Training with Computer-Supported Motor Imagery in Post-Stroke Rehabilitation

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ABSTRACT

Converging lines of evidence suggest that motor imagery (the mental simulation of a motor act within working memory) is associated with subliminal activation of the motor system. This observation has led to the hypothesis that cortical activation during motor imagery may affect the acquisition of specific motor skills and help the recovery of motor function. In this paper, we describe a clinical protocol in which we use interactive tools to stimulate motor imagery in hemiplegic stroke patients, thereby helping them to recover lost motor function. The protocol consists of an inpatient and an outpatient phase, combining physical and mental practice. In the inpatient phase, patients are trained in a laboratory setting, using a custom-made interactive workbench (VR Mirror). After discharge, patients use a portable device to guide mental and physical practice in a home setting. The proposed strategy is based on the hypotheses that: (a) combined physical and mental practice can make a cost-effective contribution to the rehabilitation of stroke patients, (b) effective mental practice is not possible without some form of support, from a therapist (as in our inpatient phase) or from technology (as in the outpatient phase), (c) the inclusion of an outpatient phase will allow the patient to practice more often than would otherwise be possible, therefore increasing the speed and/or effectiveness of learning, and (d) the use of interactive technology will reduce the patient’s need for skilled support, therefore improving the cost-effectiveness of training.

INTRODUCTION

HEMIPLEGIA is total paralysis of the arm, leg, and trunk on one side of the body. The paralysis presents a weakness that may be associated with abnormal muscle tone (e.g., rigidity or spasticity). The most common cause is stroke, which occurs when a rupture or blood clot reduces blood flow to a specific area of the brain, killing cells and disrupting the abilities or functions they control. Hemiplegia can be caused by damage to a variety of structures including primary sensorimotor areas, supplementary motor, premotor, and parietal cortices, basal ganglia and/or the thalamus. Strokes affect some 700,000 individuals every year in the United States alone; in 2003, Americans paid about...
$51 billion for stroke-related medical costs and
disability.2

Traditional rehabilitation after stroke focuses on
passive (non-specific) movement or on compensa-
tory training of the non-paretic arm.3 Recently, sev-
eral researchers have proposed the use of mental
practice as a therapeutic tool to promote motor
recovery in stroke patients with upper-limb disabil-
ity.4,5 Mental practice, also called symbolic re-
hearsal or motor rehearsal, is a training technique
in which the patients repeatedly “rehearse” a
motor act in working memory,4 without producing
any overt motor output.6 In the first section of this
paper, we describe the rationale for using mental
practice in neurological rehabilitation, focusing on
the conditions under which it is believed to be most
effective. We then describe a clinical protocol in
which we use interactive tools, to help hemiplegic
stroke patients to use mental practice during their
rehabilitation. The authors intend that this protocol
will serve as the basis for a small-scale pilot trial,
designed as a feasibility study for a larger-scale
randomized clinical trial. The protocol described
below and an earlier version of the protocol, de-
scribed elsewhere,7 have been developed as part of
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Program.

MENTAL PRACTICE AND
MOTOR IMAGERY IN
NEUROLOGICAL REHABILITATION

“Motor imagery” can be defined as the mental
simulation of a motor act in working memory with
no gross muscular activation. “Motor imagery”
should be distinguished from “visual imagery”: in
visual imagery subjects imagine the environment
in which they are moving, in motor imagery they
imagine the kinesthetic sensations associated with
movement.8 To avoid confusion, sport psycholo-
gists often refer to kinesthetic imagery.

Scientific investigation of motor imagery dates
back to 1885, when the Viennese psychologist,
Stricker, collected empirical evidence that overt
and covert motor behaviors involve the same pro-
cessing resources.9 Over the past 30 years, many re-
searchers have used subjective, behavioral and
physiological methods to investigate this hypothe-
sis further.10 These studies have provided converg-
ing evidence that imagining a motor act is a
cognitive task that engages parts of the executive
motor system: in particular the supplementary
motor area, the cerebellum, as well as the premotor,
cingulated, superior, inferior parietal, sensorimotor
and primary motor cortices. Drawing on these
findings, investigators have suggested that training
with motor imagery (mental practice) could be ef-
fective in learning new motor skills or in promoting
motor recovery after damage to the central nervous
system. Pascual-Leone et al.,11 for example, used
TMS to compare changes in the functional organi-
zation of the brain after mental and after physical
rehearsal of a one-handed piano exercise. The ex-
periment showed not only that mental and physi-
cal rehearsal over a five day period produced
 equivalent improvements in performance, but that
these were marked by equivalent increases in the
size of the contralateral cortical output map for the
long finger flexor and extensor muscles. Though
mental practice took five days to produce the same
improvement that physical practice produced in
three, the investigators showed that a single physi-
cal training session was enough to bring the mental
practice group to the same level as subjects who
had trained physically.

Jackson et al.4 have recently created a model,
comparing the potential therapeutic effects of men-
tal practice with other forms of training. The model
assumes that practice involves declarative knowl-
edge, non-conscious processes and physical execu-
tion. In their model, declarative knowledge is the
explicit knowledge that subjects need before prac-
ticing a motor task (i.e., a knowledge of the se-
cquence of movements to be performed); skills that
are not directly accessible to verbal description,
such as the timing of motor responses to cues or the
co-articulation of small segments of movement
and the rapid, sequential activation or inhibition
of different muscle groups are regulated by non-
conscious processes; physical execution is the mus-
culoskeletal activity necessary to carry out the
intended action.

According to Jackson et al.,4 these different levels
of processing interact in different ways in different
forms of training. Physical practice involves all
three levels of processing; in mental practice, on the
other hand, learning depends crucially on the
interaction between declarative knowledge and
non-conscious processes: in physical practice it is
possible to learn a motor task implicitly; in mental
practice subjects have a good declarative knowl-
edge of the different components of the task before
they start practicing. The similarity between the
circuitry involved in imagining and executing
movements suggests, however, that the neuronal
network implicated in the non-conscious aspects of
a task can be primed as effectively through mental
as through physical practice. In addition, the model
predicts that internally driven images, promoting
kinesthetic “sensations” of movement, could be highly effective in activating the non-conscious processes involved in motor training. According to Jackson and his colleagues, this would explain why kinesthetic imagery is more effective than purely visual imagery. According to their model, mental practice with motor imagery can be conceptualized as a means to access the otherwise non-conscious learning processes involved in a task. They recognize, however, that the absence of direct feedback from physical execution makes mental practice on its own a less effective training method than physical practice.

SUPPORTING MENTAL PRACTICE WITH INTERACTIVE TECHNOLOGY: THE I-LEARNING REHABILITATION PROTOCOL

Clinical studies have shown that the rehabilitation of hemiplegic and hemiparetic patients can be made more effective by combining physical practice with mental rehearsal.\textsuperscript{5,12,13} However, for many patients with damage to the CNS, mental simulation of movements can be difficult, even when the relevant neural circuitry has been spared.\textsuperscript{14} The goal of the I-learning rehabilitation protocol is thus to use interactive technology to assist patients in creating motor imagery which they can then use during “mental practice.” The treatment consists of an inpatient phase and an outpatient phase.

**Inpatient phase**

The rehabilitation program starts 15 days after hospitalization. The intervention consists of one daily session (in the morning), 5 days a week, for 4 consecutive weeks. In each session, the patient sits at a table in front of the apparatus. To ensure comfort, the patient’s ankles are in neutral dorsiflexion, the knees and hips are placed at 90°, the shoulders in 0° flexion, the elbows in 60° flexion, the wrists are neither extended nor flexed. The apparatus used by the patients consists of a movement tracking system and a custom-designed interactive workbench that we call the virtual reality (VR) mirror (Fig. 1). The idea of the VR mirror is inspired by previous work with stroke patients by Stevens et al. in which mirror images of movement by a healthy limb (created by a physical mirror) were effectively used to stimulate motor imagery of movement by the paretic limb.\textsuperscript{5} In the I-Learning protocol, the VR mirror displays a 3D electronic image of the movement performed by the patient’s healthy limb. This is viewed from an ego-centric perspective that facilitates the generation of kinesthetic motor imagery by the patient.

Each session of inpatient treatment consists of four consecutive sub-phases: pre-training, physical training with the unimpaired limb, imagery training, and VR mirror training. The training focuses on elbow flexion/extension, pronation/supination of the forearm, wrist flexion/extension, open/closure of the hand, and fine finger movements. During the pre-training phase the patient receives...
instructions, which explain how the treatment works, encouraging the patient to relax and reducing fear and performance anxiety. The instructions are accompanied by relaxing music. In the next, physical training phase the therapist shows the patient how to perform the movement with the unaffected arm. The movement is accompanied by rhythmic auditory cues, designed to stabilize the speed of the movement (guaranteeing that the patient performs the same movement each time), and to provide the patient with an attentional goal, (matching the sound with the movement), a strategy known to facilitate motor learning. When the patient then performs the task, the system tracks her arm, identifying “key frames” and creating a 3D model of the movement. Next, in the imagery training phase, the patient is asked to create a mental image (kinesthetic imagery) of the impaired arm performing the movement, as viewed from an internal perspective. When the patient starts to imagine the movement, she presses a button (using her healthy hand), pressing it again when she has finished. This allows the therapist to measure the time she takes to imagine each movement. This is the patient’s Response Time (RT). Basic research has shown that response times for physical and imagined movements are subject to common laws and principles: comparing a patient’s RTs, while imagining and physically performing the same movements, allows the therapist to statistically assess the quality of the patient’s motor imagery.

After the patient has completed the mental rehearsal exercise, she is instructed to watch the display on the VR mirror (VR mirror training phase). The 3D model created earlier is used to generate a mirror image of the movement originally performed by the unimpaired arm. As the movement is displayed, it is accompanied by the same rhythmic auditory cues used in the physical training phase. This multimodal sensorial stimulation has two advantages: the image of the reflected limb provides the patient with direct perceptual cues, suggesting how the impaired limb could complete a smooth, well-controlled movement; meanwhile, auditory cueing synchronized with key frames helps the patient to memorize the rhythmic structure of the movement.

After watching the reflected limb on the screen, the patient is invited to physically perform the exercise, moving her arm in time with the mirror image (Fig. 2). In the early stages of treatment, the patient may be completely unable to execute the exercise. It is expected, however, that, as the treatment advances, motor function will improve. During execution of the task, the system tracks the movement of the impaired arm, measuring the deviation between the movement the patient performs with the impaired arm and the “ideal” movement, as performed by the healthy arm. Using this measurement, which is performed in real time, the system provides the patient with audio feedback describing her performance on the task. After the patient has repeated the movement 5–10 times, the therapist introduces a more difficult exercise, restarting the procedure from the beginning.

FIG. 2. The execution of a rehabilitation exercise with the VR mirror (design by Marta Mantovani, ATN-P Lab).
**Outpatient phase: home-based rehabilitation**

Home-based rehabilitation has the advantage that stroke patients can practice skills and develop compensatory strategies in the environment where they normally live. The benefits of this approach, most frequently cited in the literature, include focus on long-term outcomes, a reduction of the risks associated with inpatient care, respect for patient preferences and savings in the direct cost of treatment.\(^{17,18}\) It is nonetheless necessary to provide patients with specialized equipment to support the rehabilitation process.\(^{19}\) In the I-learning outpatient program, the equipment provided is a Home Portable Device (a portable computer or a PDA) with multimedia capabilities. The device provides patients with instructions and visual cues allowing them to mentally rehearse and physically practice the motor tasks prescribed by the training protocol; the same device monitors their performance.

At the beginning of each home-based rehabilitation session, the Home Portable Device displays a sequence of computer-generated movies, picturing the movement to be learned, performed at different speeds, using both the left and the right arm, and viewed from different angles, as prescribed in Stevens and Stoykov’s protocol.\(^{5}\) The movements displayed on the screen are accompanied by rhythmic auditory cues. After viewing the movies, the patient is instructed to take a first-person perspective and to imagine performing the task with the impaired arm. At the start and on completion of the task the patient uses her healthy hand to press a key on the HPD. Once this mental practice has been completed, the patient is asked to physically perform the movement with the impaired arm.

The patient performs this sequence of exercises on a daily basis for the first two weeks after discharge from hospital, three times a week starting from the 21st day after discharge, and two times a week from the fourth week after discharge on. When she returns to hospital for follow-up (at 3 and 6 months after discharge), the therapist connects the portable device to a desktop computer and downloads the data recorded during the exercises. This includes: (a) mental performance data, the response times recorded by the patient during mental practice—by comparing RTs for mental practice with data recorded during physical exercise the therapist can assess the quality of the patient’s motor imagery; and (b) compliance data, data describing the dates and times of sessions allows the therapist to assess how far the patient has complied with the schedule specified in the treatment protocol.

**Assessment**

Assessment—based on behavioral and clinical indicators of physical competency—will be carried out before the intervention, immediately after discharge from the hospital, at 3 months, and at 6 months after discharge from the hospital.

**DISCUSSION**

The rehabilitation technique described in this paper combines mental and physical practice, using interactive technology to provide the patient with visual and auditory cues that draw her attention to the underlying dynamic structure of a movement, facilitating the generation of mental imagery. The protocol integrates inpatient treatment—using novel apparatus—with outpatient treatment. As far as concerns the inpatient phase, the solution we have developed has at least four advantages. First, the combination of audio and visual cues provided by the VR mirror greatly facilitates the patient’s task in generating the kind of motor imagery required for effective mental rehearsal; second the use of a mirror metaphor eliminates the need for pre-programmed computer exercises, a well-known shortcoming of traditional computer-based rehabilitation exercises; third, the use of an external display avoids the need for the patient to wear cumbersome or invasive equipment (such as a Head Mounted Display, or shutter glasses), and last, but not least, arm-tracking makes it possible to record the dynamic features of a movement, allowing objective, real-time comparison between the movement of the impaired limb, and the “ideal performance” as recorded with the healthy limb. As a result, the computerized system provides the therapist with a continuous flow of feedback about the patient’s performance, making it possible to adjust the treatment accordingly. The same data is used to provide performance feedback to the patient: a key requirement for effective motor learning.\(^{20,21}\)

As far as concerns the outpatient phase, the use of a Home Portable Device to support mental practice makes it possible to increase the duration, frequency and intensity of the therapy provided to patients. In the longer term it may become possible to connect these devices to the Internet allowing a therapist to remotely monitor a patient’s progress.

The strategy presented in this paper is justified by four key hypotheses: (a) combined physical and mental practice can make a cost-effective contribution to the rehabilitation of stroke patients; (b) effective mental practice is not possible without
some form of support, from a therapist (as in our inpatient phase) or from technology (as in the outpatient phase); (c) the inclusion of an outpatient phase will allow the patient to practice more often than would otherwise be possible, therefore increasing the speed and/or effectiveness of learning; and (d) the use of interactive technology will reduce the patient’s need for skilled support, therefore improving the cost-effectiveness of training. If clinical trials show these hypotheses to be correct the protocol described in this paper could make a useful contribution to improving the effectiveness and reducing the duration and cost of post-stroke rehabilitation.

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REFERENCES


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