-level games. For example, current offerings in the sports-themed digital gaming arena feature texture-mapped real-life characters that can be controlled by the user to produce lifelike behavior using acquired motion data. VR applications for targeting psychological processes related to social interaction will require dynamic interaction with virtual human characters that are intelligent and autonomous. For example, such applications would be of value for addressing social phobia in adults, as well as for helping children with autism to learn appropriate social skills. This has been the goal of artificial intelligence for a long time, and even though producing a software agent with human intelligence seems insurmountable at this moment, the traditional AI and VR fields are merging to produce virtual characters that are adaptive and convincing for many applications. Laird (2001) has been applying a general AI architecture called Soar to game engines such as the Quake II to create agents that are challenging opponents, not because of their superhuman reaction times and aiming skills, but because of their complex tactics or game knowledge. This will be an important component in future VR rehabilitation applications, and such approaches have the potential for creating scenarios in which social interactions are targeted. The Sims electronic game series provides an excellent example of how social interactions can be the basis for an engaging virtual arena (Sims, 2004). While development costs and the lack of processing power prevent games for today's computers and consoles from exhibiting a high level of artificial intelligence, that will soon change. Currently, developers devote more resources to advancing a game's graphics technology than to enhancing its AI. However, the recent USC/ICT-developed game, Full Spectrum Warrior (ICT, 2004) now devotes 60% of processor resources to the AI component. It is likely that within two to three years, the emphasis on graphics will have run its course as incremental advances lead to only marginal improvements in the game experience. At that point, the market drivers to create games with higher AI "quotients" could have significant impact on VR rehabilitation applications.

4.4 Gaming-Industry Drivers

There is no doubt that the recent growth in the interactive gaming-industry arena will continue to drive developments in the field of VR rehabilitation. The gaming-industry-juggernaut's growth is evidenced by the fact that it has now surpassed the Hollywood film industry in total entertainment market share, and, in the USA, sales of computer games now outnumber sales of books (Digiplay Initiative, 2002). While the 18–24-year-old male population initially comprised the largest group of users of commercial interactive computer gaming applications, this popularity has also extended to other age groups and to females at a rapid pace (Lowenstein, 2002). As such, it appears that gaming applications have become a standard part of the "digital homestead" as delivered on PCs and specific gaming consoles (i.e., Playstation, Xbox, etc.). From this, interactive gaming has become well integrated into the lifestyles of many people who at some point may require rehabilitative services. For this segment of the population, familiarity with and preference for interactive gaming could become useful assets for enhancing client motivation and engagement when designing VR-based rehabilitation tasks.

VR therapy and rehabilitation scenarios are also increasingly being built off of a variety of software engines developed by the gaming industry. Whether built from the bottom up (DMW, 2004) or in the form of "mods" whereby sections of a popular game title can be modified to create a new scenario (Robillard, Bouchard, Fournier, & Renaud, 2003), the graphics and audio options available with these systems are fast becoming the tool of choice for developers. Just as the advances in game-industry-driven graphics cards have helped bring high-quality VR rendering to the PC, we can expect rehabilitation applications to benefit from the continued growth of this field. With further advances, it is expected that gaming hardware will soon become a common low-cost platform on which many VR rehabilitation applications will be built.

4.5 VR Rehabilitation Applications Have Widespread Intuitive Appeal to the Public

As much as developers and scientists working in the field of virtual reality are cognizant of the challenges and limitations that exist for creating usable applications, the general public is still drawn to the idea of using VR when it is linked to a pressing therapeutic target. Regardless of whether the public interest and excitement is due to realistic media and scientific reports or to the illusions created about the state of VR as presented in such movies as *Lawnmower Man* or *The Matrix,* it is generally observed that people have an initial favorable view of the concept of VR. An example of this can be seen in the growing number of articles and TV reports on VR health-related applications that appear in mainstream media outlets (i.e., the *New York Times;* the *Washington Post;* Tech TV; Discovery Channel, etc.). For better or worse, reporters often choose what scientific news to cover with the public interest in mind and this has driven the increasing appearance of VR and therapy/rehabilitation reports in both print media and television. Another example that our research group has noted is in the enthusiasm seen in participants attending non-VR events, when an HMD demo is available at a booth in an exhibition hall. We have recently set up such demonstrations at a wide range of diverse scientific and general non-VR-specific public events and have consistently observed a steady stream of participants waiting in lines, eager to try VR. While this public interest should not be mistaken as a measure of the validity or value of VR, this positive "vibe" can be seen as reflecting a state of curious acceptance that bodes well for future adoption of well-executed applications. However, overhyped applications can as well lead to negative VR impressions if an imbalanced "expectation to delivery" ratio is created, as will be discussed later in the "Threats" section of this paper.

4.6 Academic and Professional Acceptance

There has recently been a noticeable positive shift in the perception of VR applications in therapy and rehabilitation by mainstream scientists and professionals. While once viewed as an "expensive toy," VR is gradually being accepted as a "tool" that can provide new options for how therapy and rehabilitation is done. Evidence for this can be seen in the growing appearance of VR articles in mainstream journals, along with theme issues devoted to VR and associated technologies (i.e., *Disability and Rehabilitation, Neuropsychological Rehabilitation, Journal of Head Trauma Rehabilitation, Psychological Inquiry, Psychotherapy: Theory, Research, Practice, Training*), acceptance of papers and symposia at mainstream conferences (APA, RESNA, INS, NAN, ACRM, AABT), and in the increased funding by such organizations as NIH, NIMH, NIDA, NIDRR, and so forth. Other indicators include such things as VR being cited as "one of the emerging areas in the future of neuropsychology" during the presidential address at the National Academy of Neuropsychology in 2001, and in the fact that in a poll published in the journal *Professional Psychology: Research and Practice* (Norcross, Hedges, & Prochaska, 2002), a group of 62 therapy experts ranked VR and computerized therapies 3rd and 5th out of 38 interventions that are predicted to increase in the next 10 years. Much of this shift in attitude can be attributed to the highly visible initial clinical studies yielding positive results using VR for exposure therapy in persons with anxiety disorders. This application area is intuitively appealing, well matched to the assets available with VR, and solid research has consistently produced clinical outcomes that support its added value (Riva, 2002; Glantz et al., 2003; Zimand et al., 2003). Further signs of mainstream acceptance can be seen by the fact that the oldest and largest psychological test publisher, The Psychological Corporation, has now begun to support R&D for standardized VR test development (DMW, 2004), along with interest growing in similar rival test and therapy aid publishers. As VR technology and application development continues to evolve, this trend is expected to continue.

4.7 Close-Knit VR Rehabilitation Scientific and Clinical Community

The "closeness" of the community of researchers and clinicians that focus on VR rehabilitation has continued to evolve. Perhaps this is partly due to an innate human drive to form alliances with others of similar interests, and especially so when the interest area is novel, risky, and still seeking credibility from the mainstream. Regardless of the underlying reason, evidence for this growing close-knit community can be seen in the number of conferences that have formed to focus on this area (i.e., MMVR, CyberTherapy, The International Conference on Disability, Virtual Reality and Associated Technology, The International Workshop on Virtual Rehabilitation), the growth over the last five years in membership on the VRPSYCH listserver (450 members from 25 countries), and in the continued expansion in multiuniversity VR collaborations.

4.8 Integration of VR with Physiological Monitoring and Brain Imaging

There is a rather compelling rationale for the integration of VR with human physiological monitoring and brain imaging for advanced research in areas relevant to rehabilitation. Research in such areas as psychophysiology, biokinesiology, and neuropsychology have similar goals in that they aim to noninvasively record bodily events or processes that are hypothesized to correlate with some human mental and/or physical activity. Examples of such efforts would include measuring galvanic skin responses (GSR) while a person attends to emotionally laden stimuli, electromyographic recording of muscle responses as a person reaches for a target, and functional magnetic resonance imaging (fMRI) of hippocampal brain function while a person performs a wayfinding task. While these monitoring technologies have existed for some time, the stimulus-delivery media has remained essentially the same for many years, relying mainly on fixed audio and visual content. The use of VR now allows for measurement of human interaction with realistic dynamic content, albeit within the constraints of the monitoring apparatus. Thus far, heart rate, GSR, and other psychophysiological measures have produced useful results within VR studies examining attention and presence (Pugnetti, Mendozzi, Barberi, Rose, & Attree, 1996; Meehan, Insko, Whitton, & Brooks, 2002) and have been used to enhance treatment effects using a VR biofeedback paradigm for fear-of-flying clients in Wiederhold et al. (2002). Even within the confines of a 3-tesla magnetic-imaging device with the user's head in a fixed position, humans can navigate and interact in a VR world with specialized nonmetal displays and interface devices. In fact a significant body of research has emerged using fMRI to study brain function in normal and clinical groups operating in virtual environments (Maguire et al., 1998; Gron, Wunderlich, Spitzer, Tomszak, & Riepe, 2000; Astur, Mathalon, D'Souza, Krystal, & Constable, 2003; Baumann, 2005). The strength of VR for precise stimulus delivery within ecologically enhanced scenarios is well matched for this research and it is expected that continued growth will be seen in this area.

4.9 Telerehabilitation

The concept of delivering rehabilitation and therapy to patients in remote locations for independent use has been a popular topic since health care professionals recognized the growing reach and power of the Internet. The application of VR within a telerehabilitation format is the next logical opportunity for considering ways to improve access to this technology by a wider group of potential beneficiaries. VR applications that are Internet-deliverable could open up new possibilities for home-based therapy and rehabilitation, which, if executed thoughtfully, could increase client access, enhance outcomes, and reduce costs. Future Internet distribution of VR applications could also be supplemented by maintaining connectivity between the remote client using the system and a primary server at a rehabilitation facility. In this manner, the client's home-based performance within the VR application could be tracked, quantified, analyzed, and graphically represented in an intuitively understandable format for analysis by key rehabilitation professionals charged with monitoring this information. In addition, continual updating of the VR world and the actions and activities that it requires of the client during rehabilitative exercises could be implemented both by the monitoring therapist and via "intelligent" systems on the main server. This functionality would allow client progress to be efficiently tracked, and this information could be used to evolve the performance demands on the client in a manner designed to foster effective and efficient rehabilitative outcomes. An example of some early efforts to apply VR in a telerehabilitation format for physical therapy are detailed in other articles in this issue (Holden, Dyar, Schwamm, & Bizzi, 2005; Deutsch et al., 2005), However, the possible benefits that could be accrued from VR telerehabilitation applications are equally matched by the enormous challenges that still need to be faced. It would be unfortunate for clinicians to become enamored with the obvious *potential* that exists with VR telerehabilitation, yet lose sight of the sheer technical, practical, clinical, and ethical complexities that still need to be addressed (Rizzo, Strickland, & Bouchard, 2004).

5 VR Rehabilitation Threats

5.1 Too Few Cost/Benefit Proofs Could Negatively Impact Mainstream VR Rehabilitation Adoption

While both intuition and early research findings suggest that VR offers many strengths for rehabilitation purposes, the field lacks definitive cost/benefit analyses. Such analyses must spell out both the clinical and *economic* benefits, weighed against the costs for using VR over already-existing traditional methods (Rizzo, Buckwalter, & van der Zaag, 2002). This is a significant challenge in view of the high initial development costs of "one-off" systems that have often characterized many inspired VR applications thus far. Without such cost/benefit proofs, health care administrators and mainstream practitioners who are concerned with the economic bottom line may have little motivation to spend money on high-tech solutions if there is no expected financial gain. This could result in a "Catch-22" scenario whereby limited investment is put into R&D that integrates enabling-technology advances into working systems that might produce favorable cost/benefit proofs at a later time. Favorable cost/benefit proofs for VR use have been reported for military artillery-training applications (Stone, 2003), where tangible metrics are readily available (i.e., criterion artillery performance as a function of costs for real ammunition and equipment + maintenance, etc., vs. VR hardware/software costs, etc./over time). However, for rehabilitation applications in the age of modern health care, the metrics are often quite challenging for "experimental" treatments. While improving "quality of life" may be a lofty goal to target for a patient following a stroke, that type of successful outcome is typically of less interest to third-party payers, who are more focused on a "return to work" metric. Ironically, problems may also arise when a VR treatment shows *too much* value in attracting clients to therapy who would ordinarily avoid treatment. This has been observed in phobic clients who are willing to try VR therapy after avoiding "standard" talk therapy for many years. Health care payers are sometimes more interested in having fewer numbers of patients seek treatment if it negatively affects their bottom line (K. Graap, personal communication, January 11, 2004). While this complex topic is beyond the scope of this article, a fine example of a health care cost/benefit analysis can be found in Holder (1998).

5.2 Aftereffects Lawsuit Potential

As discussed in the "Weaknesses" section, aftereffects may occur in users for various periods of time following interaction in a VE. The potential for such aftereffects following VR usage opens the possibility that a developer, clinician, researcher, or supporting institution could be held liable for damages in the event that some injury should befall a patient upon leaving a VR session. One can easily imagine an unfortunate scenario in which a patient has a car accident while driving home from a VR session and the potential legal difficulties that might ensue if a case were made that the accident was due to VR-induced perceptual aftereffects that impaired depth perception. Kennedy, Kennedy, & Bartlett (2002) present an excellent detailing of these issues in a chapter on VEs and product liability. They suggest that certain human-factors safety actions be undertaken that include: "*1) Systems should be properly designed; 2) Aftereffects should be removed, guarded against, or warned against; 3) Adaptation methods should be developed; 4) Users should be certified to be at their pre-exposure levels; 5) Users should be monitored and debriefed*" (p. 543). Until we have better data on these issues, extra caution may be needed, especially with clinical populations having some form of central-nervous-system dysfunction where readaptation to the real world could cause them to operate differently from unimpaired populations. For example, in one of our recent VR studies testing visuospatial abilities with an elderly group (+65 years old), since we couldn't be confident regarding the absence of potential perceptual aftereffects, we had funding built into our grant to provide transportation from the test site, thereby minimizing any possible risk for altered driving behavior resulting from the VR exposure. Concerns such as these must be addressed in order to ensure a positive course for developing VR applications for all persons and particularly for clinical groups.

5.3 Ethical Challenges

The feasibility of designing, developing, and implementing VR rehabilitation applications has radically advanced in the last five years and it is expected that this evolution will continue into the foreseeable future. Along with any technological advance in the health care domain come ethical questions that require thoughtful consideration. As professionals directly involved in the application of this technology and as members of society at large with a moral-ethical responsibility for the promotion and maintenance of health, we are accountable to consider and address incumbent ethical threats that surround this emerging technology. This is especially important in the rehabilitation sciences, where research and clinical applications with patient populations require a rational accounting of the potential risks and benefits. Additionally, larger pragmatic and societal issues need to be addressed for VR applications with unimpaired users regarding the general human experience and its impact on mental health. As in any area of ethical debate, clear-cut answers that cover all dilemmas are rarely found. For example, while immersion and interactivity may enhance the realism of a VE, these same features may also create difficulties for certain individuals with psychiatric conditions or cognitive impairments that produce distorted reality testing. Specifically, such conditions could result in increased vulnerability for negative emotional responses during or following VR exposure. Although such incidents have yet to be reported in the VR literature, insurance for monitoring responses related to VR exposure becomes an ethical responsibility for the professional. While current therapeutic uses of VR still require a clinician to be present, future applications may not have this requirement, and this potential "opportunity" again underscores the need for advance consideration of the ethical issues pertinent to the use of VR as a clinical tool. As well, as potent VR tools become more readily available for clinical purposes, some clinicians may not have the qualifications or expertise to deliver services in the area that the tool was designed to address. Such inappropriate administration of treatment by a tech-savvy but unqualified health care provider could tarnish the credibility of the field in general and create a public image of VR rehabilitation professionals as high-tech charlatans! Since a full accounting of potential ethical threats in VR rehabilitation is beyond the scope (and page limits) of this article, the reader is referred to Rizzo, Schultheis, et al. (2002) for a detailed review of the use of VR in clinical practice and its potential societal impact.

5.4 The Perception That VR Tools Will Eliminate the Need for the Clinician

Discussion of the use of VR as a therapeutic tool can sometimes raise concerns regarding the status of the clinician when applying technology for therapeutic purposes. One issue cited as a barrier for implementation of computerized therapies is the potential impact on the sanctity of patient-therapist relationship (Gould, 1996). Ironically, a strong form of this argument can be seen in writing on the use of computerized therapy by MIT AI researcher Joe Weizenbaum, who wrote a language-analysis program called ELIZA that was initially designed to imitate a Rogerian psychotherapist. Weizenbaum (1976) concluded that it would be immoral to substitute a computer for a human function that "involves interpersonal respect, understanding, and love" (cf., Howell & Muller, 2000). While admittedly his view emerged out of the "shock" he experienced upon learning how seriously people took the ELIZA program, even basic automated computer applications in "drill and practice" cognitive remediation were met with criticism from some professionals who argued that the introduction of computers was equivalent to the removal of the therapist (cf. Robertson, 1990). Although supporters of VR therapy and rehabilitation are quick to point out that these applications are simply tools that extend the therapist's expertise, there still exists a view in some clinical quarters that any technology serves to subvert the clinical relationship. The impact of this threat will likely increase as more-believable human agents begin to populate VR applications.

The issue of therapist acceptance will likely be surmounted in time if VR applications continue to demonstrate benign added value, but similar impressions on the part of potential patients also need to be considered. For example, will greater access to VR applications via the Internet encourage individuals to undertake self-treatment without feeling the need for professional guidance? Or will slick marketing of costly VR rehabilitation programs that lack evidence for effectiveness entice both desperate family members and naïve clients to self-diagnose and self-administer treatment, yet deliver no tangible benefit? These practical clinical issues need to be considered in advance of widespread availability and adoption of VR rehabilitation applications.

5.5 Limited Awareness/Unrealistic Expectations

This threat is a counterpoint to the "opportunity" cited above regarding widespread intuitive appeal of VR to the general public. All first-time VR users bring into the situation a set of expectations. Oftentimes, these expectations are based on overhyped media representations of what VR can deliver. If someone's expectation is the Holodeck, it is likely that they will be disappointed when they are required to don an array of encumbering devices that support primitive interaction in an imperfect replica of the real world. Perhaps the best remedy for this (aside from continuing to innovate) is in the conduct of research that tests (and hopefully supports) the validity and added value of a given VR application, along with the honest acceptance that we still in fact have a long way to go. Our lab's rule of thumb for VR demos is to usually spend some time preexposure to brief the person on the rationale for a VR application, discuss some of the methods that we have been previously limited to with traditional non-VR tools, and have posters in the lab from previous conferences that present efficacy data from the application being demonstrated.

On the other hand, modulating expectations that continue to be unrealistic in those who *are* familiar with VR can serve another purpose. Mainstream researchers and clinicians are beginning to take notice of this emerging technology and it is important that it is not viewed as a panacea for all rehabilitation concerns. The history of medicine provides numerous examples of the overexploitation of new technologies based on overwrought expectations and little data. The medical use of electricity serves as an example of a commonly accepted procedure in the nineteenth century, during which time faulty expectations combined with an urgency to implement a potential "miracle" cure resulted in many clinicians with minimal to no experience in the physics of electricity misapplying the technique to patients (Whalley, 1995). Similarly, with today's growing interest in the use of VR for clinical research and treatment, it is essential that hype does not displace reason in both the presentation and use of the technology.

6 Conclusions

The view that emerges (to us) from this SWOT analysis suggests that the field of VR rehabilitation is still in an early phase of development characterized by successful "proof of concept" systems, encouraging initial research results, and a few applications that are finding their way into mainstream use and clinical practice. Many VR strengths are specified that will continue to provide a justification for evolving existing applications and creating new ones. Weaknesses exist, particularly with certain limitations in areas of interface and display technology, but do not threaten the viability of the field in light of recent and expected opportunities in the form of advances in the underlying VR-enabling technologies. With thoughtful system design that targets clinical and research applications that are well matched to current technology assets and limitations, it is predicted that VR rehabilitation will continue to gradually grow and gain acceptance as a mainstream tool. Threats to the field do exist, but none are "fatal" and all are likely addressable with the high motivation and thoughtfulness that seems to exist with the many researchers, clinicians, and general proponents of this field. From this analysis, our general prescription for advancing VR rehabilitation can be summed up succinctly. Applications need to be developed with strong multidisciplinary collaboration and with continuous user-centered input/evaluation methods. This is needed to ensure the soundness of the rationale for the application and to create something that is usable within the current limits of technology. Researchers need to initially collect incremental data over numerous small-scale parametric studies to test and evolve usability, usefulness, and access, especially with targeted user groups. During this time, in advance of deployment of a system, ethical, professional, and cost/benefit issues need to be considered and specified. And along the way, share your applications with other interested researchers to see if they can independently operate your system and replicate your results! While the field is not without its challenges, as the technology continues to catch up with the vision, it is our view that VR will have a significant positive impact on the rehabilitation sciences.

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