Emergence of Virtual Reality as a Tool for Upper Limb Rehabilitation: Incorporation of Motor Control and Motor Learning Principles

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The primary focus of rehabilitation for individuals with loss of upper limb movement as a result of acquired brain injury is the relearning of specific motor skills and daily tasks. This relearning is essential because the loss of upper limb movement often results in a reduced quality of life. Although rehabilitation strives to take advantage of neuroplastic processes during recovery, results of traditional approaches to upper limb rehabilitation have not entirely met this goal. In contrast, enriched training tasks, simulated with a wide range of low- to high-end virtual reality–based simulations, can be used to provide meaningful, repetitive practice together with salient feedback, thereby maximizing neuroplastic processes via motor learning and motor recovery. Such enriched virtual environments have the potential to optimize motor learning by manipulating practice conditions that explicitly engage motivational, cognitive, motor control, and sensory feedback–based learning mechanisms. The objectives of this article are to review motor control and motor learning principles, to discuss how they can be exploited by virtual reality training environments, and to provide evidence concerning current applications for upper limb motor recovery. The limitations of the current technologies with respect to their effectiveness and transfer of learning to daily life tasks also are discussed.

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The primary focus of rehabilitation for individuals with loss of upper limb movement as a result of acquired brain injury (ABI) is relearning of specific motor skills and daily tasks. The focus on relearning of skilled upper limb behavior is important because its loss often results in a reduced quality of life. Although rehabilitation strives to take advantage of neuroplastic processes during the recovery period from brain injury, results of traditional approaches to upper limb rehabilitation have not entirely met this potential. One explanation is that traditional rehabilitation approaches may not promote an optimal recovery because they do not adequately target motor control deficits and access the learning potential of the brain. Another explanation is that traditional rehabilitation methods may not account for individual differences in motor and cognitive impairments that may result in learners reacting differently to specific information provided during motor retraining programs. A third explanation is that even repeated performance of a movement may not lead to meaningful improvement unless the task is performed within the functional demands of a relevant environment.

Clinical goals of optimizing motor learning can be addressed using virtual reality (VR) technology. Using treatment interventions created in virtual environments, practice conditions can be manipulated to explicitly engage motivation, cognitive processes, motor control, and sensory feedback–based learning mechanisms.[1] Such virtual environments may be programmed to operate with a wide range of "low-tech" to "high-tech" simulations that include simple video games, camera-based gesture recognition systems, and high-end three-dimensional (3D) multimodal VR platforms. Display systems also can vary, ranging from standard computer screens and television monitors to head-mounted display and CAVE (Computer-Assisted Virtual Environment)* systems. The clinical utility of using enriched training environments such as those created in VR has been explored in which the variety and flexibility of interventions and the manipulation of salient feedback can be used to maximize neuroplastic processes. The objectives of this article are to review the principles of motor control and motor learning for upper limb rehabilitation and to discuss how the attributes of training environments created within VR interactive simulations have addressed these principles. The limitations of the current technology also are discussed with respect to its effectiveness and transfer of learning to daily life tasks.

Motor Control and Motor Learning Principles for Sensorimotor Rehabilitation

Acquired brain injury contributes significantly to the incidence of upper limb impairments affecting the ability of individuals to participate in activities of daily living and diminishing their quality of life. Following ABI, tissue damage and denervation lead to immediate reductions in the size and connectivity of cortical sensory and motor maps.[2] There is growing evidence that recovery continues for months and even years after an initial, rapid recovery period.[3] Late recovery may be attributed to sensorimotor learning and adaptive plasticity in the remaining cortical and subcortical brain tissue.[4]

Recent research has focused on exploring ways to drive and shape neuroplasticity to maximize recovery through rehabilitation. For example, the experience-dependent approach[5] contends that task-specific training causes reorganization in sensory and motor cortices. On the other hand, "bad plasticity" also can occur: not using the affected limb leads to "learned nonuse"[6,7] even beyond the actual constraints imposed by the lesion, and learning less optimal movements using motor compensations may lead to "learned bad use."[8] If such undesirable behavior is learned, it is more difficult to replace that movement with the desired one, potentially leading to long-term disability.

The key factors for driving neural plasticity are similar to those important for new skill acquisition through motor learning processes,[9] which are founded on the principles of motor control in healthy individuals. In this section, we focus on the principles underlying the voluntary execution of purposeful movements. We summarize some basic principles of motor control and learning and identify how the use of enriched virtual training tasks can take advantage of these principles to maximize motor recovery after neurological system injury. Despite the potential of conventional therapy to apply many of the principles of motor learning and motor control, it is beyond the scope of the current perspective article to assess this evidence.

Movement Planning

Movement is planned in end-effector or environmental coordinates. To reacquire a lost motor skill after neurological damage, the focus of the learner should be on the movements of the end effector (eg, the hand or fingertips), since movement is produced by shifting this effector from one position to another rather than by "programming" the contraction of individual muscles or the rotation of individual arm joints.[10–12] Movement planning and organization also need to account for redundancy in

* The CAVE is a registered trademark of the Board of Trustees of the University of Illinois.

the muscle and joint degrees of freedom and how to coordinate these degrees of freedom to produce the desired end effector movement. A movement is considered to be well-executed if the hand trajectory is characterized by spatiotemporal smoothness and done with adequate speed and precision.[12,13] Movement planning also occurs in relation to object location and distance from the body[14,15] and is tightly linked to perception.[16] According to Fitts' Law,[13] a movement is more difficult if it covers a larger distance in a shorter amount of time and requires more precision. Thus, movements can be graded in difficulty according to Fitts' Law with feedback about endpoint variables such as movement speed, precision, and smoothness provided to the learner in the form of knowledge of results (see below).

The Sensorimotor System Is Characterized by Kinematic Redundancy

Because of both muscle and joint redundancy,† the sensorimotor system can find different kinematic solutions to achieve the same movement goal (shift in end effector), often by recruiting additional or alternative joints, leading to motor compensations at the kinematic level.[17,18] Thus, in the motor relearning process, feedback about movement patterns (eg, joint rotations, use of compensations) should be provided to the learner in the form of knowledge of performance (KP) to avoid the development of nondesirable compensatory movement patterns.

The Central Nervous System Is Concerned With Actions and Recruits Individual Joints Most Suitable for Each Goal

Cortical neurons represent movement direction and extent as well as other features such as biomechanical configurations (synergies)[19] and muscle activation patterns.[20] A recent study by Ilmane et al[21] also indicated that the output of the motor cortex—the corticospinal system—sets and resets spatial thresholds of reflexes, thus converting them from a movement-resisting mechanism to a movement-producing mechanism. Therefore, motor re-education should focus not only on the kinematic characteristics of movements but also on other characteristics of movement production such as deficits in regulation of reflex thresholds and multijoint coordination. In addition, the choice of tasks practiced should be meaningful to the learner because cognitive and emotional engagement is a key factor for motor recovery.[9]

The Central Nervous System Learns New Skills Through Problem Solving

Within the context of task specificity, training should focus on tasks that encourage the nervous system to find its own solutions to motor control problems.[22,23] This training can be done by organizing practice so that it involves the use of a variety of objects arranged in several different orientations. Thus, the emerging arm movements would be related to the affordances of the objects that are to be manipulated in the environment.[24,25] Better motor learning occurs when practice conditions allow the learner to find the best motor solutions based on the kinematic redundancy of the system.[10] Plasticity also is enhanced by using enriched training environments that engage cognitive abilities of the learner (eg, problem solving) as well as those that increase the motivation to succeed in the task, particularly after brain injury or disease.[26] Cognitive factors such as attention deficits and visual spatial neglect, executive dysfunction, and lack of awareness are major barriers to recovery.[27] Effectiveness of rehabilitation approaches involving different modalities, such as visual search training, phasic alerting, eye patching, prism adaptation, or cognitive imagery, show a differential impact on functional outcomes,[28] suggesting that activation of sensory and cognitive processes is essential for recovery.

Learning Is Experience-Dependent and Related to Feedback Delivery

Enhanced learning occurs when participants practice a variety of related tasks and receive feedback intermittently to allow time to integrate sensory information into movement.[29] Motor learning also is largely dependent on the type and intensity of practice as well as on the environmental context in which practice occurs.[9] These key motor learning elements need to be integrated into rehabilitation paradigms aimed at motor recovery to maximally engage neuroplastic mechanisms.

† In other words, there are more kinematic degrees of freedom (DOF) than are necessary to perform a movement task. Take the example of how we move the arm from one position in space to another. Each position is characterized by 3 coordinates of the hand in space (horizontal, sagittal, vertical), and the arm has 7 angular DOFs (3 shoulder, 1 elbow, 1 forearm, and 2 wrist). To move the hand, the central nervous system shifts the hand position from one 3-coordinate location in space to another by rotating a large number of DOFs (7 DOFs of the arm and 3 DOFs each of the scapula and trunk). Normal movement is characterized by the ability to solve this redundancy problem because of prior experience with similar tasks. However, in the brain-damaged system, the mechanisms by which the redundancy problem may be solved may be impaired, as evidenced by decreased redundancy due to limitations in the regulation of stretch reflex thresholds at particular muscle groups.[73] Another manifestation of reduced redundancy is the presence of abnormal flexion or extension synergies and the recruitment of the trunk, an additional DOF, to compensate for the lack of redundancy in upper limb arm joints.[3]

Enriched Training Environments to Enhance Motor Learning

Normal movement production requires the integration of multiple sources of sensory information occurring at different levels of processing.[30] Multisensory processing of relevant proprioceptive, sensory, and visual information in the parietal lobe, for example, contributes to perception and is linked to action execution in peripersonal space.[31] On the other hand, contradictory tactile and visual information may hinder effective cross-modal integration and result in perceptual illusions.[32] Overall, in the intact nervous system, multilevel sensory interaction is used to shape movement and improve motor learning.[30] This approach also may apply in the damaged nervous system, where, for example, enhanced somatosensory input associated with hand use was shown to increase cortical excitability and to potentiate neuroplastic changes in people with stroke.[26] However, a large proportion of people with ABI have deficits in multiple sensory processing (eg, cutaneous sensation, proprioception, vision),[33] and it is unknown to what extent such deficits may interfere with their ability to learn new motor skills and to physically interact with the environment.

Better rehabilitation outcomes are likely to occur by integrating principles of motor control and motor learning involving relevant multimodal sensory feedback and cognitive processes.[9] Rehabilitation approaches using a range of low- and high-technology simulations can potentially provide rich exercise environments that entice patients to work longer, harder, and more often and solve motor control problems. Specifically, tasks practiced within virtual environments aim to enhance motor skill learning through the integration of multiple sensory processes such as proprioceptive, visual, auditory, and vestibular information with the engagement of cognitive processes. Simulated training environments have the potential to enable manipulation of multiple types of feedback to maximize motor learning. Thus, training in virtual environments is designed to enhance conventional therapy by providing a tool to deliver more intensive and enjoyable therapy.[34]

VR System Characteristics

Virtual reality is a continually developing technology used to simulate an engaging environment that users experience as being comparable to the real world.[35] The use of enriched virtual environments in rehabilitation was previously limited by the lack of inexpensive, easy-to-use systems that promote the use of valid movement patterns. Development of such platforms with more user-friendly software launched a wave of potential applications for medicine and rehabilitation.[36,37]

Virtual environments allow behaviors to be measured during challenging but safe and ecologically valid tasks while control is exerted over stimulus delivery, feedback, and measurement in real time.[37,38] They can be created and displayed on platforms that range from simple two-dimensional (2D) displays to more "immersive" 3D displays. In many VR and video gaming applications, visual feedback is supplemented by auditory cues that provide information about task completion. For upper limb sensorimotor rehabilitation, users may interact with virtual objects directly via hand gestures and body movements or through haptic or nonhaptic interfaces (eg, glove, joystick, mouse) and perform actions that engender a feeling of "virtual presence" in the simulated environment (ie, engendering user performance that is similar to what would occur in the case of comparable real-world stimuli).[39]

Tactile feedback may be incorporated into VR applications for upper limb training via haptic gloves or robots to provide appropriate sensory information during object manipulation and to avoid sensory conflicts.[40] However, to date, the technology available for feedback delivery has several caveats. Vibratory or force feedback delivered by haptic gloves that are lightweight and easy to don and doff such as the piano-touch glove[41] have poor position tracking, which may affect the relevance of the tactile feedback. More accurate force feedback devices such as the Cyberglove/grasp system (CyberGlove Systems LLC, San Jose, California) are cumbersome and may modify movement characteristics.[42] Thus, use of this technology for rehabilitation of sensory and motor function of the hand remains limited but continues to evolve as technology advances.

Validity of Movements Made in VR Environments

An important issue when evaluating the impact of VR movement retraining with respect to transfer of gains to real-world situations is determining the validity of movement kinematics made in different 2D and 3D VR displays. Improvements in upper limb motor performance are usually measured in terms of endpoint kinematics in which better movements are faster, more precise, and smoother, as well as in the quality of movement or the magnitude and coordination between movements of the individual body segments (joint range of motion, interjoint coordination, and compensatory movements).[43] Upper limb movements made in 3D VR are reportedly more similar to those made in physical environments than those made in 2D VR. Knaut et al[44] and Subramanian and Levin,[45] for example, compared

Table 1.
Principles of Motor Control That Can Be Incorporated Into the Design of a VR Training Environment and How They Can Be Implemented by Using the Affordances of VR Technology[a]

Motor Control Principles That Can Be Incorporated Into Task Practice	VE Design to Enable Implementation of Motor Control Principles
The difficulty of the task takes into account both the speed and precision of the intended movement (Index of Difficulty, Fitts' Law[13]) such that movements made rapidly to small targets are more difficult than those made slowly to large targets. The organization of the movement (ie, number of joint degrees of freedom, timing, and coordination of joint rotations) is related to the location and distance of the object from the body. Movements made to the contralateral arm workspace (when the arm crosses the midline) are more difficult than those made to the ipsilateral arm workspace in patients with stroke.[76]	Virtual objects should be adjustable so that task difficulty can be graded according to Fitts' Law. An example is the Pixel Waves game in the Jintronix (Jintronix, Montreal, Canada, http://www.jintronix.com) system that allows the therapist to manipulate object size and location. Tasks should involve interacting with objects placed at different distances from the body as well as in different locations in the workspace (contralateral, midline, ipsilateral) to encourage the coordinated use of different combinations of arm and trunk segments. An example is the IREX (http://www.gesturetek.com/) and SeeMe (http://www.brontesprocessing.com/health/SeeMe) video-capture systems that allow the therapist to program where objects will appear.
The organization of the movement is related to the quality of the viewing environment that affects the perceived distance of the object from the body, as well as visual cues of the user's arm and the interaction of the arm with the object.[77]	The VE should include 3D visual cues such as perspective lines, shading, and drop lines to improve depth perception. Some computer games such as Jintronix and CAREN (http://motekmedical.com) incorporate visual illusions to create 3D effects. Other systems do not, such as video-capture and commercially available games.
The orientation of the hand for grasping and, as a consequence, the hand path trajectory during the reaching phase of movement are related to the location, size, and orientation of the object to be grasped.[78]	Objects included in a VE should be of various shapes, sizes, and locations. As hand tracking and haptics are not usually incorporated into VR applications, this requirement is not always met.
The organization of a reach-to-grasp movement depends on the affordances of the object and what the user intends to do with the object.[24]	Tasks involving grasping should have purposeful goals. Despite the lack of control over the grasping component, most VR applications include task goals such as Kitchen Clean by Jintronix and VMall in SeeMe.
Salient feedback about motor performance (eg, quality of movement, joint ranges used) is essential to improve motor behavior.	High-fidelity visual and auditory as well as tactile feedback can be incorporated into VEs. Most VR applications provide continuous visual monitoring. Additional feedback is provided in Jintronix as KR about task success (precision) and negative KP about trunk use. Most applications also provide a game score and time score without specific feedback about task performance or movement quality.

[a] VR=virtual reality, VE=virtual environment, 3D=three-dimensional, KR=knowledge of results, KP=knowledge of performance.

pointing movement kinematics into different parts of the arm workspace in a physical environment with those made in fully immersive 3D VR viewed through a head-mounted display or on a large screen display. For healthy individuals, precision was higher and trajectories were straighter in VR when pointing to targets located in the contralateral arm workspace, but movements were slower for all VR targets. Movements made by individuals with stroke also were slower, less accurate, and more curved in VR. Overall, when wearing the head-mounted display, people used less compensatory trunk displacement during reaching in VR. The results differed in the stroke group depending on the level of stroke motor impairment.[45]

Principles of Motor Control and Motor Learning as Implemented in Enriched Training Environments

The basic aspects of motor control including movement planning, redundancy, task specificity, problem solving, and experience outlined above can be implemented as guidelines for the organization of practice in both VR and conventional training environments. Some of these guidelines and their practical implications specifically for enriched training environments are outlined in Table 1.

From a motor control perspective, enriched training environments can enhance recovery by manipulating the workspace area as well as the level of precision and speed required for the arm to successfully interact with virtual objects. Specific manipulation of these variables can enhance recovery by training the system how to find solutions to motor problems, such as the redundancy problem, in a task-specific manner. Task difficulty (movement speed, accuracy, and complexity) should be programmable via a user-friendly

Table 2.
Outline of the Principles of Motor Learning, Including the Use of Tactile Cueing and Feedback That Can Be Incorporated Into the Design of a Virtual Reality Training Environment and How They Can Be Implemented by Using the Affordances of Virtual Reality Technology[a]

Principles of Motor Learning	Application of Motor Learning Principles
Learning occurs through repetitive, varied practice of meaningful tasks	Tasks should include multiple repetitions of different movements. Game goals should be meaningful to the user.
Learning occurs when task difficulty is progressively increased according to the user's ability	Adaptive routines or clinician-selected difficulty levels should associate task difficulty with ongoing abilities of the user. Decision rules should identify optimal times for increasing or changing task difficulty based on the ability of the user and progression through difficulty levels.
Learning should include problem solving in order to engage cognitive and executive function mechanisms	Tasks should be varied in their level of problem solving to challenge different cognitive and meta-cognitive abilities
Learning occurs when the individual is motivated to improve	Presentation of game scores and use of techniques to enhance virtual presence (eg, ambient and directed feedback) should be used to motivate individuals
Sensory feedback that is related to the task is necessary for learning (eg, haptic feedback from the fingers when an object is touched)	Multimodal sensory feedback should be explicitly mapped to patient performance and progression through difficulty levels
Learning occurs when an individual receives positive feedback about task performance (KP) and task accomplishment (KR)	Both KP and KR should be presented to the patient during task practice
Learned bad-use can be avoided by providing salient negative feedback to limit movement compensations made during the task, especially excessive trunk displacement (KP)	KP of maladaptive performance should be presented to the patient in a way that does not disrupt task performance

[a] KR=knowledge of results, KP=knowledge of performance.

interface by the clinician or should adapt automatically in real-time (via computer algorithm) to changes in patient performance.[46,47] Many motor control principles have been intuitively incorporated into VR applications without specifically being manipulated. For example, activities requiring the user to intercept stationary or moving objects with their hand in various parts of the screen exploit the principle of task-specific motor planning and problem solving within a kinematically redundant motor system.

From a motor learning perspective, the goal of training is to harness neuroplastic mechanisms that support acquisition and retention of new motor skills. *Neuronal plasticity* refers to the regeneration or reorganization of neuronal structures in response to injury or practice. Measurable parameters that have been explored in motor learning include repetitive and varied practice, progression of task difficulty, problem solving or error correction, motivation, and the quality and frequency of feedback (Tab. 2). Virtual reality lends itself well to the application of such principles, given its capacity to encompass task-specific training, appropriate exercise intensity and repetition, and salient experiences.[9]

Exercise Repetition and Task Progression

Virtual reality is a flexible technology that supports high-intensity, repetitive training that is often found to be motivating, engaging, and enjoyable.[48] Virtual reality systems can be tailored to the individual needs of the learner to include meaningful, challenging, and progressive exercises that can be carried out in a variety of settings. Movement behavior can be modified in training with only small changes in the task kinematics, and kinematic variables can be related to training goals so that the motor learning can be made task specific. For example, training with virtual activities that required integrated hand and arm movements versus activities that required separate hand and arm movements produced different kinematic outcomes in the upper limb of individuals following stroke.[47]

Matching task difficulty to the skill level of the performer is an important factor for the prevention of frustration, boredom, and fatigue when engaging the learner in a repetitive exercise program.[48] It is not evident how precisely matched each repetition of a functional activity must be to promote optimal motor learning,[49] but the principle of kinematic redundancy[10] suggests that kinematics need to be varied for the system to learn a variety of possible movement solutions and to sustain attention. Attention and motivation can be maintained by progressively increasing task difficulty as the performer improves. In one application, this approach was taken through the presentation of a "paretic" virtual arm that performed tasks varying from simple (hitting objects) to complex (grasping and moving objects). Changing the effort requirements of the nonparetic limb assisted with motion of the paretic virtual limb, and patient motivation was optimized through graduated task success.[50]

Appropriate Sensory Array

Repetition refers to the number of times a particular behavior is practiced, but task specificity may be equally important.[9] Specificity for task learning has been examined through VR protocols that examined visuomotor discordances between an imitation of a moving virtual hand and an actual hand. Attempts to mirror the virtual hand were shown to facilitate activity in select brain networks that may support motor relearning via the action-observation network.[51] In the early stages of recovery from traumatic brain injury in individuals who are severely impaired, a “virtually minimal” approach was taken using robot-rendered haptics in a virtual environment.[52] Patients were assisted with repetitive reaching toward targets that were both seen and felt through gentle haptic cues. As training progressed, patients increased the number of targets acquired and gradually improved in their attention to the visuomotor task. Thus, motor learning in VR can be similar to the physical world where synchronicity between the action and the sensory array supports cortical representation for subsequent production of movement.[53] However, exact replication of a single trajectory may not lead to optimal recovery because of the kinematic redundancy of the system, and a hallmark of recovery of normal movement is the ability to reproduce a movement using a variety of joint rotations.

Problem Solving and Feedback

Sensorimotor learning is based on the principle of minimization of end-point error.[49] One reason to expect that training in VR supports motor learning is that the performer must resolve differences between sensory signals, thereby requiring active error correction.[54,55] For example, motion of the visual field of view may not match motion of the performer, thus producing a difference between visual and vestibular feedback requiring a corrective movement.[56] Virtual reality also can use augmented feedback to focus the attention of the learner on movement details that are the most relevant to the task. Training protocols can incorporate multisensory (auditory/visual) feedback as well as KP feedback about undesirable motor compensations. An example of the latter is the incorporation of a “buzzer” sound that occurs when a patient uses excessive trunk compensatory movement during a reaching task in the virtual environment.[57] Thus, virtual reality applications can incorporate positive or negative KP about desirable/undesirable movement patterns while tasks are being performed in order to address rehabilitation goals. In another study, performers who received augmented feedback while learning a multijoint table tennis movement in a virtual environment performed significantly better on the real-world task than those who received a comparable amount of real-world task practice or coaching.[58]

Virtual reality technology can use haptic gloves and robots to supply appropriate feedback for motor learning, although this equipment adds to the cost of the systems.[40] For example, participants with chronic hemiparesis were trained with haptic forces via a robot and graphic distortions via a virtual environment to amplify upper limb tracking errors.[58] Small but significant improvements in Fugl-Meyer Assessment and Wolf Motor Function Test scores emerged following 2 weeks of training with error augmentation compared with simple repetitive practice.

Motivation and Reinforcement

One reason VR has become a popular therapeutic tool is that it is generally believed to support repetitive practice because it is fun to engage in the game-like virtual activities.[36] Positive reinforcement is fundamental to motivating an individual to perform a particular motion or task repeatedly. Exercise can be presented in a gaming environment, and virtual environments have been created that support the performance of activities of daily living, including kitchen skills,[59] reaching skills,[57] street crossing,[60] shopping,[61] and social interactions.[59] Individuals in the acute stage of stroke who participated in a therapeutic gaming system over 12 weeks in addition to conventional therapy displayed significantly improved performance in paretic arm speed that was matched by better performance on the Fugl-Meyer Assessment and the Chedoke Arm and Hand Activity Inventory compared with a control group receiving occupational therapy or nonspecific interactive games.[46]

Positive reinforcement derived from a simple message or symbol indicating that the task was performed correctly encourages a performer to keep going. Although the image of a smiling face or the phrase “nice job” may motivate continued performance, it is unlikely to be precise enough to produce real learning. Indeed, a study that analyzed the direction of gaze during exercise showed a reduction in the time spent paying attention to the video feedback across sessions.[62] When the video feedback was associated with music, however, participants became more focused on the task for longer periods. Thus, sensory feedback linked to the actual task performance may generate more accurate repetition than indirect verbal or visual reinforcement. In a study by Subramanian et al,[57] provision of knowledge of results feedback in the form of a game score provided an added motivation to the participants to succeed in the task.

Transfer of Training Effects to Real-World Situations

If we are to determine that VR is an effective tool for motor relearning, we need evidence that skills learned in the virtual environment can be transferred to the physical environment and other tasks. Few studies have addressed some of the important indicators of motor learning such as long-term retention of motor gains, transfer of training effects, and generalization.[58] In one study, daily exercise of participants with cerebral palsy using a sensor glove that activated a screen avatar of their hand resulted in improvement of general hand function outside the virtual environment,[63] but more evidence for generalization is needed.

An example of skill transfer is provided in a study by Katz et al[60] that demonstrated the potential of using a desktop-based VR system for rehabilitation of poststroke unilateral spatial neglect. They compared training on a 2D VR street-crossing task with a standard computer-based visual scanning task in 19 patients with right hemisphere stroke divided into 2 groups. Although improvements in standard neglect testing were similar between groups, the VR group transferred street-crossing skills better to the real-world situation. Two-dimensional video-capture VR systems also have been used to assess and treat cognitive and motor deficits with similar beneficial effects compared with conventional treatment.[64,65]

Different functional virtual environments that simulate complex shopping tasks controlling for the type, speed, location, and direction of stimuli also have been developed that record performance variables. One (CAREN, Motek Medical BV, Amsterdam, the Netherlands, http://motekmedical.com), simulating a virtual mall consisting of 3 stores,[61] and others (eg, GX, GestureTek, Toronto, Ontario, Canada, http://www.gesturetek.com/), simulating a supermarket, have been used for training upper limb and executive functions poststroke.[66,67] These studies suggest that virtual shopping environments may offer effective ways to meet rehabilitation goals of increasing participation by improving the ability of the person to function in the real world. Some upper limb studies have shown improvement in complex everyday activities in addition to immediate improvements of performance.[67,68]

Despite the caveats related to the validity of movements made in different VR environments, studies suggest that movements acquired through practice in VR may transfer to meaningful real-world function.[69] Thus, it may not be essential for there to be exact reproduction of real-world movement kinematics in VR training situations for improvements in clinical motor function to occur. Indeed, it is unknown to what extent the joint rotations used to produce movements affect functional motor recovery. The potential for transfer of training gains may be related to other advantages afforded by VR, including the provision of meaningful feedback to the user within enriched virtual environments. Overall, VR permits the manipulation of important task (difficulty, ecological validity) and individual (motivation, enjoyment, adherence) variables during rehabilitation.[37]

Limitations of Using VR to Implement Motor Learning and Motor Control Principles

The evidence of the effectiveness of VR in terms of motor learning (retention, transfer, generalization to real-world situations) is still in its early stages. One of the drawbacks is that explicit information used to accomplish the tasks is not always provided and users may inadvertently reinforce nonoptimal or compensatory movement. This limitation is particularly problematic when off-the-shelf gaming systems (eg, Nintendo Wii, Nintendo, Redmond, Washington; Microsoft Kinect, Microsoft Corp, Redmond, Washington) are used. These games and tasks were designed to be used by individuals who do not have motor or cognitive impairment, and there is limited possibility to specifically manipulate feedback (although they have been used in some small-sample clinical studies).[70] The focus of the activity is primarily on task accomplishment, rather than task performance, for which an overall game score is provided. Despite extensive research and promising results of VR for rehabilitation, a recent review concluded that it also is still unknown what type or combination of feedback will best enhance upper limb motor function.[71] These challenges, as well as the challenge of providing evidence that VR training leads to changes in participation outcomes and activities not trained in the virtual environment, are yet to be met. A final challenge is the integration of novel technologies such as Microsoft Kinect into clinical practice.[72] Even with all of the affordances of VR, it is ultimately the clinician who needs to set the treatment program to take advantage of the technology in client-centered ways.[72,74]

Concluding Remarks

In summary, there is a growing body of evidence that illustrates how enriched virtual environments may be used as a therapeutic training tool in which many principles of motor control and motor learning can be incorporated to provide a learning experience tailored to individual clients. The flexibility of the computer environment allows the clinician to target specific motor control deficits and to provide meaningful feedback that encourages motor learning based on motor control principles of movement organization. A review of both off-the-shelf and customized technologies applied to motor rehabilitation[37] concluded that a range of VR technologies provide therapeutic interventions within a functional, purposeful, and motivating context. It is important to bear in mind, however, that the potential of VR to meet motor control and motor learning goals has not yet been fully realized.

Several important challenges remain to researchers who develop and evaluate applications of VR for rehabilitation. First is the need to identify which clients are most likely to benefit from enhanced training via VR technologies. Much of the research has been conducted on clients in the chronic stage post-ABI, so the potential for VR to drive early neuroplasticity is still unknown. In addition, VR-based movement therapy may not be appropriate for clients who have little motor recovery, but the level of the severity cutoff has not been identified. Virtual reality–based motor therapy also may be of more limited benefit to those with severe cognitive or visual field deficits, including neglect and apraxia, unless the virtual environment is adapted to meet their specific abilities. Second, there is no clear consensus about how often a task needs to be practiced in a virtual environment in order to be learned. One systematic review[75] showed that training sessions could vary in duration from 20 minutes to a maximum of 3.5 hours. Training occurred 3 to 5 times per week and lasted from 2 to 6 weeks to 11 to 13 weeks. Rehabilitation benefits resulted in all of these studies, implying a strong likelihood of positive effects with VR as a rehabilitation tool even with varying dosages.

Finally, some areas of rehabilitation that have not been extensively addressed using VR are sensory re-education and hand function. Despite these limitations, VR has been shown to be a flexible technology that can be continuously modified to meet the needs of the individual. Novel methods of augmenting feedback and grading the intensity of the task demands in the virtual world continue to show great promise for effective interventions.

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