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REVIEW ARTICLE

MOTOR IMAGERY AND STROKE REHABILITATION: A CRITICAL DISCUSSION*

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Motor disorders are a frequent consequence of stroke and much effort is invested in the re-acquisition of motor control. Although patients often regain some of their lost function after therapy, most remain chronically disabled. Functional recovery is achieved largely through reorganization processes in the damaged brain. Neural reorganization depends on the information provided by sensorimotor efferent-afferent feedback loops. It has, however, been shown that the motor system can also be activated "offline" by imagining (motor imagery) or observing movements. The discovery of mirror neurones, which fire not only when an action is executed, but also when one observes another person performing the same action, also show that our action system can be used "online" as well as offline. It is an intriguing question as to whether the information provided by motor imagery or motor observation can lead to functional recovery and plastic changes in patients after stroke. This article reviews the evidence for motor imagery or observation as novel methods in stroke rehabilitation.

Key words: motor imagery, mirror neurones, rehabilitation, stroke.

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INTRODUCTION

Stroke is a major cause of impairment and functional disability in millions of people worldwide. Due to ageing of the world population, the number of people affected by strokes will increase substantially over the coming years. A stroke can be seen as a massive distortion of the capacity of the brain to process neural information, with heterogeneous consequences. Not only the motor system is affected after a stroke, but also the cognitive and emotional systems may be seriously impaired (for an overview of cognitive impairments, see ref. 1). Although we are well aware of the multifaceted character of stroke, in this paper we focus mainly on the recovery of motor skills (for a recent overview of cognitive rehabilitation after stroke, see ref. 2).

Motor impairments frequently occur after stroke. It is estimated that after acute stroke approximately 80% of the patients have some form of motor impairment (3). About 20% of these patients regain at least part of their lost motor functions in the subsequent months; thus, of the patients surviving stroke, 50–60% are left with a chronic motor disorder (4). These disorders are often related to balance, timing and co-ordination, and to loss of strength and/or spasticity in the affected limbs. These motor impairments may substantially compromise quality of life after stroke. For instance, independent gait is estimated to be impaired in 50% of the post-stroke population (5). Therefore, much therapeutic effort is invested in functional recovery of motor skills after stroke.

Functional recovery is attributed to reorganization processes in the damaged brain. Within-system reorganization (self-organization) may be possible when damage to a functional system is partial. However, when a functional system is completely damaged, recovery is achieved largely by a process of substitution, i.e. other brain areas are recruited to take over the functions of the areas damaged by stroke (6, 7).

The efficiency and speed of the (motor) recovery process depends partly on the availability of (sensory) information provided by motor activity (8). Traditionally, 5 sources of information can be distinguished in relation to motor (re-)learning: (*i*) proprioceptive information; (*ii*) tactile information; (*iii*) vestibular information; (*iv*) visual information; and (*v*) (to a lesser extent) auditory information. It is an intriguing question as to whether information provided by imagination (motor imagery) and observation may also play a role in the re-learning process.

Indeed, recent papers suggest that information provided by imagination and observation of movements might form an additional source of information that could be useful for motor rehabilitation after stroke (9–12). The rationale behind this is that brain areas that are normally involved in movement planning and execution are also active during the imagination of a movement. It is known that the imagination of a movement activates more or less the same brain areas as the actual execution of a movement. Several studies using brain-mapping techniques have found that, during motor imagery,

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brain areas related to motor execution were activated (13–25). The areas that were activated during imagery as well as during the execution of the movement are the prefrontal cortex, the pre-motor cortex, the supplemental motor area, the cingulate cortex, the parietal cortex and the cerebellum. Some functional magnetic resonance imaging experiments also found activation in the primary motor cortex (18–22), although, in other studies, primary motor cortex activity was found to be absent (23–25).

The same is true for the observation of a movement. During observation of a movement, areas in the pre-motor cortex become activated that are also active when the (same) movement is executed. The concept of mirror neurones plays a central role in these findings (26). This concept refers to neurones that fire when a monkey performs a movement, but also when someone else executes the movement and the monkey observes that performance. Fadiga et al. (27) provided the first evidence in favour of the existence of a mirror system in humans, by showing that the observation of a movement resulted in motor facilitation. To date, however, no systematic studies exist in the field of neurological rehabilitation that employ observation-based activation for the re-learning of motor control.

It has been shown that motor imagery can be effective in optimizing the execution of movements in athletes (28, 29). A meta-analysis by Feltz & Landers (28) showed that practice using motor imagery is better than no practice at all. They showed that subjects who mentally trained for a specific task usually displayed less improvement than those who trained physically. However, compared with control subjects who did not practice at all, it could be shown that motor imagery, indeed, facilitated performance. Some studies showed that the neural reorganization following motor imagery training is similar to the changes that take place as a result of actual physical training (30, 31).

However, to date it is not clear what the causal mechanisms are behind ”learning to move without moving”. As indicated above, the primary motor cortex is not consistently found to be active during motor imagery. This is a relevant aspect since many studies show that neural reorganization related to motor recovery takes place in the primary motor cortex (32). Furthermore, while many parallels can be drawn between imagery, observation and execution, the exact correlation between these processes and, specifically, the role of mirror neurones herein is still poorly understood. This paper discusses these problems and reviews the available evidence for motor imagery training and observation-based learning. We argue that a better understanding of these novel neuroscientific findings may be of value for the improvement of neurological rehabilitation.

A DEFINITION OF MOTOR IMAGERY

Mental imagery, which is the capacity to imagine objects and/or events that are not there, is one of the most interesting cognitive abilities of humans. We are able to imagine that we are flying an aeroplane or that we are a professional football player or a rock star. We can imagine how objects would look from the opposite side while we are sitting motionless in a chair in front of the object. We can imagine how it would feel if we picked up the object, we are able to describe its form and basic features without actually touching it. These are all different varieties of mental imagery. Although visual imagery has traditionally received most attention from cognitive science (33–35), a rapid growth of interest in motor imagery has been seen during the past 10 years.

Motor imagery can be defined as the covert cognitive process of imagining a movement of your own body(-part) without actually moving that body(-part) (36, 37). Kosslyn et al. (37) showed that visual and motor imagery depend on distinct neural processes. In their experiment, motor areas of the brain were found to be activated during the mental rotation of pictures of hands, but not during the mental rotation of three-dimensional (3-D) cubes. The mental rotation of 3-D cubes was associated primarily with activity of visual cortical areas.

Motor imagery should be distinguished from another form of mental movement-related imagery: motion imagery. Motion imagery processes are concerned with the prediction of path and direction of movements of non-bodily objects moving in space; for example, the trajectory of a ball. Another important distinction that has to be made concerns the first and third person perspective. An individual knows where their arm is in space and they also know how it would look to others. These, however, are different varieties of mental imagery, and research suggests that they are also related to different neural subsystems (39, 40). The first, knowing were one’s arm is, e.g. feeling the (angular) position of one’s arm relative to one’s body, is defined as the first person perspective or kinetic imagery, whereas the other perspective, knowing how one’s arm would look like if one were watching it from the outside as another person, is termed the third person perspective and is more visual in nature. In this paper we are interested primarily in research on motor imagery concerned with the first person perspective, or kinetic perspective, and its possibilities for neurological movement rehabilitation.

SIMILARITIES BETWEEN EXECUTION AND MOTOR IMAGERY

Over the past decade, neuroimaging and psychophysical research on motor control has shown that there are striking similarities between real and imagined movements. These findings have led to a theoretical position termed ”the simulation hypothesis” (36). This hypothesis states that overt movement and motor imagery (covert movement) are essentially based on the same processes. Movement execution, motor imagery and action observation are all driven by the same basic mechanism. Motor imagery and action observation are conceived as ”off-line” operations of the motor areas in the brain. The similarity hypothesis is based on 2 different lines of evidence.

First, it has been shown that there are similarities in the behavioural domain. For instance, the time to complete an imagined movement is known to be similar to the time needed for actual execution of that movement; this phenomenon is known as mental isochrony. Parsons (for a review see ref. 41) showed that the time needed to judge whether a rotated picture of a hand is a left or a right hand is related to the degree of the rotation of that picture. Moreover, and even more remarkably, he showed that when the hand positions depicted were awkward or biomechanically difficult to perform the imagined rotation time increased more than for equally rotated pictures in biomechanically easy positions and that the rotation time was similar to real hand rotation time for these positions. The fact that motor imagery seems to respect the normal biomechanical constraints of real online movements indicates that these tasks are not accomplished by mere visual imagery, but must be solved by imagining the movement of one's own arm and hand.

These results were confirmed in an experiment by Frak et al. (42). Participants judged whether a glass cylinder that was placed in different orientations would be graspable or not. They showed that the time it took the participants to make a judgement was similar to the time it would take them actually to grasp the glass cylinder. Here also, more awkward movements took longer to imagine than biomechanical easy movements. Thus, if imagined movements obey the same biomechanical laws as real movements, would that mean that they also rely on the same brain areas?

A second line of evidence for the simulation hypothesis shows that the neural system, used for action control is, indeed, activated during imagination of these actions. An increasing number of brain imaging studies have shown this similarity at the neural level (9, 36). The parts of the neural system that are most frequently reported to be involved in motor imagery are areas of the brain that are related to functions of planning and control of movements including the pre-motor cortex, the dorsolateral pre-frontal cortex, the inferior frontal cortex, the posterior parietal cortex, the cerebellum and the basal ganglia. However, as indicated, there is ongoing discussion about the involvement of more executive areas of the central nervous system, such as the primary motor cortex.

THE PRIMARY MOTOR CORTEX

In the above-mentioned definition of motor imagery, a key aspect is the absence of any imagery-related motor output. If the primary motor cortex is primarily involved in the execution phase of an action, as is the traditional view, then no activity would be expected during motor imagery, since during imagery no actual movements are executed. However, a few studies do find imagery-related motor cortex activity.

For example, Ehrsson et al. (43) showed an activation of specific limb-areas in the primary motor cortex. They showed that imagined toe movements could be distinguished from imagined finger and tongue movements. Finger movement imagination activated the associated finger area in the primary motor cortex, whereas imagination of toe and tongue movements activated the toe and tongue area, respectively.

However, other studies do not report motor imagery-related activity in the primary motor cortex. For example, a study by de Lange et al. (25) showed clear evidence of pre-motor activation during a mental (motor) rotation task, but showed no activity in the primary motor cortex, suggesting that motor imagery is primarily related to the planning phase of motor control and not to the execution phase.

It could be that these differences are due to methodological differences in research designs. For example, some of the studies that report primary motor cortex activity did not control for small muscle movements during the scan. In addition, the scanning techniques and motor imagery tasks employed differed across studies. A possible solution in this debate came from recent transcranial magnetic stimulation (TMS) studies by Ganis et al. (44) who showed clearly that the left primary motor cortex was involved in mental motor rotation in right-handed participants. They showed that a short magnetic pulse over the primary motor cortex hand area led to an increased reaction time in the mental rotation of hands, but not of feet. These results were confirmed by an experiment by Tomasino et al. (45) in which a neurological patient received electrical stimulation via an implanted electrode grid over his motor cortex. His reaction time was considerably impaired in a mental motor rotation task but not in a visual rotation task. Based on these stimulation experiments, these authors subscribed a more cognitive role to the primary motor cortex during offline movement representation in addition to the mere executive role with which it has been identified in the past (44, 45).

However, a study by Sirigu et al. (46) showed that after hemiplegic stroke a patient with a primary motor cortex lesion was as accurate as controls on a motor imagery task. The fact that the patient's accuracy was as high as that of control subjects suggests that the primary motor cortex may not contain representations of movements itself, but is involved in other information-processing tasks related to the movement planning and control based on representations that are located in other areas of the brain. Indeed, if it was involved in movement representation, this patient could not have shown a perfect accuracy on the motor imagery task. The studies of Ganis et al. (44) and Tomassino et al. (45) showed impaired reaction times, but they also showed that there were no decrements in accuracy scores following stimulation, suggesting that participants were still perfectly able to imagine a movement and that stimulation only slowed down their response times. Taken together, these results seem to suggest that the primary motor cortex is not necessarily involved in motor imagery, it can be activated by motor imagery as is shown in some neuroimaging studies, but its activity is not necessary for accurate movement representation.

However, since a detailed discussion of the exact role of the primary motor cortex in motor imagery is outside the scope of the present paper, we conclude that the role of the primary motor cortex in motor imagery remains a matter of debate that requires further research.

OBSERVATION AND IMITATION

Movement observation can be defined as perception of the actions of others. Similar phenomena, as described above for motor imagery, have been found for the observation of movements. Grezes & Decety (47) performed a meta-analysis on activation patterns of execution, observation, motor imagery and verbalization of an action. They showed, in their analysis of 30 neuroimaging studies, that the areas of the pre-motor cortex, the temporal gyrus, occipital areas, and the parietal cortex were all consistently activated by the observation of movements. As with motor imagery, activation of the primary motor cortex was not consistently found during action observation. However, a recent TMS study by Maeda et al. (48) did show involvement of the primary motor cortex during action observation.

Maeda et al. (48) applied a short magnetic pulse over the primary motor cortex during observation of hand movements and during rest. They showed that the motor evoked potential was significantly larger during observation of hand movements than during rest. Contrary to the neuroimaging studies, these results suggest an increase in motor-spinal activation during movement observation. However, the same discussion exists for movement observation as for motor imagery. Also here a definite explanation of the, sometimes puzzling, experimental results is still lacking.

Taken together, these results show that a similarity exists not only between action and motor imagery, but also between action and observation. As Jeannerod & Decety (49) argued more than a decade ago: ”Motor imagery is a cognitive state that can be experienced by virtually everyone with minimal training. It corresponds to many situations experienced in everyday life, such as watching somebody’s action with the desire to imitate it, anticipating the effects of an action, preparing or intending, to move, retaining from moving, or remembering an action.” (49, p. 727).

The study by Maeda et al. (48) also shows that ”passive” movement observation, as opposed to observation with ”the intention to imitate”, activates brain structures normally involved in planning and execution of movements. Hence, an active intention to imitate does not seem to be crucial for movement observation related neural activity in motor areas. Other studies also showed that the motor system can also be used for ”passive” movement observation (47, 50). In a recent experiment by Brass et al. (50) subjects had to execute either an upward finger lifting movement or a downward finger tapping movement. While they executed one of these movements they watched a video of a hand performing the same finger movement. This video could be congruent, that is, the observed fingers were moving in the same direction as the movement they were executing, or incongruent, where the observed fingers moved in the opposite direction as their real fingers.

They showed that performance of the finger movements improved when the video was in the congruent format, whereas their movements were impaired when the video was in the incongruent format. The fact that the subjects passively observed the video without any intention to imitate and that this observation impaired their performance suggests that imitation is based on an automatic use of our action system. It seems that when we watch human movements we are also covertly using our own movement representations. These results confirm the well known ”echo effect”, which can be observed when 2 people mirror each other’s movements, for example by crossing the legs when the other crosses his/her legs, without the wilful intention to do so. It can be argued that this coupling between execution and observation has important consequences for daily life.

First, these results suggest that we can use our own action system to understand the meaning of the behaviour of others. By (mentally) simulating a perceived action as performed by another person, it is possible to predict the potential outcome of that action and to change our own behaviour accordingly. Action observation in this sense enables us to interact with other people and thus has a clear social function. Secondly, we can use this shared action system for learning new actions. Research has shown that even very young children learn by observing how their parents do things (51) and that they are able to match their own action system with the observed action of others. Hence, action perception enables the learning of new movements.

MIRROR NEURONES

The above-mentioned results show that motor imagery, observation and execution are closely related phenomena sharing neural control processes. Although differences exist between execution, observation and motor imagery, these results suggest the existence of a general system involved in the representation of our own bodily actions that plays a role in the control of action as well as in imagination and observation. It has been argued that mirror neurones may play a crucial role in this process (26).

Mirror neurones were initially discovered in monkeys. In 1987, Rizzolatti et al. (52) found that a group of cells in monkey area F5, in the pre-motor cortex, fired when a monkey reached for a peanut. These neurones also fired when the monkey saw the experimenter reaching for the peanut. When the peanut was occluded behind a screen the same neurones fired when the experimenter reached for the object behind the screen. However, when the peanut was removed before the screen was put in place these neurones did not fire. These results suggest that mirror neurones are involved in the coding of the goal of actions. In other words, mirror neurones are related to intentional behaviour and seem to be involved in understanding the actions of others. It has been shown that mirror neurones also exist in humans and many researchers believe they may play a role in (motor) learning (53), although it is, to date, not entirely clear what exact role they play in these processes.

REHABILITATION: CLINICAL EVIDENCE

Although the discussion, so far, indicates that the neural mechanisms behind motor imagery are not yet fully understood, it is clear that we use our action system not only for online actions (execution) but also for offline actions (imagination, observation). Moreover, it has been shown that we can improve our movements by using this offline action system. In sport sciences it has been shown that repeated motor imagery, in particular imagery from the first person perspective, can facilitate the learning of movements (28, 29). Positive effects of motor imagery training have also been described outside the sport domain. For example, Yue & Cole (54) showed that muscular force increased following motor imagery training.

More recently, Mulder et al. (55) showed that subjects could learn to abduct their big toe without moving the other toes by means of motor imagery. In this experiment subjects were randomly assigned to a group where they had to train by means of motor imagery, to a group were they had to physically practice the outward movement of the toe or to a control group that did not practice at all. They showed that motor imagery significantly improved the ability to abduct the toe, whereas the control group showed no improvement. Furthermore, it was shown that motor imagery only improved the toe movement in subjects who already had some ability to perform the abduction movement and not in subjects who found it impossible to abduct the toe at the start of the experiment. These results suggest that a representation of a movement must exist for motor imagery training to be effective.

Although numerous reports of motor imagery training in sport science exist, clinical studies using motor imagery in rehabilitation are scarce. The same is true for the therapeutic use of observation and imitation. We are not aware of any studies that use these processes for rehabilitation. There is an ongoing study by Buccino et al. (56) that shows some promising results of observation therapy in stroke rehabilitation. However, these results are preliminary and need to be confirmed when the study is completed. Therefore, in the next section we will focus primarily on the empirical findings that exist in relation to motor imagery.

Before that, however, the reader is referred to a study of Altschuler et al. (57) which comes close to a motor imagery study. Patients after stroke were trained to use their hemiplegic arm with the aid of a mirror. The mirror was placed in front of the patients on top of a table somewhere around the body's midline. In mirror therapy a reflection of one limb gives the illusion of watching the other limb move. This illusion of limb movement was first used by Ramachandran et al. (58) to treat phantom limb pain and might also prove to be a valuable tool to train hemiplegic stroke patients.

In the Althschuler et al. (57) study patients after stroke were instructed to simultaneously move their arms, both the impaired and the healthy arm, in the same manner. While moving their arms they watched the reflection of their healthy arm in the mirror. This evoked the visual illusion of having a normal moving arm. It was interesting that a number of patients reported an illusion of feeling their impaired arm moving in a normal way although the movement pattern in fact was significantly disturbed. Although this was not an observation or motor imagery study in the strict sense, it did show that significant changes occurred following information generated by the illusion of the arm in the mirror. It seems likely that this illusion primes the action system in a similar way to observation or motor imagery (59, 60).

A study by Page et al. (61) was the first randomized controlled study that showed that after stroke patients could improve following motor imagery intervention. Thirteen patients after stroke received one hour of physical therapy 3 times a week during a 6-week period. Eight of these patients received additional motor imagery training, whereas 5 received a control intervention consisting of exposure to general information about stroke. Contact time was the same for both groups. They showed that the patients who received motor imagery training improved significantly more on motor impairment tests then those in the control group. The patients in this study were all relatively early patients after stroke, varying from 2 to 11 months post-stroke, which poses the question as to whether patients after chronic stroke with a more stabilized motor status could also improve after motor imagery training.

In another study Page et al. (62) investigated this question. They trained 6 one-year post-stroke patients for 6 weeks with physical therapy combined with mental practice (motor imagery) and compared improvements in hand function with a control group that received physical therapy combined with relaxation exercises. They showed that arm function and daily arm use improved more for the group that received the combined physical therapy and motor imagery training than the group that received the combined physical therapy and relaxation training. This study shows that motor recovery might be possible even if the patients are one-year post-stroke and show stable motor deficits.

Liu et al. (63) showed that a group of 26 patients after stroke who received mental imagery in addition to physical therapy for one hour a day for 3 weeks improved significantly more on tasks related to daily living than a control group of 20 patients after stroke who received additional assistance from the therapist. However, their intervention protocol was not aimed at re-learning basic motor skills. Their intervention emphasized learning sequences of movements for solving daily living tasks, such as the steps necessary in folding laundry. Specific instructions for forming a kinesthetic image or to use first person imagery were absent from this study. This suggests that these patients did not use motor imagery but instead used imagery in the third person or visual imagery. Although they did show a beneficial effect on daily living tasks, they failed to show a significant difference in motor performance between the groups, as measured with Fugl-Meyer test. Moreover, the patients in the mental imagery group did improve on neuropsychological tasks that measure attentive processing, the colour trial test, suggesting that their capacity in attentive processing might also been increased following mental imagery training. This suggests that visual imagery might be used for relearning the more cognitive and planning aspects of movements, whereas motor imagery could potentially lead to recovery of basic motor skills. However, this argument refers to just a single study. The differential effects of first person and third person motor imagery is still a question deserving further research.

Several other studies have shown beneficial effects of motor imagery training on post-stroke motor recovery (64–71). However, the methods and research designs used vary considerably across studies, thus it is extremely difficult and risky to compare them. The majority of motor imagery studies to date can be characterized as case studies or non-controlled small sample studies (64–66, 68, 70). The training methods used also show a large variability. Some studies used guided imagery sessions as a therapeutic intervention (61–63), whereas in other studies patients had to exercise at home with the aid of written instructions (69). Some studies did not use motor imagery as defined by us in the present paper, but instead seem to use a more visual imagery training strategy (e.g. see the example in ref. 63). A review by Sharma et al. (12) showed that, to date, only 5 studies exist that are methodologically well designed. They conclude that the results of motor imagery justify some optimism for stroke rehabilitation, but that definite conclusions cannot be drawn yet.

MEASURING MOTOR IMAGERY ABILITY

Failure to measure motor imagery ability accurately is a major limitation of all of the reported clinical motor imagery studies. Research by Sirigu et al. (72) suggests that left parietal lesions can affect motor imagery ability. It is not unlikely that, in some of the clinical studies, patients with impaired motor imagery ability were included, leading to confounding results. Preliminary results of our own research[1] with 40 patients after stroke show that approximately 18% of the patients were selectively impaired in their motor imagery ability, whereas approximately 40% were simultaneously impaired on motor and visual imagery. Furthermore, it is not clear yet which patients could benefit most from motor imagery training, and why some are unable to imagine movements. The correlation between imagery ability and motor imagery training outcome in patients after stroke has not yet been studied. It therefore seems clinically relevant to determine whether a patient after stroke is, indeed, able to imagine movements before starting an imagery therapy. There are 3 different methods often used to measure motor imagery ability: questionnaires, mental chronometry and computer tasks.

Questionnaires

Motor imagery ability is often measured using a questionnaire such as the Motor Imagery Questionnaire (MIQ) (73) or the Vividness of Movement Imagery Questionnaire (VMIQ) (74). On the VMIQ, subjects have to indicate whether they are able to imagine a certain movement, such as walking or jumping. They have to rate this mental image with a score from 1–5. Often these questionnaires dissociate between first person, kinesthetic imagery and third person, visual imagery. Although frequently used, the scores remain a subjective reflection of the estimated capacity. Using these questionnaires in stroke rehabilitation is further complicated by the very nature of the brain damage itself, so that the results, even if validated in age-matched cohorts, are difficult to interpret and might not always reflect what they are supposed to measure.

Mental chronometry

Another way to probe someone's motor imagery ability is by using mental chronometry. Mental chronometry refers to the measurement of the duration of cognitive processes. Mental isochrony is based on the fact that the duration of mentally performed movements is more or less equal to the duration of actually performed movements. For example Decety & Boisson (75) measured the mental and actual duration of writing a signature, drawing a cube and a hopping movement in unilateral stroke patients and spinal cord injury patients. They showed that motor imagery of the hemiplegic side of stroke patients was comparably slower than imagery of a movement performed by the non-affected side. Motor imagery of the hemiplegic side was slowed, as was the actual movement of the affected limb. Motor imagery of movements by the non-affected side was not slowed at all. The match between imagined movement time and real impaired movement time suggests that the motor system used for online actual execution was also used for imagination of the movement duration. Consistent duration times of repeated measurements of the same movement are also a good indication of reliable motor imagery (75).

Computer tasks

A third, and promising, method may be found in the employment of computer tasks based on the mental rotation paradigm. Mental rotation tasks are based on the fact that the mental rotation time of a picture depends on the angular rotation of that picture. An example discussed earlier in this paper is the use of the hand recognition task (41). In this task, pictures of hands in different orientations are shown on a computer screen. Patients have to decide as fast as possible, by pressing 1 of 2 buttons, whether the picture is a left or a right hand. Response time and accuracy (number of errors) are registered via these key presses. As we have seen earlier in this paper, response times showed an angular dependence but more importantly, and in contrast with non-bodily stimuli, the response times were dependent on biomechanical constraints, in that the responses for biomechanically difficult orientations were slower than the response times for biomechanically easy rotations. Recall, that this fact indicates that the motor system is used covertly to solve this task. A few studies have successfully used different versions of these kinds of tasks in neurological patients (76–78).

MOTOR IMAGERY AND NEURAL REORGANIZATION

If motor imagery training results in significant changes in task performance, then it seems plausible that at the neural level a reorganization should have taken place, similar to the one related to normal (physical) training. There are a few studies that, indeed, report imagery-related neural reorganization. A well-known study by Pascual-Leone et al. (30) showed that motor imagery of finger movements resulted in the same reorganizational changes as actual physical practice. Subjects were taught a 1-handed 5-finger sequence on a piano keyboard. One

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[1] DeVries, Tepper and Mulder, manuscript in preparation..

group of subjects trained this task physically and another group of subjects practiced the task with motor imagery. The subjects were trained for 5 consecutive days, 2 hours a day. After each training session, TMS was used to determine whether the motor cortical map of the fingers had changed. The study showed that the obtained improvement in performance was reflected in changes in the cortical motor map of the fingers.

Similar findings have been reported in a number of recent neuroimaging studies (31, 79, 80). Jackson et al. (31) showed that the same changes in the cerebellum were observed for mental and physical practice. Cerebellum reorganization was also observed in a study by Lacourse et al. (80).

CONCLUSION

The literature reviewed here shows that imagery and/or observation-based training may be valuable new methods for post-stroke motor rehabilitation. Although the underlying mechanisms are not yet clear, it is evident that motor imagery, observation and execution rely on the same neural processes. Future research should pay particular attention to the role of the primary motor cortex in covert action representation processes and in motor recovery. Furthermore, it has been shown that neural reorganization may take place in a similar manner as would have occurred following physical practice.

The first clinical studies are promising and suggest that motor imagery training influences motor recovery in a positive way. Patients after early stroke and patients after chronic stroke both showed beneficial effects as a result of motor imagery training.

To date, reports on observation-based learning for post-stroke motor recovery are lacking. The designs of the clinical studies on motor imagery as well as the interventions used are very heterogeneous. Besides, almost all studies are characterized by very small sample sizes. Therefore, it is not possible to draw any general conclusion on ”best practice guidelines” for post-stroke motor imagery. Moreover, imagery ability and its relation to motor recovery remain (largely) unexplored in the reported studies.

The study by Liu et al. (63) showed that different imagery training strategies can potentially improve different aspects in post-stroke movement rehabilitation. It might be that a third person, visual strategy might be important to improve the relearning of new skills, whereas motor imagery could play a role in the recovery of actual motor co-ordination processes. Evidence from outside the rehabilitation setting seems to support the idea that co-ordination and timing of motor skills is learned better using first person imagery than using the third person perspective. The latter would result in a better performance on motor tasks that emphasize the form of a movement (81). The dissociation between kinesthetic imagery and visual imagery, and the fact that different neural processes were found that regulate these processes (39, 40), seem to support this hypothesis. This suggests that third person and first person imagery have to be used differently in a rehabilitation setting, depending on the aim of the therapy. However, the exact nature of the correlation between kinesthetic and visual imagery and their relationship to motor learning is not yet fully understood and the differential use of these both methods requires further study.

Hence, on the basis of the evidence reviewed in this paper, the use of motor imagery and observation seem to be justified. This justification is based primarily on theoretical grounds, since robust evidence-based clinical results are lacking. It is expected that the results of clinical trials will appear within the next few years. We hope that the present paper will be seen as a modest contribution to the further development of a neuroscience-based neurological rehabilitation.

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