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The Use of Technology-Supported Mental Imagery in Neurological Rehabilitation: A Research Protocol

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ABSTRACT

The human brain can simulate motor actions without physically executing them, and there is a neuro-psychological relationship between imaging and performing a movement. These are shared opinions. In fact there is scientific evidence showing that the mental simulation of an action is correlated to a subliminal activation of the motor system. There is also evidence that virtual stimulation can enhance the acquisition of simple motor sequences. In some situations, virtual training was found to be as beneficial as real training and more beneficial than workbook and no training in teaching complex motor skills to people with learning disabilities. Moreover, studies of brain-injured hemiplegics patients suggest that these patients retain the ability to generate accurate motor images even of actions that they cannot perform. Combined with evidence indicating that motor imagery and motor planning share common neural mechanisms, these observations suggest that supporting mental imagery through non-immersive, low-cost virtual reality (VR) applications may be a potentially effective intervention in the rehabilitation of brain-injured patients. Starting from this background, our goal is to design and develop a new technique for the acquisition of new motor abilities—"imagery enhanced learning" (or I-learning)—to be used in neuro-psychological rehabilitation. A key feature of I-learning is the use of potentially low-cost, Virtual Reality enhanced technology to facilitate motor imagery creating a compelling sense of presence. This paper will discuss the rationale and a preliminary rehabilitation protocol for investigating mental imagery as a means of promoting motor recovery in patients with a neurological disorder. The treatment strategy aims at evoking powerful imaginative responses using an innovative technique which makes no attempt to simulate the real-world motor behavior, but draws the patient's attention to its underlying dynamic structure. This is done by displaying highly stylized sketches of the motor behavior on a computer screen and gradually increasing the perceptual realism of the visualization. This strategy assumes that optimal learning will be achieved when the patient is allowed to elaborate his own schema and sequences of movements, thereby constructing his own personal image of the motor behavior to be trained.

INTRODUCTION

MOTOR LEARNING is generally considered as the acquisition of temporal and spatial characteristics of movement resulting from physical practice. It generally occurs after a preliminary acquisition phase of modifying and consolidating the motor program for the execution of specific movements. Learning a motor skill, in fact, sets in motion neural processes that continue to evolve after practice has

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ended. A recent study showed that newly acquired motor skills are rapidly consolidated from an initially unstable state to a more stable state, whereas neuroimaging studies demonstrated that as a result of this consolidation the brain engages new regions for performing the task.[1] Motor skills reflect the capabilities of the motor systems to plan, to coordinate and to voluntary execute movements in order to achieve specific goals. To do this several different body movements should be performed to accomplish the same action and goal.

Using imaging techniques such as PET and fMRI several authors have demonstrated how similar cortical regions are involved in imaging and performing actions.[2–5] Motor imagery may be defined as a dynamic state during which a representation of a given motor act is internally rehearsed in working memory without any overt motor output. This type of phenomenal experience implies that the subject feels himself performing given actions without executing them. Moreover, mental simulation of an action seems to be correlated to a subliminal activation of the motor system.[6,7] Linked to the previous issue there are scientific evidences supporting the hypothesis that cortical activation produced during motor imagery may affect the acquisition of specific motor skills.[8] Therefore, it seems reasonable to expect that central changes produced during motor imagery should even affect the recovery of motor functions.

Starting from this background, the goal of our work is to design and develop an integrated technique to recovery lost motor abilities using potentially low-cost technology in order to facilitate the use of motor imagery.

THE GENERATION OF MOTOR IMAGERY

It has been proposed that motor imagery might be considered as a neuronal process that involves specific brain structures. Apparently, these structures are of basic importance for cognitive control and movement's planning. They also appear to participate in the execution of actual movements mediated by appropriate executive sensory-motor regions. Converging evidence from several sources indicates that motor imagery shares neural mechanisms with processes used in motor control. Motor imagery, in fact, pertains to the same type of processes as those which are involved in programming and preparing actual actions, with the difference that in the latter case, execution would be blocked at some level of the cortico-spinal flow.[9]

At the end of the 18th century, Carpenter proposed that vividly imagined movements stimulate the muscles in the same way.[6] Some decades later, Edmond Jacobson[7] offered scientific evidence for this hypothesis by showing that imagined bending of the arm causes small contraction in the flexor muscles.

Three converging lines of evidence suggest that real and imagined movements are controlled within the same neurocognitive networks. First of all, behavioral studies in normal individuals show that the speed of imagined motor performance is highly correlated with the speed of actual motor performance,[10–14] although the speed and accuracy of imagined movements are subject to the same environmental and physiological constraints as real motor performance. The second evidence is given by neuroimaging studies that consistently found patterns of activation common to both mental simulation of motor performance and generation of overt motor movements.[3,4,13] Finally, several studies of patients' lesions in motor areas of the frontal lobe and basal ganglia or cerebellum found that abnormalities in motor imagery are qualitatively and quantitatively similar to impairments in actual motor task performance.[15–17]

Ingvar and Philipsson[18] measured the regional cerebral blood flow (rCBF) in human subjects who where instructed either to imagine a clenching hand movement with a slow rhythm, or to actually carry out the same movement. During mental simulation they found significant blood flow increasing in the premotor and frontal regions. When the hand movements were actually carried out there was mainly an activation of the same magnitude in the primary motor cortex. A later study[19] showed how, asking normal subjects to imagine a rapid and skilled sequence of digit movement, it is possible detect a significant and localized rCBF change mainly in the supplementary motor area (SMA). These results confirmed that the SMA plays an important role both for internal programming and simulation of complex motor sequences. Decety and colleagues[20] also found a bilateral cerebellum participation in an imaginative motor task using a single-photon emission computed tomography (SPECT) during motor imagery of a repetitive arm movement. Furthermore, during the mental simulation of grasping movement significant activation was observed in cortical areas and subcortical structures involved in motor behavior.[21] The mentioned cortical, as well as subcortical areas, found to be activated during motor imagery pertains to the neural network known to be involved in the early stage of motor control, like motor programming. This evidence supports the hypothesis that motor imagery and motor preparation share common neural mechanisms.

For these reasons, I-learning intend to use mental imagery to recover damaged motor function in neurological patients.

INTEGRATING MOTOR IMAGERY EXERCISES IN NEUROPSYCHOLOGICAL REHABILITATION

Recent discoveries branched from neurophysiologic research show how central nervous system responds to injury and how patients reacquire lost behaviors by training. The discovery of these physiological factors has yielded to the definition of promising new therapies for neurorehabilitation. Nowadays the conjunction of basic behavioral science with neuroscience promises entirely new approaches to improving behavioral, perceptual and cognitive capabilities after neurological damage. After injury to the central nervous system (CNS), the initial deficit in cognitive ability is frequently followed by a spontaneous recovery of function. This natural recovery may be considered as one type of functional reorganization due to brain plasticity.[22] A more recent study has shown how the recovery of neuropsychological functions is possible not only in a compensatory way but also as partial restitution of the impaired processes. Normal associative learning, in fact, evokes changes in cortical sensory and motor representation and the mechanism underlying such normal learning may be fundamental to the mechanism involved in recovery of function following acquired brain damage.[23] Nowadays neurological evidences tell us that human brain is capable of a large degree of self-repair through experience-dependent synaptic turnover and that recovery processes following brain damage share common mechanism with normal learning. Variating the experience and the inputs to damaged neural circuits would make it possible to shape synaptic interconnections and hence influence recovery.

Starting from this experimental evidences several approaches were already tempted in motor rehabilitation the different physiotherapeutic approach are proven to be fundamentally equivalent in motor recovery. Lately physical exercises were integrated with multimodal supports like proprioceptive feedbacks or rhythmic and auditory stimulation.

Many authors indicate that mental practice should be a viable tool for rehabilitative performance improvement,[24,25] and also that kinesthetic imagery should be combined with physical practice to accelerate the acquisition of motor learning.[25] There are several existing rehabilitation protocols that provide for mental imagery exercises in physiotherapeutic training. In a randomized study Page and colleagues[26,27] investigated the feasibility and the efficacy of imaginative training in rehabilitation of stroke patients founding a significative improvement in arm function and impairment reduction in general motor functions. Shortly before Fansler and his colleagues[28] have demonstrated greater improvements on balance tasks among elderly combining mental practice with physical practice.

Actually there is consistent evidence that motor imagery has a significant positive effect on motor skill learning and significant positive unilateral and bilateral transfer after mental practice has been reported.[29,30] Neurophysiological experiments demonstrated that strength increases may result from mental training–induced changes in voluntary motor programs.[31]

Starting from this evidence, a specific psychophysiological and psychomotor paradigm was developed to rehabilitate injured athletes based on the use of mental imagery with specific physical exercises.[32] In neurological patients studies of brain-injured, hemiplegics people suggest that these patients retain the ability to generate accurate motor images even of actions that they cannot perform.[21,33–35] This result suggests that hemiplegics can activate the regions of the partially damaged motor system involved in the planning of movements. This observation supports the idea that such activation can facilitate changes in computational strategy within partially damaged neural networks.

The introduction and the growth of new technologies have opened multiple innovative possibilities in the field of motor rehabilitation. In particular, there are evidences that virtual stimulation can enhance the acquisition of simple motor sequences. In some situation, virtual training was found to be as beneficial as real training and more beneficial than workbook and no training in teaching complex motor skills to people with learning disabilities.[36] Virtual technology allows the execution of repetitive learning trials offering the capacity of gradually varying the complexity of the tasks. Furthermore, virtual simulation in some specific case may support the feedbacks provided by therapist.

In I-learning, integrated approach mental imagery meets virtual reality in order to design and develop a new technique for the acquisition of motor abilities.

INTEGRATING BASIC VR WITH MOTOR IMAGERY

The use of new technologies could enhance the production of mental images in order to stimulate motor behavior. Combining new technologies, we intend to create an imaginative training for the execution of action plans and complex motor tasks. The final objective is to facilitate learning of complex motor patterns through visual-haptic mediation, using imagination. Supporting mental imagery by means of non-immersive, low-cost virtual reality applications may be a potentially effective intervention in the rehabilitation of brain-injured patients.

Until now, virtual stimulation has been used to assist learning of simple motor schema, always in laboratory conditions. No attempts have been made to apply these techniques to practical learning problems. Combining new (potentially low-cost) virtual reality technology and innovative training strategies, it will be possible to develop the capability to teach complex motor routines.

Starting from the hypothesis that virtual stimulation of motor imagery can enhance motor learning, the goal of the I-learning approach is to design and develop a new technique for recovering lost motor abilities. A key feature of I-learning is the use of VR technology to facilitate motor imagery modifying the sense of presence. Even a low cost virtual system could create a sense of presence functional for motor imagery tasks. The effect of the virtual stimulation of motor imagery on an individual sense of presence and the way in which it affects the effectiveness of learning have not yet been properly explored in a rigorous laboratory setting. To further investigate this issue, it will be interesting to evaluate how the sense of presence can influence the motor imagery in different virtual stimulations. Presence-enhancing virtual environments, in fact, can assist individuals in acquiring new skills by allowing them to view a given behavior at many different speeds and from many different viewpoints.

VR can be used to provide the user with both an egocentric and an allocentric viewpoint. By repeated exposure to successful execution of the motor pattern, users will not only become acquainted with new skills tasks and learn to mimic them, but will reinforce successful execution of the skill in their mind. This experiential learning process will help the users to achieve better understanding of correct technique before attempting to execute a given motor task. As a result, users will spend less time in trial and error learning, and acquire skills more rapidly.

The added value of I-learning is to stimulate and not to simulate the internal motor imagery of the trainee. This may require less "realism" of today's simulators. Simple interactive technologies may help to acquire new motor skills, rapidly and with more effectiveness. However technology may support something that already exists in human cognitive capacity: the possibility to create and use mental imagery.

RESEARCH PLAN AND EXPECTED RESULTS

The general idea is to integrate physical and imaginative protocols already present in rehabilitation with low cost new interactive technologies. The new rehabilitative protocol basic idea is to evoke complex motor task through multisensorial stimulation. The trainee is not yet a passive observer of motor behaviors but becomes "an active mental images creator" supported by new technologies. For that reason, it will be important to choose novel forms of virtual reality technologies to support powerful imaginative motor response.

Until now, VR applications have used immersive technologies, such as head-mounted displays coupled with head-tracking sensor. This modality has the advantage of producing a strong feeling of immersion, but it results to be too much invasiveness and may produce "cybersickness" symptoms. For these reasons we think it's not a good hardware solution especially for neurorehabilitation. I-learning intends to propose a "Powerwall" system that consists in a configuration of DLP projectors, passive stereopsis and optical (wireless) head-tracking. This hardware configuration should guarantee fully interactivity and a high sense of presence, giving at the same time freedom of movement to the participant. These hardware devices will help patients to create an internal model of desiderable motor behaviors modifying pre-existing motor schemas without interfering with motor execution.

Within this hardware package we intend to develop specific software that will be able to support imaginative training. The training could be customized according to the motor primitives to be trained. The idea is to allow the patient to have both an allocentric and an egocentric view of the movement to be trained.

Possible strategies for the definition of the rehabilitation protocols

The protocol will implement different learning modules, each targeting a specific motor learning phase. It should also be necessary the integration possibility of different levels of task complexity. An actor voice will be used to instruct the patient about how to create realistic mental images of a predefined scenario and then ask him/her to imagine specific motor exercises that are congruent with this scenario. The imaginative scenario created will be supported by a multisensorial stimulation and the imaginative scenario will be augmented by virtual reality egocentric stimulation. At the end of a supported imaginative training, participants can physically practice the motor behavior.

The protocol is articulated into three main subphases (Fig. 1). In each phase, specific technological tools are used to support I-learning motor imagery strategies. In the first main phase, called "motion tracking and setup phase," the patient is required to perform a movement in order to acquire fundamental parameters of pre-selected motor actions. In this manner, it is possible to construct patient's personal image of the motor behavior to be trained. This is possible subdividing these movements into geometric primitives and using these primitives to create the geometric model of the movement. It will be necessary to display highly stylized sketches of the motor behavior on a computer screen and gradually increase the perceptual realism of the visualization. In a specific pathology like hemiplegia, for example, it is also possible to display the mirrored image of the movement performed with the healthy limb and increasing gradually the visual realism cues. In this first main phase, it is very important to synchronize movement's keyframes with multimodal feedbacks.

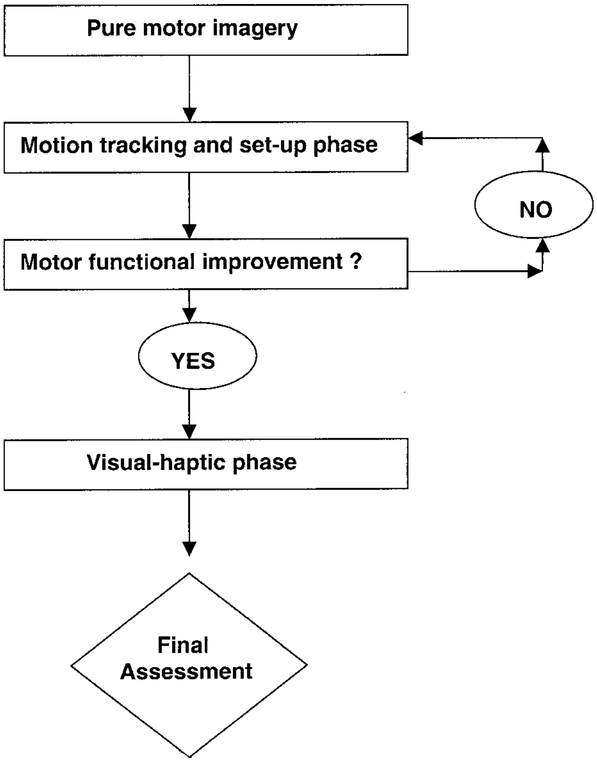

FIG. 1. Structure of the rehabilitative protocol for brain-injured patients presenting partial motor deficits.

During motor learning, in fact, in order to coordinate physical skills, the subject has firstly to memorize the reaction patterns associated with each primary stimulus involved in the skill. In motor rehabilitation a motor impaired patient generally does this by directing his body through the appropriate coordinated sequence of primitive actions whenever the trainer presents to him an appropriate stimulus. Generally, he has lost the specific capacity to guide his association of the desired physical response with the stimulus. Also, he could not be skilled in interpreting where his reactions went wrong. His own procedural motor path and unskilled guidance is awkward, and is limited by his highercenter capability for remembering what should be done, and at the same time consciously controlling his body, monitoring its performance, and establishing corrective changes in his mental and physical processes. In rehabilitation the trainer, observing the subject's progress, can help considerably in suggesting changes in his way of doing things. But these changes still have to be envisioned accurately by the subject and integrated into his other conscious controlling activity by highercenter processes. If the action is quite complex to refine learning process the trainer can provide feedback cues about the changes that should be made, and let the subject try to incorporate these cues in succeeding practice trials. The general idea of I-learning is to relieve the load on the subject's highercenter faculties by means of multimodal virtual feedbacks to guide him through his practice motions. Each of these signals is initially to be associated in the subject's mind with one of the primitive action components that structures the physical action of the skill to be learned. The nature and location of each cue stimulus will be chosen to make as "natural" as possible its association with the primitive action which it is supposed to prompt. The patient can even, and he'll be recommended to do, repeat these synchronized exercises at home in order to reacquire the complex motor skill rapidly and with more effectiveness.

On each week's first day of rehabilitation, it will be necessary to start the second main phase called "reassessment phase" in order reset to fit the actual motor sequence provided by patient's motor imagery. As in all the other rehabilitative treatment, the progression of recovery is chequered and depends on several factors. For this reason, a periodical reassessment of the treatment is largely recommended. The use of technology may facilitate this phase allowing the quick modification in multimodal feedback synchronization and letting the increasing of virtual stimulation congruent with the patient motor improvement.

Finally, in the "visual-haptic phase," when the patient begins to be able to perform, the movement will be furnished by visual/haptic cues following, which he can actively perform real movements. Virtual simulation in this case is used to create real life situations where the patient can actively and perform and repeat everyday recovered movement during rehabilitative progress.

The final open question that I-learning purpose is strictly addressed the effectiveness of treatment: Could a motor behavior learned in an observative and imitative modality supported by technology really enhance motor recovery? Starting from evidences supporting this issue future research will investigate these aspects.

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REFERENCES

1. Muellbacher, W., Richards, C., Ziemann, U., et al. (2002). Improving hand function in chronic stroke. *Arch Neurol* 59:1278–1282.
2. Seitz, R.J., Canavan, A.G., Yaguez, L., et al. (1997). Representations of graphomotor trajectories in the human parietal cortex: evidence for controlled processing and automatic performance. *Eur J Neurosci* 9:378–389.
3. Stephan, K.M., Fink, G.R., Passingham, R.E., et al. (1995). Functional anatomy of the mental representation of upper extremity movements in healthy subjects. *J Neurophysiol* 73:373–386.
4. Roth, M., Decety, J., Raybaudi, M., et al. (1996). Possible involvement of primary motor cortex in mentally simulated movement: a functional magnetic resonance imaging study. *Neuroreport* 7:1280–1284.
5. Leonardo, M., Fieldman, J., Sadato, N., et al. (1995). A functional magnetic resonance imaging study of cortical regions associated with motor task execution and motor ideation in humans. *Human Brain Mapping* 3:83–92.
6. Carpenter, W.B. (1874). *Principles of mental physiology, with their applications to the training and discipline of the mind, and the study of its morbid conditions.* London: Henry S. King.
7. Jacobson, E. (1931). Electrical measurements of neuromuscular states during mental activities. *American Journal of Physiology* 93:115–121.
8. Hummelsheim, H. (1999). Rationales for improving motor function. *Curr Opin Neurol* 12:697–701.
9. Decety, J., & Boissnon, D. (1990). Effect of brain and spinal cord injuries on motor imagery. *Eur Arch Psychiatry Clinical Neuroscience* 240:39–43.
10. Jeannerod, M. (1995). Mental imagery in the motor context. *Neuropsychologia* 33:1419–1432.
11. Maruff, P., Wilson, P.H., De Fazio, J., et al. (1999). Asymmetries between dominant and non-dominant hands in real and imagined motor task performance. *Neuropsychologia* 37:379–384.
12. Decety, J. (1996). The neurophysiological basis of motor imagery. *Behavior Brain Research* 77:45–52.
13. Decety, J., Perani, D., Jeannerod, M., et al. (1994). Mapping motor representations with positron emission tomography. *Nature* 371:600–602.
14. Decety, J., & Jeannerod, M. (1995). Mentally simulated movements in virtual reality: does Fitts's law hold in motor imagery? *Behavior Brain Research* 72: 127–134.
15. Dominey, P., Decety, J., Broussolle, E., et al. (1995). Motor imagery of a lateralized sequential task is asymmetrically slowed in hemi-Parkinson's patients. *Neuropsychologia* 33:727–741.
16. Sirigu, A., Duhamel, J.R., Cohen, L., et al. (1996). The mental representation of hand movements after parietal cortex damage. *Science* 273:1564–1568.
17. Kagerer, F.A., Bracha, V., Wunderlich, D.A., et al. (1998). Ataxia reflected in the simulated movements of patients with cerebellar lesions. *Exp Brain Research* 121:125–134.
18. Ingvar, D.H., & Philipsson, L. (1977). Distribution of cerebral blood flow in the dominant hemisphere during motor ideation and motor performance. *Ann Neurol* 2:230–237.
19. Roland, P.E., Larsen, B., Lassen, N.A., et al. (1980). Supplementary motor area and other cortical areas in organization of voluntary movements in man. *J Neurophysiol* 43:118–136.
20. Decety, J., Philippon, B., & Ingvar, D.H. (1988). rCBF landscapes during motor performance and motor ideation of a graphic gesture. *Eur Arch Psychiatry Neurol Sci* 238:33–38.
21. Decety, J., & Boisson, D. (1990). Effect of brain and spinal cord injuries on motor imagery. *Eur Arch Psychiatry Clin Neurosci* 240:39–43.
22. Luria, A.R. (1963). *Restoration of function after brain injury* Oxford, England.
23. Bailey, C.H., & Kandel, E.R. (1993). Structural changes accompanying memory storage. *Annu Rev Physiol* 55:397–426.

24. Carr, J.H., & Shepherd, R.B. (1998). *Neurological rehabilitation: optimising motor performance.* Oxford: Butterworth.
25. Warner, L., & McNeill, M.E. (1988). Mental imagery and its potential for physical therapy. *Phys Ther* 68:516–521.
26. Page, S.J., Levine, P., Sisto, S., et al. (2001). A randomized efficacy and feasibility study of imagery in acute stroke. *Clin Rehabil* 15:233–240.
27. Page, S.J., Levine, P., Sisto, S.A., et al. (2001). Mental practice combined with physical practice for upper-limb motor deficit in subacute stroke. *Phys Ther* 81:1455–1462.
28. Fansler, C.L., Poff, C.L., & Shepard, K.F. (1985). Effects of mental practice on balance in elderly women. *Physical Therapy* 65:1332–1338.
29. Denis, M. (1985). Visual imagery and the use of mental practice in the development of motor skills. *Can Journal Appl Sport Science* 10:4S–16S.
30. Kohl, R.M., & Roenker, D.L. (1983). Mechanism involvement during skill imagery. *Journal of Motor Behavior* 15:179–190.
31. Yue, G., & Cole, K.J. (1992). Strength increases from the motor program: comparison of training with maximal voluntary and imagined muscle contractions. *J Neurophysiol* 67:1114–1123.
32. Green, L.B. (1992). The use of imagery in the rehabilitation of injured athletes. *The Sport Psychologist* 6: 416–428.
33. Gandevia, S.C. (1999). Mind, muscles and motoneurones. *J Sci Med Sport* 2:167–180.
34. Johnson, S.H., Rotte, M., Grafton, S.T., et al. (2002). Selective activation of a parietofrontal circuit during implicitly imagined prehension. *Neuroimage* 17: 1693–1704.
35. Sirigu, A., Cohen, L., Duhamel, J.R., et al. (1995). Congruent unilateral impairments for real and imagined hand movements. *Neuroreport* 6:997–1001.
36. Brooks, B.M., Rose, F.D., Attree, E.A., et al. (2002). An evaluation of the efficacy of training people with learning disabilities in a virtual environment. *Disabil Rehabil* 24:622–626.

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