

Motor imagery

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Abstract

We describe general concepts about motor imagery and differences to motor execution. The problem of controlling what the subject actually does during imagery is emphasized. A major part of the chapter is dealing with mental training by imagery and the usage of motor imagination in athletes, musicians and during rehabilitation. Data of altered representations of the body after loss of afferent information and motor representation due to limb amputation or complete spinal cord injury are demonstrated and discussed. Finally we provide an outlook on additional work about motor imagery important for further understanding of the topic.

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1. Introduction

1.1. General introduction

According to Jeannerod (1994, 1995) motor imagery (MI) represents the result of conscious access to the content of the intention of a movement, which is usually performed unconsciously during movement preparation. He concluded that conscious motor imagery and unconscious motor preparation share common mechanisms and are functionally equivalent. This may be the reason why mental practice using MI training results in motor performance improvements (review in athletes: Feltz and Landers, 1983).

Therefore a high overlap of active brain regions for movement execution (ME) and imagery is not astonishing. Interestingly, a clear image of an intended action can be present even without the limb involved in movement execution as it has been demonstrated in patients after traumatic limb amputation (Schilder, 1935) or deafferentation of half

of the body after complete thoracic spinal cord injury (SCI, Decety and Boisson, 1990).

In this chapter the recent literature on motor imagery is reviewed. We describe results on imagery in patients with cerebral, spinal and peripheral damage of the nervous system. Furthermore, we will provide insight in recent results about imagery training and relate knowledge of imagery to other fields such as movement observation.

1.2. The relation between motor execution and imagination

James (1890) and Jacobsen (1930) described that the mental image of a movement is always followed by discharges of its target muscles. In order to discriminate between movement execution and imagery these discharges have to be avoided. Therefore, subjects are instructed not to execute any movements of the target muscles and this is controlled by electromyography (EMG) feedback. By inhibiting the execution of a movement a conscious access of motor preparation may be possible (Jeannerod, 1994).

Nevertheless, imagery training in athletes, musicians and in stroke patients is usually associated with increased EMG activation of the target muscles as compared to rest.

On the physiological basis an execution of a movement and its imagery show several parallels. For instance,

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imagined weight lifting the forearm muscles shows a linear increase of amplitudes of the EMG-recordings with the magnitude of weight (Shaw, 1940). Since the autonomous nerve system cannot be directly modulated voluntarily, the immediately observed changes of heart rate (32–50% above rest) during imagined foot movements but also an increase in CO₂-pressure and in respiration frequency (Decety et al., 1991, 1993; Wuyam et al., 1995) may probably be grounded in a cerebral process as a part of the motor program. Decety (1996) proposed that during imagined activities a significant portion of the observed increase in autonomic response is of central origin as though the mind deludes the body into believing that some movements are being executed. The subjective rating of the mental effort to imagine a task correlates with the amount of force which is needed for the task execution.

Executed and imagined writing of the same letters, independently of the hand used, or executed and imagined walking of the same distances show the same durations (Decety and Michel, 1989). If the task is more difficult – for instance if subjects have to carry a heavy rucksack (25 kg) during the walk – they tended to overestimate the duration of IM. Therefore, Fitt's law (Fitts, 1954) – which states that more difficult movements take more time to produce physically than do easier ones – also applies to imagined movements (Decety, 1996; Decety and Jeannerod, 1996).

The process of imagination is not dependent on the ability to execute a movement but rather on central processing mechanisms. Compared to healthy controls, patients with lesions of the motor cortex and patients with Parkinson's disease (Dominey et al., 1995) show decreased movement velocity during ME and MI whereas patients with spinal lesions only show prolonged duration of ME but the same duration of MI (Decety and Boisson, 1990).

One central question is the contribution of the contralateral primary motor cortex (cM1) to motor imagery. This problem points to a basic understanding of the functional organization of the motor system. If cM1 would be a purely executional part of the motor system, no activity would be expected during the imagination of movements, or if so, it should be due to undetected movement execution during imagery. Several recent studies, using functional magnetic resonance imaging (fMRI), reported cM1 activation during MI (Leonardo et al., 1995; Sabbah et al., 1995; Porro et al., 1996, 2000, Roth et al., 1996; Lotze et al., 1999; Gerardin et al., 2000; Nair et al., 2003). Most of them did not avoid possible muscle discharges during MI of a sequential finger-to-thumb opposition task. Some fMRI studies avoided muscle activity during MI using an EMG controlled training (Leonardo et al., 1995; Lotze et al., 1999; Gerardin et al., 2000; Lafleur et al., 2002). Studies using Magnetoencephalography (MEG; Lang et al., 1996; Schnitzler et al., 1997) or transcranial magnetic stimulation (TMS; Pascual-Leone et al., 1995), controlling EMG-activity during the measurement, also support the involvement of cM1 during MI. In contrast, positron emission tomography (PET) studies did not find a significant activation in

cM1 during MI (e.g. Roland et al., 1980; Decety et al., 1994; Stephan et al., 1995). There may be predominantly two reasons for these discrepant results and both are methodologically grounded. The first is the factor time: it could be that cM1-activation during MI is present during a much shorter time period than during EM. Therefore it can be detected with electrophysiological measurements but not with methods with poor temporal resolution such as PET. Recent data support this view (Dechent and Frahm, 2003). The second may be grounded in the imagination technique: very simple motor images (which have been originally trained using movement execution and then stepwise with imagination of the movement avoiding EMG-responses of the target muscles) may access more assemblies of the primary motor cortex as compared to more complex movements or even visual imagery of “third person” techniques, for instance of observing a moving limb. This argument is supported by several studies: those with simple motor imagery using a kinesthetic training of MI (e.g. Leonardo et al., 1995; Lotze et al., 1999) demonstrated some cM1-activation; those with visual imagery, for instance of rotating the hand, did not see any contribution of the precentral gyrus neurons at all (Wolbers et al., 2003). Interestingly, it was found that an involvement of the cM1 is also absent if professional musicians perform music mentally. These subjects do frequently train musical performance with imagery techniques (Langheim et al., 2002; Lotze et al., 2003).

In Fig. 1 it is demonstrated that the contribution of cM1 in MI is also dependent on the evaluation method used. Although MI results in approximately 50% activation (activated voxels or significant activation of single subjects in a group) within the precentral gyrus in comparison to execution of the same hand movement (Porro et al., 1996; Lotze et al., 1999; Gerardin et al., 2000; Nair et al., 2003) a conservative threshold (correction for false positive responses in the whole brain volume) results in the impression that it is completely absent. In fact the representation is centered more anterior in the premotor cortex (PMC).

Although these activations seem to be functionally relevant because MI results in increased excitability of the muscle groups involved in the MI task if tested with TMS (Fadiga et al., 1999) damage of the precentral gyrus does not result in an impairment to imagine a movement (Sirigu et al., 1995). Nevertheless, imaging of moving different body parts (foot, hand and tongue) activates the precentral gyrus in a somatotopic manner (Stippich et al., 2002). Although there is some activation in the precentral gyrus during MI too, a direct comparison of ME minus MI reveals significant differences in the cM1 and the ipsilateral anterior cerebellar hemisphere during simple movements (Nair et al., 2003) and in musical performance (Lotze et al., 2003). It has been demonstrated cytoarchitectonically, that the dorsal bank of the primary motor area is separated in an anterior area (Brodmann's area: BA 4a), closely connected to BA 6 and a more posterior area (BA 4p), which is merely involved in pure motor execution.

Both areas contain different finger representations (Geyer et al., 1996). Whereas BA 4p is highly modulated by attention activation in BA4a showed to be independent on the attentional self-assessment of a task (Binkofski et al., 2002). It is not astonishing, that the activation sites during MI are located in area 4a, whereas those neurons within the precentral gyrus which are active during simple movement execution are more closely connected to the primary somatosensory areas (Stippich et al., 2002).

A recent paper combined fMRI and TMS measurements in complex and simple imagined movements (Kuhz-Buschbeck et al., 2003) and demonstrates that the primary motor cortex is increasingly involved in more complex movements which may support the hypothesis that the MI contribution to motor imagery is intensity and threshold dependent.

Taken together the primary motor cortex is involved in MI but the involvement is decreased, not essential for imagery and the neurons are located more anterior to those active during movement execution.

Cerebellar activations are highly correlated with those of the sensorimotor cortex since they are involved in the somatosensory feedback of the movement organizing a perfect transfer of the internal image of the movement into the actual physical conditions of the external world (Braitenberg et al., 1997). Astonishingly, the cerebellum is also activated during imagery of simple hand movements (Decety et al., 1994; Ryding et al., 1993). A closer look revealed distinct areas activated during MI than those active during ME: MI is located more posterior–inferior (centered in Larsell's lobule HVII) than those described during actual movements (centered in Larsell's lobule HIV; Lotze et al., 1999; Grodd et al., 2001). It has been assumed that the decrease of activation in the anterior cerebellum during MI is due to missing afferent information. The anterior cerebellar hemisphere is predominantly active during sensorimotor exploration movements (Gao et al., 1996) and receives sensory information via the spinocerebellar tract (closely connected via the dorsal nucleus dentatus to cM1 and the contralateral somatosensory cortex; cS1). Information about cortical control of movement is provided by the corticopontino-cerebellar tract, which is closely connected via the ventral part of the nucleus dentatus to the dorsolateral prefrontal parts of the cortex (Middleton and Strick, 1994). This tract closely links the upper part of the posterior cerebellum to the SMA and the premotor cortex. Along this pathway, aspects of movement coordination but also inhibition of movement execution may be connected between the SMA and the lateral cerebellar hemisphere (Rao et al., 1997).

Especially the posterior SMA and the premotor cortex (BA 6) seem to be the predominant areas of movement imagery. They have been consistently reported to be activated in all motor imaging studies (e.g. Roland et al., 1980; Stephan et al., 1995). Neurons in the SMA are involved in the preparation of movements and it is reasonable that preparatory aspects of a movement may be closely related to motor imagery.

Nevertheless Stephan et al., 1995 demonstrated that MI activates different areas within the SMA than motor ME which also included motor preparation: MI neurons were located in the posterior rostral SMA whereas ME activated a caudoventral part. Other studies confirmed these activation sites in the posterior SMA but reported additional pre-SMA activation during MI (Gerardin et al., 2000). Whereas the pre-SMA is involved in movement selection (Deiber et al., 1992) and preparation (Humberstone et al., 1997) the posterior parts are those active during execution (Deiber et al., 1992; Stephan et al., 1995) and in initiation (Passingham, 1997). In conclusion imagery seems to activate both the pre- and the post-SMA showing differential activation sites within the posterior SMA.

Several studies described that also the lateral part of BA 6 and here especially the dorsal part of the premotor cortex (PMC) is involved in MI (e.g. Stephan et al., 1995; Gerardin et al., 2000). Whereas these dorsal part may be closely overlapping with areas active during movement execution more ventral parts are activated in almost every subject during MI (Gerardin et al., 2000; for group statistics see Fig. 1). Different imagery strategies involve different parts of the PMC: whereas somatosensory imagination involves the dorsal PMC, visual strategies involve more ventral parts (Binkofski et al., 2000). Furthermore, a somatotopic representation within the PMC has to be considered: during movement observation the observed limbs are somatotopically organized (Buccino et al., 2001). The ventral part of the PMC is neighboring BA 44/45 involved in language production in human primates but also in movement observation and in action recognition in human (Grafton et al., 1997; Hari et al., 1998) and non-human primates (e.g. Rizzolatti et al., 1996). During imagery of observing trajectorial movements Binkofski et al. (2000) described activation not only in frontal medial wall areas, the bilateral intraparietal sulcus but also in the opercular part of the inferior frontal gyrus localized in BA 44 after overlay with cytoarchitectural probability maps. These activations can be interpreted to possibly demonstrate the location of the human analogue to the so-called mirror neurons found in inferior frontal cortex of non-human primates. A left-hemispheric dominance was found for egocentric movements and a right-hemispheric dominance for movement characteristics in space. Bilateral activation in the opercular part of the inferior frontal gyrus is also observed in kinesthetically trained imagery of fist movements (see Fig. 1). This neuronal activation contributes to both kinesthetic and visual imagery. Therefore, these neurons may be associated with the internal representations of movement concepts. Patients with left lateral prefrontal lesions were unable to imagine a motor task (Johnson, 2000) which points to the important functional role of this area for MI.

The superior parietal lobe and especially BA 7 has been reported to be activated during MI involving higher spatial aspects (joy-stick movement: Stephan et al., 1995; trajectorial movements: Wolbers et al., 2003). Parietal activation is often absent during kinesthetic imagery of simple move-

ments (see Fig. 1). The superior parietal lobe is closely connected with the posterior SMA but also with the PMC (Rizzolatti et al., 1998). Spatial trajectories of the movement may be transformed in corresponding motor programs processed and stored in the PMC (Sirigu et al., 1996). Patients with parietal lesions were found to have problems to predict the time necessary to perform differentiated imagined finger movements and visually guided pointing gestures. Damage restricted to the primary motor area does not result in these impairments (Sirigu et al., 1995). Therefore the parietal lobe seems to be crucial for training of MI in patients, musicians and athletes. In these groups the coding for the spatial qualities of the movement and the access to the storage of the movement trajectory may be predominantly interesting. Whereas the anterior part of the intraparietal sulcus is more involved in somatosensory imagery, the posterior is more active during visual imagery techniques (Binkofski et al., 2000).

We have seen that MI and ME share many anatomical substrates but are not completely overlapping. Imagery seems to have an important function in movement preparation but also in movement training. An interesting speculation for the role of MI, which would nicely go along with the findings of shared anatomical substrates, is to avoid actual injury of the subject in movement training and planning of complex or risky movements (Gerardin et al., 2000). And indeed, MI-training in athletes predominantly is used for risky disciplines like jumps into the water, on ice and over snow.

1.3. *What does the subject do during MI and how to control it*

Motor or kinesthetic imagery has to be differentiated from visual imagery because it shows different qualities: not the virtual environment is imagined in a third person's view but introspective kinesthetic feelings of moving the limb in a first persons view (Jeannerod, 1994).

The quality of imagery should be controlled as precisely as possible to guarantee a maximal homogeneous task over the group of participants of the study but also to have a better understanding of the task performed by the subjects for the interpretation of the data. Therefore a good description of the image which should be produced and a precise training of imagery is needed before performing the mapping. This training should include an actual execution of the movement for performing the kinesthetic task and an avoidance of actual execution during MI by using EMG control outside the scanner. To train visual imagery, an observation task may proceed to the actual imagery task.

The training time differs between subjects: in healthy subjects without previous experience in MI we performed the training as long as subjects rated their imagination vividly on a visual analogue scale (VAS of at least 4 from 0 to 6). Subjects who have experience in mental practice show substantially shorter training times before scanning than those who did not use MI-techniques (Lotze et al., 2003). Most

groups do not control EMG during actual scanning since the recording is hampered by fMRI artefacts. The physiological parameters such as heart and respiratory rate and of skin conductance (Roure et al., 1999) and the control of the time of the imagined movement in comparison to movement execution (Langheim et al., 2002) should be controlled additionally. Nevertheless, we have to admit that only very basic information is provided by these measures and a precise control of what the subject actually does during imagery remains an illusion. In order to control quantitative aspects of imagery techniques it has to be considered that frequencies easy to be performed during ME may be too fast to imagine for subjects who are not used to imagery training and most investigators therefore use frequencies with half of the velocity (0.5 Hz) predominantly used for movement execution in simple movements (1 Hz; Lotze et al., 1999). In trained subjects imagery of higher frequencies is possible (see musicians, Lotze et al., 2003).

Additionally, not only the frequency but also the force needed for the kinesthetic image has to be controlled, since the mental effort for MI is force dependent as described before.

2. Training motor skill with imagery

2.1. *What does mental practice mean, who uses it and what effect does it have?*

Jackson et al. (2001) summarized that “contrary to the conditions in which a motor task can be learned implicitly with physical practice, mental practice with MI requires that subjects have all the necessary declarative knowledge about the different components of the task before practicing. However, as with physical practice, the rehearsing of the task with MI can also give access to the non-conscious processes involved in learning the skilled behaviour”. Jackson concluded, that “internally driven images which promote the kinesthetical feeling of movements would best activate the different non-conscious processes involved during motor task training”.

Imagery techniques complement training in athletes and musicians. Interestingly, in both groups only highly specialized professionals apply these techniques for training pointing to the importance of a high level of execution training for the use of imagery. Jeannerod (1994) highlighted the role of a preceding execution for a vivid kinesthetic image. Therefore mental training can be seen as a complementary technique to execution training but should not be used as a substitute to EM. Training by using imagery techniques improves the strength of an isometric movement (EM 30%; MI 22%) without increasing EMG activity above rest in a 4 week training period (Yue and Cole, 1992). Obviously, no increase in muscle mass has been observed – the increasing strength may be caused by adaptive changes in the central processes. Furthermore, it has also been reported that motor imagery improves the dynamics of motor performance, for

instance the movement trajectories (Yáñez et al., 1998; Gandevia, 1999). The lower effect of MI training compared to ME training (see Feltz and Landers, 1983) may be caused by lacking sensorimotor feedback which results in decreased progress in motor training in lesion patients (e.g. Han et al., 2002).

By training sequential foot-movements with ME and MI Lafleur et al. (2002) observed overlapping areas during the late versus the early training sequence in the left orbito-frontal lobe and the left and right striatum. During early training the inferior left parietal lobe and the left cerebellar hemisphere (IM was located more inferior–anterior) was activated during both ME and IM. Observations during the early training periods of ME revealed a decrease of cerebellar activation sites with continued practice over several days to 4 weeks (e.g. Penhune and Doyon, 2002) which is followed by an increase of activation within the basal ganglia (e.g. Doyon et al., 1996).

In both groups who extensively use mental practice, the athletes and the musicians, the imagery technique is not purely kinesthetic but includes visual (for instance in ski-jumping, gymnastics, high diving) and auditory (musicians) imagination components. Furthermore, as it has also been mentioned before, tension in the target muscles is increased up to visible movements (e.g. fingers in violin players).

2.2. MI-training in athletes

Athletes predominantly use repetitive kinesthetic imagery for training in the intention to improve performance. By repetitive activation of motor networks characteristic for a movement sequence a strengthening of synaptic transmission in these neurons may be possible in the same way as it has been shown for motor execution training (Sakamoto et al., 1987). Mental practice improves performance in athletes (Driskell et al., 1994). Roure et al. (1999) showed a positive correlation between rating of the quality of imagery using changes in autonomic measures such as heart rate, respiratory frequency and skin conductance and the improvement in performance of volleyball. The better the imaging the better the training effect of mental practice. Professional players use these imagery strategies much more often than amateurs (Cumming and Hall, 2002).

2.3. MI-training in musicians

While learning to play an instrument has led one to focus mainly on the overt, observable behavioural aspects of skill acquisition, the benefits of mental imagery in motor skill learning and its use as a tool to probe the neural basis of actual motor performance have recently become increasingly appreciated (e.g. Yue and Cole, 1992; Langheim et al., 2002; see Pascual-Leone, 2001 for a review). Contrary to findings during kinaesthetic MI of simple movements, Langheim et al. (2002) investigated imagined musical performance, and did not find cerebral activations in cM1. Instead, they reported an activated network of lat-

eral cerebellar, superior parietal and superior frontal activation and concluded that this network is likely to coordinate the complex spatial and timing components of musical performance.

Experienced musicians are known to employ motor imagery to improve their performance as well as to memorize the aesthetic-emotional concept of the musical piece. It is conceivable that with increasing experience in the mental performance, the activation sites related to motor imagery may also undergo systematic changes. Activations may become more focused and shift to tertiary areas which deals with more abstract, less motor-centered internal representation of the musical performance.

During five days of training of musical performance both MI and ME resulted in an increase of cM1 map size of the long finger flexors/extensors as assessed with TMS (Pascual-Leone et al., 1995). Again subjects with the executed training displayed a greater increase in performance, but MI resulted also in a training effect. Most interestingly, the MI group demonstrated the same training effect after one additional ME training session as the ME group pointing to the importance of combining MI and ME in musical performance training.

By comparing fMRI-activation maps of professional and amateur violinists during imagined musical performance of the first passage of Mozart's violin concerto in D-Major, we observed substantially lower BOLD-effect in the professional group focussed on very few cerebral areas whereas amateurs manifested a widely distributed activation map, and scored their vividness of imagined movement lower (Lotze et al., 2003). Professionals showed only some discrete increases: the SMA, the superior PMC, more anterior areas (Larsell's lobule HVI) in the left cerebellar hemisphere and bilateral superior parietal areas. An increased access to superior parietal and anterior ipsilateral cerebellar regions in the professional group may illustrate more efficient recruitment of stored sensorimotor engrams during IM. Furthermore, an increased cerebellar access in the highly trained group may also be caused by an increased recruitment of temporal processes such as extracting the essential temporal information (Mathiak et al., 2002) and the shaping of appropriate timed motor responses (Kawashima et al., 2000). In fact, the cerebellum may be a mediator within a necessary circuitry for the sensory-motor system to process the incoming, ongoing, and feedback sensory information through which it (1) extracts the essential temporal information, and (2) shapes the appropriate timed motor responses (Penhune and Doyon, 2002).

Although professional musicians report vivid imagination of melody's pitch during their usual imagery training, the right primary auditory cortex, which has been reported to be predominantly active during listening to musical material (Zatorre and Samson, 1991; Tramo, 2001), is not activated during imagery of musical performance (Langheim et al., 2002; Lotze et al., 2003). During ME the primary motor and auditory cortex are tightly coupled (Bangert et al., 2001) but this coactivation is completely

absent if none of the two areas is directly accessed in actual musical motor performance or listening to music.

2.4. MI-training in patients during motor rehabilitation

Although imagery training has been demonstrated to achieve less training improvements than motor execution in healthy volunteers (Herbert et al., 1998; Pascual-Leone et al., 1995; Yue and Cole, 1992) it would be of interest to combine this training with execution training. This would offer the opportunity to add additional training effects, start training earlier – even in a plegic state – and provide a training method which could be performed by the patient alone after some instructions. Up to now, imagery training with patients suffering from acute or chronic stroke is performed predominantly for research. Some centers have gained experience for years with MI-training in stroke patients (e.g. Weiss et al., 1994; Miltner et al., 1999) but all of them select specially suited patients for this intervention: low neuropsychological impairment, high imagery scores and predominantly chronic stroke patients. One study compared conventional physiotherapy and physiotherapy combined with imagery training of movements of the hand (10 minutes and training at home; 13 patients) in subacute to chronic stroke patients and demonstrated a greater improvement of hand function with the additional mental practice (Page et al., 2001). An improvement of motor function has been demonstrated in chronic stroke patients but again the effect is smaller than during execution training. In order to increase the effect of imagery training, a sensory feedback is additionally provided to the patients. The patients affected hand is passively moved to provide somatosensory feedback and the movement of the intact hand is mirrored to give the visual illusion of a movement of the affected side (Miltner et al., 1999; Stevens and Stoykov, 2003). Observation of movements, somatosensory feedback and imagined movements may have an additive effect for training. It has to be kept in mind that patients with parietal lesions (Sirigu et al., 1996) but also with left lateral prefrontal lesions (see mirror neuron system; Johnson, 2000) are not able to imagine a motor task. Bilateral parietal lesions even resulted in a complete unawareness of movement execution during imagery (Schwoebel et al., 2002). Also in a patient with lesions of the putamen, selective impairment in kinesthetic but not visual imagery has been described (Li, 2000) pointing to the role of subcortical structures in mental practice.

3. Altered body image

3.1. Peripheral lesion: amputees

Patients with upper limb amputation usually show vivid representation of the arm and hand even many years after deafferentation (Berlucchi and Aglioti, 1997). Since amputees generally perceive movement of the phantom hand as real movements rather than imagined movements, it is

likely that phantom movements in amputees substantially activate both cM1 and cS1. In an fMRI study, Erslund et al. (1996) reported cM1-activation during imagined hand movements of an upper limb amputee. In congenitally amputated patients no primary cortex activation has been observed although vivid non-painful phantom sensations were present (Brugger et al., 2000). This underlines the hypothesis that primary motor access with MI is only possible if an execution of the movements was possible before the injury occurred.

During MI of the phantom hand all 14 amputees included in our study showed increased activation in both cM1 and cS1 compared to healthy controls (Lotze et al., 2001). Twelve of fourteen amputees spontaneously reported a feeling of actual movement of the phantom hand when they were asked to imagine movements. Accordingly, cM1 activation correlated positively with the vividness of the perceived phantom movement. This may be related to a high degree of attention to the phantom limb (Berlucchi and Aglioti, 1997). To control for this attentional factor a comparison of the PLP patients with patients suffering from an acute or chronic pain problem might be useful.

In patients suffering from painful phantom sensations, imagined movement of the phantom also activates the cortical mouth representation. This coactivation is probably due to the high overlap of the hand, arm and mouth representation generally observed during sensory stimulation in amputees with phantom limb pain (see for example Flor et al., 1995; Kew et al., 1994). On the behavioral level this coactivation is reflected by the fact that stimulation of the mouth area often activates phantom sensations in the amputated arm or hand (cf. Ramachandran et al., 1992).

Fig. 2 shows the group statistics of seven patients with traumatic amputation of the upper limb (see Lotze et al., 2001) suffering from phantom limb pain and seven other patients with the same level of amputation but no PLP. Patients of both groups were investigated during fist movements of the absent fist. These data are compared with those of seven healthy controls who imagined to make a fist with their non-dominant hand. Controls were selected from 10 showing a very vivid imagery during scanning (average VAS (0–6): 4.3).

3.2. Spinal cord injury

Sabbah et al. (2002) investigated eight patients with complete thoracic to lumbal spinal cord injury (TH 6–L 2, one month to 33 years after the injury; ASIA A) and one patient with some somatosensory information from the lower limb (ASIA B) during imagined (all 0.5 Hz), attempted and passive toe movements with and without visual observation. Whereas the passive movements elicited only activation around the rolandic sulcus in three patients, the movement observation increased the amount of cS1 and cM1-activation to four patients and movement imagination demonstrated MI-activation in six of nine patients whereas eight showed SMA and PMC activation.

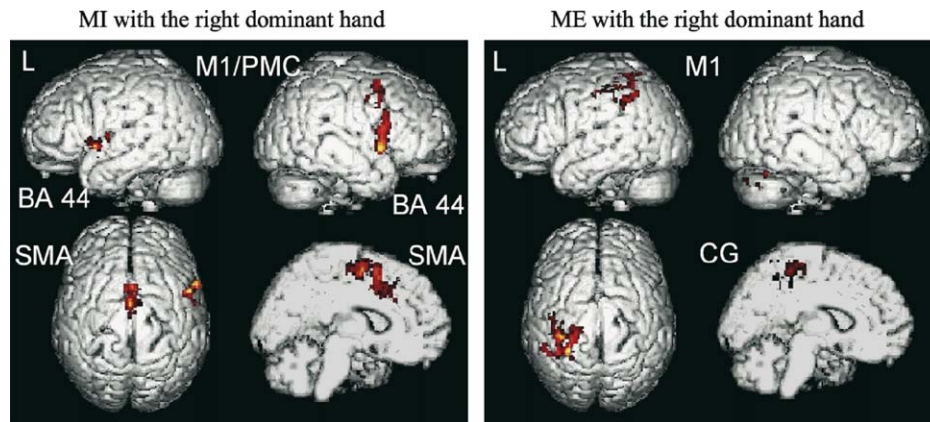


Fig. 1. Normalized data of 10 subjects imagining fist clenching with their right, dominant hand. With a very conservative cut off of $p < 0.01$ and a spatial correction for the whole brain volume ($p < 0.05$) cM1 activation is absent but premotor cortex (PMC), bilateral activation in the pars opercularis of the gyrus frontalis inferior (mirror neuron system) and SMA-activation is prominent. Movement execution of the same subjects showed only activation in the contralateral M1 and the motor part of the cingulate gyrus (CG) (right).

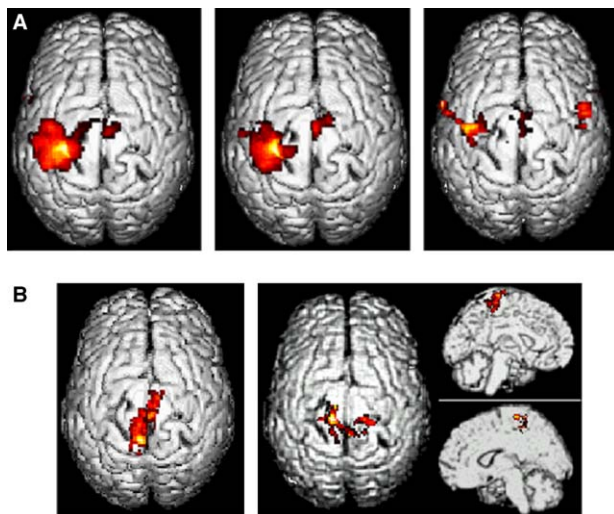


Fig. 2. (A) Left: seven upper limb amputees with phantom limb pain during imagined fist movement (VAS: 4.00 of 7) of the phantom hand. Middle: the group-activation maps of seven patients doing the same without PLP (VAS 2.21 out of 7). Right: seven healthy controls imaging to move the left non-dominant fist (for all: statistical threshold: $p < 0.01$; corrected). (B) Left: activation map of five healthy controls performing right sided foot movements (elevation in the ankle predominantly performed by musculus tibialis anterior). Right: activation map of four patients with thoracic spinal cord injury imagining (vividness average: 3.87 of 6) to elevate the foot. Sagittal medial slices allow to control for actual activation in the primary motor cortical foot area (for all: $p < 0.01$; corrected).

Interestingly no cM1-activation was observed in the patients who were deafferented longer than 19 years. All activations in healthy controls (four of six showed significant cM1-activation during imagined movement of the toes) were stronger than those of SCI-patients. Eight of nine patients activated the primary motor area if they attempted to move the toes (no activation was observed in a patient who was deafferented since 19 years). These data support the opinion, that representations after SCI

remain active although these are deafferented. Nevertheless, most of the patients who were deafferented for decades could not access their primary toe area by imaging techniques although they accessed it if they tried to move. This may support the opinion that an access of the primary motor cortex during MI may only be possible if an actual kinesthetic image of executing the limb is vividly present and did not fade.

4. Conclusions

This chapter has offered a short overview on studies investigating motor imagery and mental practice. It has demonstrated some problems underlying investigations about MI-for instance the insufficient control of the MI-task during investigations. Furthermore, the overlap between movement imagery and execution was demonstrated in relation to the concept of movement but also concerning the areas activated during both tasks as assessed with different evaluation methods. The most challenging questions for future studies have already been a topic of interest in some latest investigations: imagery can provide a tool for investigating different movements which can not be investigated with brain mapping techniques using walking and running paradigms (Malouin et al., 2003). Imagery improves motor training in healthy volunteers and patients. The different stages of training with execution and imagery should be compared to different techniques of mental practice in respect to improvement of performance (e. g. Lafleur et al., 2002; Jackson et al., 2001). By combining both ideas, the mental practice training in different athletes can be investigated with mapping methods. Furthermore, mental practice should be investigated in patients who show different deficits of motor performance. Strategies for selective therapy with mental practice could be developed and brain maps may demonstrate different effects in patient groups than recently demonstrated in healthy controls.

Furthermore, the contribution of neurons in the pars opercularis of the gyrus frontalis inferior (mirror neurons) and their contributions to a mental image of the movement should be investigated in detail – an overlap to the chapter of Binkofski in this issue. Problems with an image generation have been described not only for patients with parietal but also with frontal lesions. The differential role of these highly interconnected systems is of special interest also for numerous patient studies (lesions, disrupted body image, gesture perception).

Last but not least the integration between distorted representation sites within the pre-and postcentral gyrus, the basal ganglia and the mirror neuron system in the relation to an altered body image after amputation, SCI and cerebral lesions would be extremely interesting.

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