Feedback and virtual environments for motor learning and rehabilitation

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The aim of this paper is to describe how environments created using virtual reality (VR) technology have been used to improve upper limb function following neurological disorders and in particular, stokes. The results provide encouraging evidence for the effectiveness of feedback delivery to perform a reaching task in a VR environment used in individuals with post-stroke hemiparesis.

Le but de cet article est de décrire comment des environnements créés à partir des techniques de réalité virtuelle peuvent être utilisés pour l’amélioration des fonctions des membres supérieurs suite à des disfonctionnements neurologiques, en particulier à la suite d’un accident vasculaire cérébral. Les résultats obtenus sont encourageants en ce qui concerne l’efficacité des systèmes de rétroaction obtenus dans un environnement virtuel, chez des patients hémiparétiques effectuant des tâches d’atteinte.

1 Incidence of upper limb movement disorder in stroke

Neurological disorders and in particular, stroke, are highly prevalent in the western world (>750,000 in the United States - NINDS website, 2008 statistics, http://www.stroke.ninds.nih.gov/, accessed on October 20, 2008). An increasing number of stroke survivors return home after acute hospitalization (69% in 2002 compared to 64% in 1988) with fewer requiring long
The prevalence of stroke survivors with incomplete recovery has been estimated at 460/100,000 [CAR 00]. Thus, motor deficits following stroke may contribute significantly to the incidence of physical impairments and activity limitations in the adult population [HUM 97; MAY 96].

Rehabilitation is viewed as a process by which individuals with motor and cognitive impairments achieve functional independence. After a stroke, survivors relearn how to move successfully to carry out their basic needs. They practice the re-attainment of skills, which crucially depends on motor learning. While rates of motor recovery of the trunk and limbs may coincide over the first three to six months post-stroke, absolute recovery of lower limb function is greater than that of the upper limb [VER 08], [DES 03]. For the upper limb, there is mounting evidence that functional recovery of arm paresis can occur well into the chronic stage of stroke (e.g., [MIC 06]). This may be attributable to sensorimotor learning and adaptive plasticity in the remaining cortical and subcortical brain tissue [NUD 07].

2 Distinction between motor compensation and recovery

One explanation for reduced functional recovery in the upper limb may be the focus of therapy on task accomplishment rather than the quality of task performance. For example, the goal of therapy may be to improve a patient’s ability to reach and manipulate different items on a tabletop or a shelf. However, the performance of much of the task may be accomplished with little if any improvements in the functional reach capacity of the arm simply by leaning forward at the trunk. Thus, if the movement pattern itself is not emphasized, the therapy may reinforce alternative (compensatory) movement strategies instead of encouraging the reappearance of pre-morbid movement patterns (recovery). The primary focus of therapy should be on motor recovery rather than compensation in order to drive cortical plasticity towards the type of re-organization that will lead to better long-term rehabilitation outcomes [ALA 08].

Unfortunately, the language used to communicate changes in motor function has also led to some confusion between fundamental and clinical researchers. Specifically, the terminology used to describe changes in motor function in both animal models of stroke and human stroke has not adequately distinguished between the concepts of motor recovery and compensation. A new terminology has been proposed in a recent paper by Levin et al. [LEV 08] and a new terminology has been proposed. In the proposed terminology, definitions are provided for recovery/compensation at the neuronal or brain level as well as at the effector or performance level. At the performance level, motor recovery has been defined as the reappearance of elemental motor patterns present prior to CNS injury. In contrast, motor compensation has been defined as the appearance of new motor patterns resulting from the adaptation of remaining motor elements or the substitution of alternative end effectors or body parts to accomplish a movement or task.

Despite the problems in nomenclature, there is much debate about the extent to which functional gains result from the recovery of lost motor patterns and/or the development of compensatory movements [SUN 92] and how rehabilitation influences these processes [KRA 04], [LAT 96], [LEV 97]. The lack of clear definitions of recovery at the performance level has led to confusion in interpretation of treatment efficacy, often leading to equivocal results. Performance measures should be sufficiently sensitive to distinguish recovery of pre-morbid motor patterns from compensatory movement defined as the use of new motor patterns. An example of such a scale is the Reaching Performance Scale for Stroke which depends on observational kinematics to distinguish between movements made with and
without compensations [LEV 04]. Motor scales that assess disability/functional limitations (e.g., Barthel Index, Functional Independence Measure, etc.) rather than impairment (e.g., Fugl-Meyer Scale, Chedoke-McMaster Scale, etc.) cannot reliably make this distinction. The distinction is particularly important in interpreting the results of neuroimaging studies because compensatory strategies are also likely to cause novel activation patterns that may be impossible to distinguish from those due to neuronal recovery.

One motor compensation, increased trunk movement, may be used to assist arm and hand transport [CIR 00], [UST 04] and hand positioning/orientation for grasping (Figure 1) [MIC 04]. Although incorporation of motor compensations may improve functional ability (e.g., drinking from a cup), the task may be accomplished using atypical movement patterns at the performance level. For example, to reach for a cup, the patient may typically lean the body forward to extend the reach of the arm instead of using elbow extension and can raise the shoulder to increase the height of the arm instead of using shoulder flexion. In spite of the use of these motor compensations, a scale measuring the ability to drink from the cup would not indicate how the cup is reached. Arguably, the rehabilitative goal for stroke patients is recovery of function whether achieved through true motor recovery or compensation. It is generally agreed that for some patients with severe impairment and poor prognosis, compensatory movements should be encouraged to maximize functional ability [BAR 01].

![Fig. 1. Increased trunk movement is used to assist arm and hand transport for grasping. Examples of compensatory movement used in individuals with post-stroke hemiparesis to perform a reaching task. Examples show a top down view of the trunk (triangle), arm and hand positions at the initial position (dotted lines), at time of maximal grip aperture (dashed lines) and at time of grasping (solid lines). Movements to midline target (top: solid circle) and ipsilateral target (bottom: open circle) are shown. Subjects could successfully reach the object with the hand. Movements of the hand however, were accomplished differently by subjects with no neurological impairment (Fig. 1, left) and by those with mild and moderate motor impairment of the reaching limb (Fig. 1, middle and right). Stroke survivors could incorporate various types of motor compensations to assist arm movement, in this case, excessive trunk rotation and forward displacement, to achieve the performance goal of reaching the object.](http://www.unicaen.fr/services/puc/preprints/preprint0022010.pdf)
However, for those with good prognosis, several arguments support emphasizing motor performance recovery. First, recent research on plasticity suggests that with appropriate training, arm motor improvements can continue into the chronic stage of stroke (e.g., [MIC 04b]). Second, use of motor compensations could lead to patterns of learned non-use or bad-use limiting the capacity for subsequent gains in motor function of the paretic arm [ALA 08], [ALL 05], [CIR 06] [TAU 93].

3 Motor Learning and Re-Learning in Stroke

Motor learning is a “set of internal processes, involving both cognitive and motor processes, that is associated with practice or experience leading to a relatively permanent change in the capacity to respond” [FIT 67] [SAL 95] [SCH 99]. The definition stresses the importance of the achievement of new motor skills, improvement of previously learned motor skills or the re-attainment of skills that are difficult to perform or cannot be performed due to injury or disease [MAG 06]. Changes that occur at neurological or performance levels as a result of motor learning and the factors influencing these changes are of particular interest for the rehabilitation of motor disorders. At the movement outcome level, motor learning can be defined as movements that are faster, more accurate and less variable [e.g., PRO 94]. At the kinematic or joint level, motor learning can be measured in terms of movement smoothness (interjoint coordination) with appropriate contributions of joint ranges of motion and patterns of muscular recruitment [e.g., CIR 07].

In the intact nervous system, motor learning is supported in part by the implicit memory system [SQU 87] while the effect of explicit information in the form of feedback on implicit sequence learning has alternatively been reported as beneficial [BOY 01], detrimental [BOY 03], [BOY 04], [BOY 06], [GRE 91], [REB 76] or of no consequence [REB 98], [SHE 01]. In the intact system, skill learning can be mediated by discrete, experience-driven changes within specific neural areas subserving task performance [HAZ 97], [KAR 95], [KAR 98]. Other key elements to optimize motor learning are practice intensity [KWA 97], practice variability [PRO 94] and motivation of the learner or the environment [NUD 99], [NUD 96], [BAR 05].

4 Neural Substrates for Motor Learning

Brain structures, including the striatum, cerebellum and motor cortical regions may be critical for acquisition and/or retention of skilled movement [DOY 97], [DOY 03], [DOY 02], [GEO 00], [SAN 00]. Different cortical and subcortical networks may preferentially be involved in early- and late-phase skill acquisition [KAR 98], [PEN 02], [UNG 02]. Animal and human studies describe distinct cortical-subcortical circuits: cortico-cerebello-thalamo-cortical loop for early learning, and a cortico-basal ganglia-thalamo-cortical loop for late learning [PIC 96], [TAN 96], as well as a role for the cerebellar motor system in late learning [DOY 97], [MAT 04]. Specifically, cerebellar activation may decrease with practice, and become undetectable for well-learned movement [DOY 02]. In contrast, the striatal motor system is increasingly activated in late learning when task performance plateaus [DOY 08]. Brain imaging techniques have confirmed the functional contribution of both cortico-striatal and cortico-cerebellar systems in motor learning and have identified the neural substrate mediating dynamic memory and functional changes occurring during skill acquisition. For example, during a delayed recall task, activity increases significantly in the primary motor area, premotor cortex, and parietal lobe [GOR 98], [PEN 02], [SEI 98]. The striatal system may be involved in motor planning [KOE 02], reward-based evaluation [HIK 99], higher order
movement control [DEB 04], and execution [ZAN 03]. The cerebellar motor circuit has also been implicated in temporal aspects of movement [BOY 04], [DOY 02], [VAN 02].

Of importance to the understanding of the impact of stroke on motor learning and recovery is the observation that no single lesion or disease process completely abolishes the neural processes involved in implicit motor learning and retention. The predominant pattern of stroke damage is in the distribution of the middle cerebral artery affecting the motor cortex (M1), sensorimotor cortex and basal ganglia [POH 00]. It is important to note that the few studies examining motor skill learning in humans with M1 [BON 93], [BOY 03], [CUS 87], [PLA 94], [WIN 96] and basal ganglia [BOY 04] stroke-related damage describe performance and learning impairments that also seem to be related to the presence and level of concomitant cognitive impairment.

5 Therapeutic Approaches to Optimize Motor Recovery

Therapists use different techniques to optimize the recovery of movement in the course of rehabilitation. It has been suggested, however, that patients with neurological injury may not benefit from variable practice as opposed to constant practice until missing motor elements are recovered [CAR 87]. Indeed, motor relearning may occur differently for those with different physical and cognitive impairments [CIR 06], [CUS 87].

Nevertheless, most of the techniques used in neurological rehabilitation are founded on well-known principles of motor learning and skill acquisition established for the healthy nervous system [SHU 07]. In the healthy nervous system, optimal learning occurs when participants are motivated [NUD 99], practice a variety of related tasks [PRO 94], [WIN 99] and are given relevant feedback intermittently to allow the central nervous system (CNS) time to integrate pertinent sensory information into movement [WIN 03], [WIN 99]. For example, variables that are known to maximally influence motor learning in healthy subjects include variability of practice and feedback [SCI 99]. Task practice can be delivered on a blocked (constant) or random (variable) schedule. In a random practice schedule, the task varies from trial to trial without advance knowledge of which task is to be practiced in the next trial [PRO 94]. Random scheduling takes advantage of the nervous system’s capacity to find its own solution to the motor redundancy problem rather than to use the same solution repeated again and again [BER 67], [GHA 02], [YAN 07]. In the healthy nervous system, compared to constant practice, variable task practice is more beneficial for motor learning as shown by greater gains in retention tests and better generalization of movement principles to related new tasks [MEM 06], [PRO 94].

6 Forms of feedback and their delivery

Aside from the type of practice, the type (intrinsic or extrinsic) and delivery of feedback are important for motor learning. For example, the use of feedback was shown to motivate participants of an exercise program to adhere to intensive exercise schedules [ANN 98]. Intrinsic feedback refers to the sensory or perceptual information associated with the movement obtained by a person due to performance of that movement. Extrinsic feedback is information related to the movement in the context of the environment in which the movement is performed [WIN 96]. It is provided by an external source and is often an additive element to intrinsic sources of feedback like kinesthetic and cutaneous signals. Extrinsic feedback can be delivered by a therapist in the form of non-verbal (auditory, visual) or verbal (words like ‘well-done’, ‘correct’, ‘needs improvement’, ‘incorrect’, etc.) information,
or by the environment itself in the form of a score or other signal of task success. Extrinsic feedback can enhance or substitute for task intrinsic feedback when such information cannot be detected by the body’s sensory systems.

Whether stroke survivors can use different forms of intrinsic and extrinsic feedback to enhance motor performance and learning is of great interest to rehabilitation researchers and clinicians. While performance improvements have been documented for patients with stroke in studies emphasizing repetitive training of isolated movements [BUT 95], [DEA 97], [KUN 99], [WHI 00], few studies have addressed whether patients retain the ability to use explicit information to optimize motor skill acquisition and whether true recovery of pre-morbid movement patterns occurs. For our purposes, explicit information is defined as extrinsic feedback in the form of knowledge of results (KR) or knowledge of performance (KP). Some studies demonstrating the effectiveness of task practice have incorporated notions of motor learning (treatment intensity, type of practice, retention testing) and have taken into account arm motor severity, since the initial impairment level impacts therapeutic effectiveness [PAR 99], [SHE 01]. Studies of the role of augmented feedback on motor learning suggest that provision of explicit information before task practice may actually disrupt motor learning especially in healthy older adults and in patients with basal ganglia lesions [BOY 04], [GRE 91], [HOW 89], [HOW 92], [REB 76], [VER 94], [WIN 03]. The equivocation may result from differences in side studied (more- or less-affected limb); type of task (discrete arm movement versus movement sequence), stage or type of learning [DOY 03], lesion location [BOY 04] and explicit feedback characteristics [BOY 03], [CIR 06], [HAN 06], [PLA 94], [POH 99], [WIN 96].

Variable practice may be more beneficial than blocked practice for motor re-learning after a stroke [HAN 06]. Variable practice is one factor related to experience-dependant neural plasticity in addition to intensity of practice, task-specific practice and motivation that have been identified as pertinent to optimize motor recovery in rehabilitation approaches [KLE 08]. However, it has been demonstrated that subjects may still use unwanted movement patterns that are considered compensatory, if they do not have task- or performance-relevant feedback [CIR 03A], [CIR 03B]. Thus feedback also plays a crucial role in motor re-learning after stroke. A systematic review on augmented feedback on recovery of arm motor function in subjects with various neurological disorders [VAN 05] found that extrinsic feedback was provided most commonly in the form of biofeedback, kinetic feedback and kinematic feedback. Kinetic and kinematic feedback is related to movement variables measured during task performance. Kinetic feedback variables may be related to force and torque, while kinematic feedback variables are usually derivatives of distance and time (e.g., displacement, velocity, movement time, trajectory straightness). Kinematic and kinetic feedback can be provided in relation to either the outcome of the movement or the movement pattern itself.

7 The Role of Cognition in Motor Learning and Re-Learning

Most stroke survivors have some level of cognitive impairment [LIN 89], [MAL 04], [TAT 94], [SER 08] that may persist for months or years post-stroke [PAT 02] characterized by impaired attention and executive function with preservation of memory processes [OBR 03]. A recent review stresses that lesion site and arterial involvement can result in different cognitive deficits [DON 08]. Deficits in executive function result from anterior cerebral artery stroke affecting the medial frontal lobe regardless of the lesion side. In contrast, middle cerebral arterial occlusion in the right hemisphere may lead to visuospatial deficits affecting attention. Importantly, cognitive impairment levels seem to be correlated with functional abilities [CAR 88], [LIN 89], [TAT 96]. For example, 23% of motor performance variance in a series of upper
Fig. 2. A. One-trial learning paradigm. Subjects made rapid 50° elbow flexion movements from an initial 3° (white vertical bar) to a final 6° target (black vertical bar) without an external load. Subjects were instructed not to make corrections in the same trial but they could correct movements in subsequent trials. Behavior was considered adaptive if the movement error was corrected in one (pattern 1) or two (pattern 2) trials after load conditions changed. Behavior was considered non-adaptive if subjects took more than two trials to correct the error (pattern 3) or did not correct the error (pattern 4). B. Frequency of occurrence of adaptive and non-adaptive correction strategies. Participants are grouped into categories according to the frequency of occurrence of different correction patterns in 12-15 blocks of trials. Category 1, 2 and 3 participants used adaptive correction strategies > 60%, 40-60% and < 40% of the time respectively.

and lower limb tasks has been related to cognitive deficits [HAJ 97]. In addition, cognitive ability was third, after motor and perceptual factors, in explaining variance in post-stroke functional autonomy [MER 01].

The link between cognition and motor function is well established in older adults and in some studies of simple upper limb reaching tasks in stroke patients [DAN 02], [CIR 06]. In the upper limb of chronic stroke survivors, Dancause et al. [DAN 02] demonstrated that the level of severity in attention and executive function was related to motor learning problems during a Fitt’s like task. Using a “one trial learning” paradigm, patients performed rapid elbow flexions while moving the hand between two targets (Figure 2). A spring-like load was
Fig. 3. A. Experimental reaching task to evaluate performance variables (precision, movement speed, movement smoothness) and movement quality (ranges of joint motion, interjoint coordination). B. Histogram showing that patients with stroke who received feedback about movement precision improved this variable while other two groups did not. Group KR received knowledge of results about movement precision; Group KP received knowledge of performance about elbow and trunk movement and Group C (control) received no feedback. Asterisk (*) indicates significant difference at the p < 0.05 level.

randomly and unexpectedly introduced while the hand moved towards the target and correction strategies were identified and quantified. Patients with greater cognitive deficits took longer to correct movement errors or had incomplete error correction. In a separate study, in order to understand how cognitive deficits may impact the ability of stroke patients to use explicit feedback, the effects of motor task practice were compared in groups of stroke patients receiving different types of feedback (KR, KP, no feedback) [CIR 06]. After practice, all groups made some motor improvements but importantly, the benefits of enhanced feedback were parameter-specific. The KR group who received information about movement precision improved this aspect of movement while those in the other two groups did not (Figure 3). Patients in the KP group improved movement variables (joint range, interjoint coordination, trunk displacement) and transferred these gains to a different pointing task (transfer task). All participants could use simple KR feedback to improve motor outcomes.
regardless of cognitive deficits. However, the ability to use information about movement performance (KP) was related to verbal and visuospatial memory processes, attention and mental flexibility. Results of this study suggested that 1) patients with hemiparesis could make use of feedback to improve motor performance; 2) the type of learning and improvements were accomplished differently depending on the type of feedback received; 3) learners with better memory, attention and decision-making benefited the most from receiving KP. These results further suggested that cognitive impairments following stroke may impact the capacity to use information to improve motor function. Further studies in this area are needed in order to determine which patients may benefit the most from which types of interventions and feedback delivery approaches.

8 Training Environments to Optimize Motor Recovery

Different levels of motivation inherent to the task as well as elements satisfying the principles of plasticity [KLE 08] and motor learning (e.g., conditions of practice and forms of feedback), can be effectively incorporated into environments created with virtual reality (VR) technology. VR is a multisensory experience in which the learner is immersed in a computer-generated environment. Using VR, environments and tasks can be individualized to the motor abilities and preferences of the learner, as well as to the goals of therapeutic intervention. The added value of using VR as a therapeutic medium is that it potentially enhances the degree of interaction between the patient and the therapy to limit boredom, fatigue, lack of enthusiasm and lack of cooperation which may negatively impact on the learner’s engagement and on the intensity of practice [TIN 89].

Motor learning can be facilitated using VR environments because of the ease with which visual, auditory and haptic/tactile extrinsic feedback to the participant can be adapted and manipulated (see SVE 06 for review). Aside from novel forms of feedback, VR environments can provide ecological validity, enjoyment, novelty and challenging and rewarding task practice which have also been linked to successful rehabilitation [RIZ 05], [WEI 06]. An advantage of using VR is to offer more interesting practice environments for motor rehabilitation in order to enhance the intrinsic motivation of the learner which has been shown to lead to better rehabilitation outcomes [KAU 86], [GRI 93], [MAC 00]. Individuals who are intrinsically motivated and believe in their physical ability adhere better to therapy, put greater effort into the activity and challenge themselves more to achieve the desired outcome.

Different forms of VR have been used to improve upper and lower limb function in neurological patients [HOL 99], [BRO 02], [MER 02], [DEU 04], [VIA 04], [ADA 05], [PIR 05], [BRY 06], [SUB 07]. To evaluate the effectiveness of feedback delivery on upper limb motor recovery in a VR environment, we created a 3D virtual environment having the same physical dimensions as a physical environment (Figure 4) [KNA 09]. Healthy and stroke subjects pointed to a series of six targets placed in the frontal workspace of the arm, in a random order (i.e., variable practice). In this environment, the subjects viewed an avatar or a computer representation of their own hand interacting with the environment in a first person view. This is similar to viewing a representation of the hand movement on a computer screen such as when one interacts with a computer via a mouse but is different from other forms of VR, such as video-capture systems (e.g., [KIZ 05]), in which an image of a body part or whole body may be seen (Figure 5). In our VR environment, Knaut et al. [KNA 09] showed that the kinematics of the reaching movements to targets placed in the central and ipsilateral parts of the arm workspace made in the physical and virtual environments were suitably equivalent, validating the use of the VR environment as a practice medium.
This environment was subsequently used to evaluate the effectiveness of different types of feedback delivery on motor recovery of the upper limb in subjects with post-stroke hemiparesis [SUB 07]. For the intervention study, extrinsic feedback was delivered in the form of KR about movement speed and precision, and KP about the quality of the learner’s movement patterns. In both environments, KR about movement speed and precision was provided in the form of a sound when the reach was both as fast and as accurate as specified. In the VR environment, in addition to the sound, the target changed color to indicate a successful reach. KP about the use of compensatory trunk movement during reaching was delivered as a different sound indicating that too much trunk movement occurred. This also occurred in both environments but in the VR environment, additional KR was available since the learner could also see that the reach was not successful. An added feature of the VR environment was the display of a game score that counted the number of successful reaches that met the criteria for movement speed and accuracy without trunk movement. This added information contributed to the learner being able to challenge him/herself to do better in each block of trials. Thus, it was possible to devise training environments in physical and virtual environments that provided the learner with salient feedback about the features of the results of movement (KR) and movement pattern (KP) that would contribute to more effective motor learning of the reaching task. In addition, performing the exercise of repetitive reaching in the VR environment provided the learner, in addition, with a challenging task performed in a novel and ‘fun’ environment.

Initial results of this training in six patients with chronic stroke and mild to moderate cognitive impairment suggest that practice of arm movements in a 3D VR environment led to greater improvements in arm joint ranges than equivalent practice in a physical environment. This was especially true for shoulder flexion range. In addition, the KP feedback provided about forward trunk displacement was sufficient to reduce compensatory trunk use while reaching. This latter result was surprising given that recent studies have only shown significant decreases in excessive trunk use during reaching in stroke survivors when the trunk was physically restrained, thus providing the system with a mechanical advantage for producing arm movements that were isolated from the trunk [MIC 06], [WOO 09]. Several interesting
observations can be made about these findings. First, using extrinsic feedback alone, the
damaged nervous system was able to reorganize the arm reaching movement patterns. Second, the patients were in the chronic stage of stroke and were thus not expected to show much improvement in movement patterns. The fact that gains in shoulder and elbow ranges were made in light of these observations following a short-term intensive intervention, thus suggests that the intervention tapped into a capacity for movement that other methods could not access. Overall, the better treatment outcomes may, in part, be attributed to the enhanced feedback delivery provided by the VR environment which may have motivated the
participants to work harder to achieve the motor goal. These results provide encouraging evidence for the effectiveness of feedback delivery in VR environments. Continuing research is needed to identify the characteristics of both the learners and the environment in order to develop the most effective interventions for arm motor recovery.

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