

Corticospinal Excitability Modulation to Hand Muscles During Movement Imagery

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Motor evoked potentials (MEPs) to magnetic transcranial stimulation (TCS) were recorded from right abductor digiti minimi (ADM) and first dorsal interosseous (FDI) muscles, sharing the same peripheral innervation but engaged in two different motor demands. In seven healthy and trained subjects, the latencies, amplitudes and variability of MEPs were investigated under the following, randomly intermingled, conditions: full muscular and mental relaxation; mental simulation of selective index finger or little finger abduction; mental non-motor activity (arithmetical calculation); and real motor task (little and index finger abduction). The whole procedure was performed by continuous audiovisual monitoring of electromyographic 'silence' in the tested muscles. The maximal facilitatory effects (= latency shortening and amplitude increase) on MEPs were induced by the real motor task. An amplitude potentiation of MEPs in both tested muscles was present during non-motor mental activity, in comparison to basal values. A further amplitude potentiation, without latency shifts, was confined to the muscle acting as 'prime mover' for the mentally simulated movement, according to the motor program dispatched but not executed by the subject. Similar results were also found in the F-wave, showing that mental simulation affects spinal motoneuronal excitability as well, although – due to the lack of MEP and F-wave latency shift – the main effect takes place at cortical level. The study shows that movement imagery can focus specific facilitation on the prime-mover muscle for the mentally simulated movement. This is mainly evident on FDI muscle, which controls fingers (i.e. the index) with highly corticalized motor representation.

Introduction

Cognitive, physiological and metabolic approaches have been explored in movement imagery in an attempt to clarify whether and how neural structures and mechanisms underlying the mental rehearsal of motor acts share similarities with those of movement preparation and execution (Decety, 1996). The growing interest in motor imagery is based on the possibility that mental training improves motor performance as in the case of actual physical training (Yu and Cole, 1992) and on its implication for possible rehabilitative strategies, as recently demonstrated in patients with neglect syndrome (Smania *et al.*, 1997). Thus, motor imagery is becoming a popular issue both in basic and clinical research protocols (Crammond, 1997).

Magnetic transcranial stimulation (TCS) has the advantage of being easily reproducible, non-invasive and able to provide useful information, both in the healthy and in the diseased (for review, see Rossini and Rossi, 1998), on the excitability and conductivity of the entire motor pathway (i.e. from the cortex to the target muscle). By using electric TCS, Gandevia and Rothwell (1987) described for the first time that trained subjects were able to focus internal motor commands to motoneuronal pools governing individual motor units of intrinsic hand muscles, giving rise to an amplitude facilitation of motor evoked potentials (MEPs). Other authors have described facilitatory

effects on motor output during different motor imagery tasks (Izumi *et al.*, 1995; Abbruzzese *et al.*, 1996; Kiers *et al.*, 1997; Kasai *et al.*, 1997; Rossi *et al.*, 1998a). The question whether MEP facilitation during motor imagery relies on a kind of corticospinal activity connected to the motor program, or is related only to an increased and generalized attentional effect, has been recently addressed (Rossi *et al.*, 1998a) for forearm muscles. Conflicting results have emerged on the possible role played by spinal mechanisms, which cannot be explored with available neurometabolic techniques: Abbruzzese *et al.* (1996) and Kasai *et al.* (1997) found no change in the H-reflex during motor imagery, while modulation on the H-reflex pathway has been described as well (Oishi *et al.*, 1994; Bonnet *et al.*, 1997; Kiers *et al.*, 1997).

In the present investigation, we wanted to address the following points: does mental simulation of hand movements facilitate MEPs through non-specific alerting mechanisms which are not directly related to movement programming? And if not, can movement imagery shift facilitation from one hand muscle to another simply by changing the mentally programmed motor task, so that it involves different prime-movers?

For this purpose, MEPs were simultaneously recorded from two hand muscles – first dorsal interosseous (FDI) and abductor digiti minimi (ADM) – that share the same peripheral innervation but are engaged in two different motor demands. In this paradigm, MEPs were simultaneously gathered from both muscles during randomized conditions, including complete muscular relaxation, mental imagery of appropriate movements, arithmetical calculation, and simultaneous voluntary index and little finger abduction (= real motor task). The same conditions were separately run during an F-wave paradigm from FDI and ADM muscles, in order to test concurrent changes, if any, taking place at spinal level.

Materials and Methods

Seven healthy right-handed (Oldfield questionnaire) fully informed volunteers from the Neurology Department staff (four males; age range 29–46 years) were enrolled in the study after the approval of the procedure by the local Ethical Committee. The examined subjects lay supine on a bed in a relatively silent room. They looked at a fixed point on the front wall and did not have visual access either to the equipment display or to their hands. All of the subjects were familiar with the procedure, having shown their ability to achieve full muscular relaxation when utilized as subjects and to produce mental activity, including motor imagery, without muscle activation (Rossi *et al.*, 1998a).

Stimulating Procedures and Experimental Design

Magnetic TCS was performed via a circular coil (inner diameter 10 cm) connected to a biphasic Cadwell MES-10 stimulator. The coil was positioned in the region of the left hemiscalp triggering MEPs with minimal threshold – defined according to international standards as the intensity eliciting reproducible MEPs of minimal amplitude in ~50% of 10–20 consecutive trials (Rossini *et al.*, 1994) – from the contralateral

examined muscles; it was then kept in the ascertained position throughout the whole session via Velcro strips fixed around the head. It is known that excitability thresholds for hand muscles usually share similar values (Wassermann *et al.*, 1992); moreover, the relatively large volume of the induced eddy currents from the round coil was simultaneously reaching the 'hot-spots' for both ADM and FDI muscles (Brasil-Neto *et al.*, 1992; Rossini *et al.*, 1994; Rossi *et al.*, 1998b). Since commercially available stimulators provide different types and intensities of magnetic impulses, these are routinely expressed as a percentage of the stimulator's maximum output (Barker *et al.*, 1985) (2.0 Tesla maximum output in our case).

Experiment 1 (MEPs from FDI and ADM)

Subjects were trained to mentally simulate either one of two different types of movements: an index finger abduction, in which the FDI muscle participates as 'prime mover' (Tomberg and Caramia 1991), or a little finger abduction, which is mainly driven by activation of the ADM muscle.

After the training period, MEPs were simultaneously gathered from the right FDI and ADM muscles under four experimental conditions, randomly administered (as indicated below) by one of the examiners, and stored on disk for off-line analysis.

The following items were included in this experimental protocol:

1. Complete mental and muscular relaxation; this condition will subsequently be referred to as '*Relax*'.
2. Imagery of index finger abduction (= mental activation of the FDI, with the ADM at rest); subsequently referred to as '*Index*'.
3. Imagery of little finger abduction (= mental activation of the ADM, with the FDI at rest); subsequently referred to as '*Little*'.

Simulated movements were performed 2–3 s after the appropriate verbal command given by one of the experimenters, and therefore outside of the usual reaction time for a normal subject; and

4. Mental calculation (progressively subtracting 7 from different numbers provided by one of the examiners); subsequently referred to as '*Calc.*'.

Electromyography (EMG) was continuously monitored at high gain, and trials contaminated by unwanted EMG bursts were discarded. It must be emphasized, therefore, that no EMG activity was present during the various experimental stages unless specifically requested by the experimenter. Finally, at the end of the task, MEPs were simultaneously gathered 6–8 times during a slight (10–15% of maximum force) active voluntary, simultaneous contraction of each of the examined muscles (real motor task).

Experiment 2 (F-waves)

In six subjects, '*Relax*', '*Index*', '*Little*' and '*Calc.*' conditions were replicated – in a separate session – during supramaximal electrical stimulation of the ulnar nerve trunk at the wrist and simultaneous recording of compound muscle action potentials and F-wave responses from ADM and FDI muscles. The F-wave is the late muscular response following maximal intensity stimulation of peripheral nerve motor fibres and is mainly due to backfiring from the large α -motoneuron pool in the spinal cord (Kimura, 1983), the same common final way travelled by the descending TCS volley (Day *et al.*, 1989).

The following parameters were evaluated: latency, peak-to-peak amplitude and duration of the compound muscle action potentials, F-wave persistence [i.e. according to Fischer (1992), the percentage of elicited F-waves in relation to the number of stimuli delivered], F-wave chronodispersion [i.e. according to Panayiotopoulos (1996), the scatter or dispersion of onset latencies in the different trials], F-wave amplitude and duration.

Recording Procedures

Ag/AgCl disk electrodes were firmly taped on the examined muscles in a belly-tendon short bipolar montage, with the active electrode placed on the motor point of each muscle, after lowering the skin-electrode impedance below 10 k Ω . A total time epoch of 100 ms was analyzed in

each trial by a four-channel electromyograph (Multibasis Esaote Biomedica), the first 50 ms serving as pre-trigger analysis time. MEPs were recorded with a bandpass filter of 5 Hz–5 kHz (–6 dB/oct), sampled at 20 kHz, with a gain ranging from 100 μ V to 1 mV.

Data Analysis

A total of at least 120 trials in each subject were analyzed, in an attempt to capture statistically valid deviations from the natural variability of MEP amplitudes at rest (Rossini *et al.*, 1991). Trials with detectable EMG activity in the pre- and post-stimulus analysis time, and with acoustic feedback of background EMG activity, were discarded from further analysis. For this purpose, on-line audio and off-line visual inspection of each trial was performed using the maximum display sensitivity. Whenever unwanted EMG or other artifactual activity contaminated one of the two traces, the other simultaneously acquired trace – even if EMG or artifact free – was discarded as well. In this way, only trials without EMG activity (i.e. in complete muscular relaxation) were processed for the 'imagery' task of the protocol.

MEPs and F-wave latencies were measured at the onset of the initial reproducible deflection; amplitudes were taken between the two largest peaks of opposite polarity. Logarithmic transformation was applied to amplitude values in order to normalize their distribution and to reduce the heteroschedasticity between different conditions. Since interest was focused on the relative effect of the experimental conditions, the average of values during '*Relax*' for each subject was considered as 100% while the effects of the other task conditions were expressed as percentage changes. Therefore, measures obtained in '*Index*', '*Little*' and '*Calc.*' have been compared with each other and with those obtained in the '*Relax*' condition. This was also useful in excluding the influence of nonspecific generalized effects of remote muscle tension due to mental activity. The above-mentioned differences were evaluated by means of one-way ANOVA, followed by *post-hoc* Tukey's comparisons.

Since MEPs, as well as F-waves, were simultaneously recorded from the two muscles, a correlation analysis was performed in order to verify whether the different experimental conditions produced different patterns of association (i.e. direct, inverse, null) between the responses obtained in the two muscles. Such an association was tested by Pearson's product-moment *r* coefficient. Significance level was set at 0.05 for every kind of analysis.

Results

On average, ~20% of trials were discarded from statistical analysis due to the presence of EMG or other artefactual activity in the pre-trigger analysis period. Discarded trials mainly pertained to the end of the experimental session, probably due to mechanisms associated with mental fatigue in maintaining EMG silence during the mental simulation of the movement. However, this point is not specifically addressed in the present paper. In one subject, despite training in electrophysiological measurements, >60% of trials were discarded because of contamination by EMG activity in pre-trigger analysis time; hence, data from this subject was excluded from further evaluation.

Experiment 1

Table 1a summarizes MEP latency variations in all of the experimental conditions. The significance of the F-test ($P < 0.001$) in ANOVA was only reached during voluntary contraction, which significantly shortened latency (Tukey's test, $P < 0.001$ with respect to every other condition). Figure 1 displays original tracings from the two hand muscles in the different experimental conditions.

As shown in Table 1b, active voluntary abductions of the index and little fingers (real motor task) produced, besides the maximal latency shortening, the maximal amplitude potentiation ($P < 0.001$) in the FDI or in the ADM respectively. Percentage amplitude changes, with the exception of the '*Contraction*' condition, are shown also in Figure 2 (upper

Table 1

Percentage variations of FDI and ADM MEPs: (a, b) mean values and standard deviations; (c) differences between percentage increments of log amplitude values and relative Tukey's significance levels

	Relax	Index	Little	Calc	Contraction						
(a) Latency (%)											
FDI	100.0 ± 2.6	99.1 ± 2.9	99.3 ± 2.2	100.0 ± 2.5	93.9 ± 5.9						
ADM	100.0 ± 3.3	99.7 ± 3.2	98.4 ± 3.3	99.2 ± 2.9	92.1 ± 6.9						
(b) Amplitude (%)											
FDI	100.0 ± 13.7	113.3 ± 13.1	106.3 ± 16.9	107.5 ± 12.7	150.3 ± 26.9						
ADM	100.0 ± 16.5	104.0 ± 17.8	110.5 ± 21.1	108.9 ± 17.8	174.9 ± 25.7						
(c) Amplitude differences (%)											
Conditions	FDI					ADM					
	Relax	Index	Little	Calc.	Contraction	Relax	Index	Little	Calc.	Contraction	
Relax	–	–13.3***	–6.3*	–7.5**	–50.3***	–	–4.0	–10.6**	–8.9**	–74.9***	+
Index	13.3***	–	7.0**	5.9*	–36.9***	4.0	–	–6.5	–4.9	–70.9***	+
Little	6.3*	–7.0**	–	–1.1	–44.0***	10.6**	6.5	–	1.6	–64.4***	+
Calc.	7.5**	–5.9*	1.1	–	–42.8***	8.9**	4.9	–1.6	–	–66.0***	+
Contraction	50.3***	36.9***	44.0***	42.8***	–	74.9***	70.9***	64.4***	66.0***	–	+

* $P < 0.05$; ** $P < 0.01$; *** $P < 0.001$.

diagram). The ANOVA demonstrates that the 'condition' factor is statistically significant for both muscles (consistently, $P < 0.005$): mental activity, including arithmetical calculation, produced a generalized increase in MEP amplitude, but the maximal facilitatory effect was reached in both muscles during the appropriate mental motor task. In fact, mental simulation of index finger abduction induced a significant increment of MEP amplitude size in the FDI muscle. Such a facilitation, related to the motor program – dispatched but not executed by the subjects – was also present in the MEP amplitude of ADM muscle during the 'Little' condition, although the difference between the latter and the 'Calc.' condition was not significant. Table 1c reports the differences between all pairs of conditions with relative Tukey's P values.

In Figure 3, the scatter plot of all sequences of MEPs (simultaneously recorded by FDI and ADM muscles) is represented for each experimental condition. During voluntary contraction, the correlation of amplitude potentiation in the two muscles was maximal ($r = 0.74$), indicating that the variation of ADM MEP increment was significantly accounted for by the variation in FDI MEP ($P < 0.001$). Also arithmetical calculation determined a significant association ($r = 0.48$, $P < 0.001$) of MEP amplitude increment in the two muscles. Conversely, in the 'Index' and 'Relax' conditions this concordance vanished (respectively $r = -0.08$, $r = 0.17$, $P > 0.20$), suggesting that the behavior of the FDI MEP amplitude changed independently from that of the ADM. Finally, in the 'Little' condition the concordance remained significant ($r = 0.31$, $P = 0.011$), suggesting that the potentiation of ADM MEPs during mental simulation of appropriate movement was quite similar to that observed during the mental non-motor activity.

Experiment 2 (F-waves)

Latency and amplitude of FDI and ADM compound motor action potentials, elicited by the stimulation of the ulnar nerve at the wrist, were similar in all conditions; thus, changes occurring in neuromuscular districts during the various experiments could be ruled out. It is worth noting that the persistence of F-waves, which in the 'Relax' condition was 76.2% for the FDI and 75% for the ADM, similarly and nonspecifically increased from 83.3 to 89.5% during every mental task. F-waves were not identifiable during voluntary contraction due to the superimposition in time

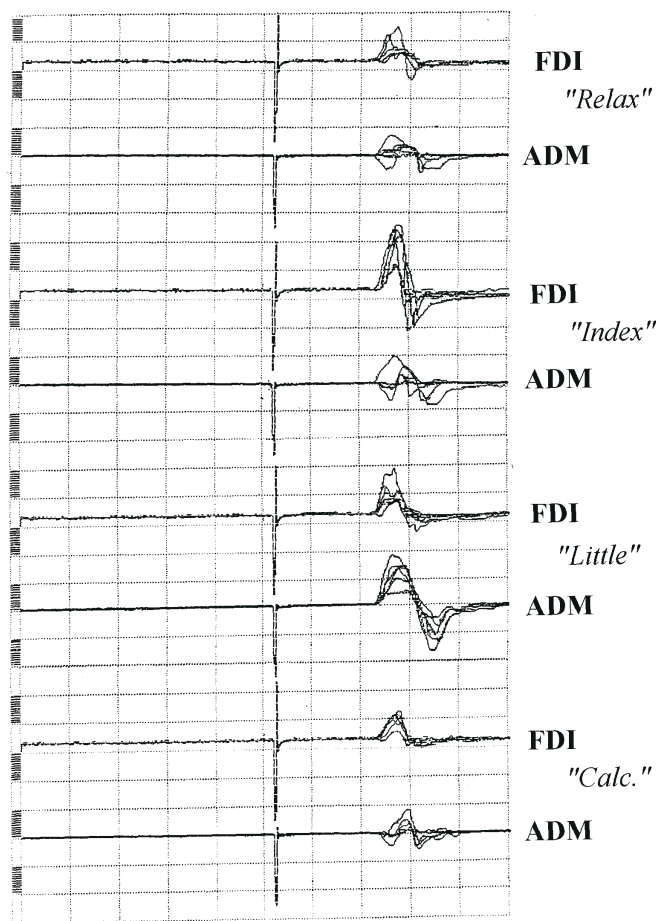


Figure 1. Pairs of MEPs simultaneously recorded from right FDI (upper line = first dorsal interosseus) and ADM (= abductor digiti minimi) muscles following TCS of the left hemisphere (10% over the threshold) in one representative subject during a random sequence of the four experimental conditions: from the top, mental relaxation ('Relax'), mental simulation of index abduction ('Index'), little finger abduction ('Little') or arithmetical calculation ('Calc.'). The initial 50 ms represent the pre-trigger (left of the vertical stimulus artefact) analysis time. Each trace contains six superimposed trials. Latencies of MEPs are unaffected, while amplitude potentiation is evident in the muscles acting as prime mover in the movement imagery.

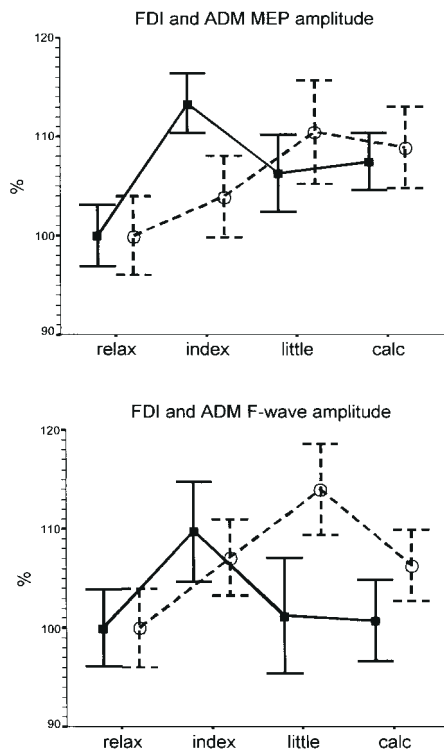


Figure 2. (Upper) Percentage changes of mean log amplitude MEP values during the different experimental conditions. A value of 100%, independently for each subject, indicates the mean value during 'Relax'. In both muscles, the non-motor mental activity ('Calc.') induced an increase of MEP amplitude compared with 'Relax'. However, the maximal potentiation is reached in the FDI muscle (filled squares) during mental imagery of index finger abduction ('Index') and in the ADM muscle (open circles) during mental imagery of little finger abduction ('Little'). Such a pattern of specific facilitation appropriately induced by the motor plan is even more evident for F-wave amplitudes (lower diagram); in this case, moreover, mean values during non-motor activity ('Calc.') return to values close to 'Relax'.

with much larger H-reflexes (a late muscular response utilizing myotatic reflex circuitry). Table 2 summarizes F-wave latency (Table 2a) and log amplitude (Table 2b) percentage variations across experimental conditions. ANOVA revealed that only amplitudes significantly changed across conditions ($P = 0.014$ and $P = 0.001$ for FDI and ADM respectively), while no significant differences were found as far as latencies were concerned. As shown in Figure 2 (lower diagram) and Table 2c, mental simulation of appropriate movement induced a significant amplitude potentiation in the ADM during the 'Little' condition and, to a lesser but still significant extent, in the FDI muscle during the 'Index' condition. However, a certain degree of potentiation was observed also in the FDI during mental little finger abduction and during mental calculation in the ADM. F-wave duration and chronodispersion did not vary significantly across conditions.

Altogether, these findings indicate that spinal motoneuronal excitability changed appropriately with the motor plan. The absence of latency shifts favors the hypothesis that such changes were due to a modulation of the same spinal motoneurons activated during 'Relax' rather than a recruitment of other neural spinal pools, which would probably have discharged also with different latencies and chronodispersion.

Discussion

Voluntary contraction of the target muscle(s) involved in a specific motor plan induces a shortening of the latency and an

Table 2

Percentage variations of FDI and ADM F-waves: (a, b) mean values and standard deviations; (c) differences between percentage increments of log amplitude values and relative Tukey's significance levels

	Relax	Index	Little	Calc				
(a) Latency (%)								
FDI	100.0 ± 2.9	100.0 ± 2.7	99.7 ± 3.0	100.0 ± 2.6				
ADM	100.0 ± 2.3	99.8 ± 2.1	99.4 ± 1.9	99.6 ± 2.0				
(b) Amplitude (%)								
FDI	100.0 ± 15.7	109.8 ± 19.5	101.2 ± 23.3	100.7 ± 16.6				
ADM	100.0 ± 16.5	107.1 ± 15.7	114.0 ± 17.8	106.3 ± 15.1				
(c) Amplitude differences (%)								
	FDI			ADM				
Conditions	Relax	Index	Little	Calc.	Relax	Index	Little	Calc.
Relax	—	-9.8*	-1.2	-0.7	—	-7.1*	-14.0***	-6.3
Index	9.8*	—	8.5*	9.0*	7.1*	—	-6.9	0.8
Little	1.2	-8.5*	—	0.5	14.0***	6.9	—	7.7*
Calc.	0.7	-9.0*	-0.5	—	6.3	-0.8	-7.7*	—

* $P < 0.05$; ** $P < 0.01$; *** $P < 0.001$.

amplitude potentiation of motor responses to transcranial stimulation of motor brain areas (Merton *et al.*, 1982; Barker *et al.*, 1985; Rossini *et al.*, 1985; Ravnborg *et al.*, 1991) that can be explained by the burst of direct and indirect waves descending the corticospinal tracts and by the 'size principle' of motoneuronal recruitment (Patton and Amassian, 1954; Henneman *et al.*, 1965, 1974; Rossini *et al.*, 1987; Rothwell *et al.*, 1987; Day *et al.*, 1989), together with lowering of the motoneuronal (both cortical and spinal) firing threshold level due to facilitatory feedback from the twitching muscle, skin stretch and joint displacement (Houk, 1974; Rossini *et al.*, 1996). The present results confirm that the maximal facilitatory effects on MEPs are reached during voluntary contraction. Obviously, such mechanisms cannot explain the facilitation observed in the present study during motor and non-motor mental activity, due to the documented lack of sensory feedback (= immobile hands and fingers, background EMG silence during recordings).

Motor facilitation is known to start well before movement onset, the maximum being reached during early EMG activation of the target muscle (Starr *et al.*, 1987; Rossini *et al.*, 1988). Such pre-movement facilitation can be switched from one muscle to another acting as 'prime mover' within a given motor program (Rossini *et al.*, 1988), and it also affects in an opposite way the agonist and antagonist muscles (Tomberg and Caramia, 1991). MEPs have been also found to be facilitated in the time interval separating the instruction to move from the 'go' signal, an epoch in which the subject is alerted and probably thinking about the forthcoming movement execution, although still well within a reaction time interval (Cros *et al.*, 1989). In the present experimental set-up, the instant of TCS followed 2-3 s after the verbal command of the examiner; therefore, a facilitatory effect on the motor output due to the alerting state, along with a reaction time period (usually ~150 ms), can be ruled out.

The present data suggest that corticospinal excitability for hand muscles can be 'internally' modulated by individuals, resulting in amplitude potentiation of MEPs without significant latency changes. These effects are strictly related to the motor strategy planned by the subject and can be switched from one prime-mover muscle to another accordingly. Facilitatory effects are more evident for the FDI rather than for the ADM. It can be

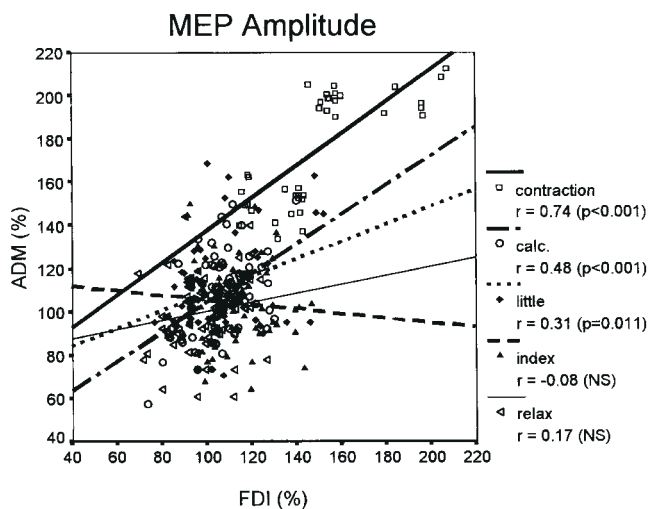


Figure 3. The scatter plot shows the whole sequence of MEPs simultaneously recorded by FDI and ADM muscles for each experimental condition. Each line represents the estimated linear relationship between ADM and FDI MEP amplitude potentiation. On the left, Pearson's r correlation values are reported (with respective P values). This was maximal during voluntary contraction and still present during arithmetical calculation. Conversely, in the 'Index' condition this concordance vanished, even more than during 'Relax', suggesting that the behavior of the FDI MEP amplitude became independent from ADM during the appropriate mental motor plan. In the 'Little' condition the correlation remained significant, indicating that the potentiation of ADM MEPs during mental simulation of appropriate movement was quite similar to that observed during the mental non-motor activity.

speculated that this difference could be related to the different role that these two muscles play in everyday life, the former being constantly involved in the manipulation of objects. Such an effect has never been described for hand muscles. At this level, mentally induced facilitation can be distinguished from natural variability of MEPs and non-specific mental alerting affects only when a large number of trials is collected and a simultaneous comparative analysis of the responsiveness of muscles involved and not involved in the motor plan is carried out.

Research findings on the effect of mental simulation of movements on spontaneous electromagnetic brain activity fit nicely with our results: (i) EEG recordings during the imagination of a sequence of hand movements (Beisteiner *et al.*, 1995; Cunnington *et al.*, 1996) suggest that the same neural elements in the sensorimotor cortex contralateral to the target limb are active both during movement execution and imagery; (ii) cortical representation of finger flexor and extensor muscles – as analyzed by TCS mapping – is progressively enlarged in subjects who mentally performed 5 days of piano practice with one hand, to the same extent as those subjects who actually undertook the practice (Pascual-Leone *et al.*, 1995); (iii) frontal components of somatosensory evoked potentials following stimulation of a mixed or a sensory nerve – which are thought to be partly generated in a loop involving motor, pre-motor and supplementary motor cortices, basal ganglia and thalamic relays – are significantly attenuated during the ideation of internal sequences of movements (Cheron and Borenstein, 1992; Rossini *et al.*, 1995, 1997). It is known from EEG and magneto-EG studies that during movements there is a suppression of contralateral brain activity deriving from the hand sensorimotor cortex (Niedermeyer, 1987; Feige *et al.*, 1996; Hari and Salmelin, 1997); furthermore, a certain attenuation of the 20Hz rhythm in the motor cortex has been found during imagination of

movements, suggesting that actual motor performances – during which that rhythm is suppressed – and imaginative tasks may share the same cortical circuitry (Schnitzler *et al.*, 1997). Such a bulk of neurophysiological evidence, together with the present findings, suggests that movement imagery significantly affects motor cortex excitability. This coherently parallels a recent functional magnetic resonance imaging study, in which activation of the premotor cortex and of the rostral part of the posterior supplementary motor area were found both during actual and mental execution of a finger-to-thumb opposition task (Roth *et al.*, 1996).

Two hypotheses, that are not mutually exclusive, can be taken into account in interpreting our results. Firstly, it may be possible that an increasing firing level of motor cortex neurons accompanying overt movements is still operating during motor act imagery. Most pyramidal cells are active even during complete muscular relaxation (Evarts, 1965). Moreover, corollary discharges of the motor programs are dispatched to parietal and cerebellar relays (McCloskey, 1981), so that neurons of these areas fire several tens of milliseconds prior to movement initiation (Evarts and Fromm, 1977; Soso and Fetz, 1980). Such mechanisms may operate also in the case of movement imagery. This would explain both the higher than normal level of excitation of the motor cortex (= lowering of the excitability threshold to TCS) and the 'gating' effect on frontal components of somatosensory evoked potentials during movement imagery (Cheron *et al.*, 1992; Rossini *et al.*, 1995, 1997). Evidence of the storage of such a 'central sense of movement' in the parietal lobe has been provided by Amassian *et al.* (1989), who first described the possibility of detecting, in relaxed subjects, centrally evoked limb paresthesias following sub-threshold magnetic TCS of the contralateral hemisphere. Moreover, corollary discharges from the motor cortex may constitute the physiological basis for learning new motor tasks in the absence of sensory feedback, a kind of training already proven to be useful and comparable to an actual motor performance (Yu and Cole, 1992).

The motor facilitation could be related to an increased spatial attention towards the specific body district involved in the task. Facilitation mechanisms due to spatial attention have been described for middle and long latency components of somatosensory evoked potentials (Garcia-Larrea *et al.*, 1991) and magnetic fields (Kristeva-Feige *et al.*, 1996), suggesting that the voluntary driving and shifting of the subject's attention is of paramount importance in the internal modulation of sensorimotor processing of the human brain.

Finally, excitability changes of spinal motoneuronal pools governing muscles involved in movement imagery might partly explain the observed changes in the F-wave recruitment pattern. Modulation of F-waves following a sub-threshold, appropriately timed, cortical magnetic stimulus has been demonstrated for hand muscles (Mercuri *et al.*, 1996), thus indicating that the F-wave can be considered a reliable marker of spinal motoneuron excitability even when motor output is minimal, as during movement imagery. Our results on F-waves indicate that specific changes in the excitability of spinal motoneuronal pools are taking place during movement imagery at the spinal level, according to the motor program. This is in line with a recent study of Gandevia *et al.* (1997), who reported activation of alpha motoneurons, but not fusimotor activity, during mental rehearsal of motor acts, and confirms that a facilitatory effect on descending impulses due to sensory feedback is unlikely to occur during motor imagery. However, we still do not know if changes at spinal level can be considered 'in series' or 'in

parallel' with the cortical ones, even if the lack of latency shortenings both for MEPs and F-waves would suggest that changes in MEP amplitude during movement imagery mainly take place at cortical level.

Facilitatory effects on MEPs (Fadiga *et al.*, 1995) and specific metabolic activation of several brain structures (Decety *et al.*, 1997) have recently been observed in subjects observing an action performed by another individual, suggesting that a neural system matching action observation and execution is present in humans and can be detectable by different exploratory methods. Whether specific facilitatory effects of different strategies of movement imagery can be employed by the subject (i.e. 'observing' himself performing the movement 'from outside' or 'internally' thinking the motor act) was not specifically addressed in this experimental set-up, but this certainly would be a matter for intriguing investigations in the future.

Notes

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List of Abbreviations

ADM, abductor digiti minimi muscle; FDI, first dorsal interosseus muscle; F-wave, late muscular response due to backfiring of spinal α -motoneurons during maximal stimulation of peripheral nerve motor fibres; MEP, motor evoked potential to brain magnetic stimulation; EMG, electromyography; TCS, magnetic transcranial stimulation of the brain; fMRI, functional magnetic resonance imaging; 'Index', imagery of index finger abduction; 'Little', imagery of little finger abduction; 'Calc.', mental calculation.

References

Abbruzzese G, Trompetto C, Schiappati M. (1996) The excitability of the human motor cortex increases during execution and mental imagination of sequential but not repetitive finger movements. *Exp Brain Res* 111:465–472.

Amassian VE, Cracco RQ, Maccabee PJ. (1989) A sense of movement in paralysed distal arm by focal magnetic coil stimulation of human motor cortex. *Brain Res* 479:355–360.

Barker AT, Jalinous R, Freeston IL, Jarratt JA (1985) Clinical evaluation of conduction time measurements in central motor pathways using magnetic stimulation of human brain. *Lancet* 1:1325–1326.

Bonnet M, Decety J, Jeannerod M, Requin J (1997) Mental simulation of an action modulates the excitability of spinal reflex pathways in man. *Cogn Brain Res* 5:221–228.

Beisteiner R, Höllinger P, Lindinger G, Lang W, Berthoz A (1995) Mental representation of movements. Brain potentials associated with imagination of hand movements. *Electroencephalogr Clin Neurophysiol* 96:183–193.

Brasil-Neto JP, McShane LM, Fuhr P, Hallett M, Cohen LG (1992) Topographic mapping of human motor cortex with magnetic stimulation. Factors affecting accuracy and reproducibility. *Electroencephalogr Clin Neurophysiol* 85:9–16.

Cheron G, Borenstein S (1992) Mental movement simulation affects the N30 frontal component of the somatosensory evoked potential. *Electroencephalogr Clin Neurophysiol* 84:288–298.

Cramond DJ (1997) Motor imagery: never in your wildest dream. *Trends Neurosci* 20:54–57.

Cros D, Day B, Fang J, Chiappa KH, Halmers SL, Shahani B (1989) Magnetic cortical stimulation: facilitation of motor responses related to instructions concerning movements. *J Clin Neurophysiol* 6: 356–362.

Cunnington R, Ianasek R, Bradshaw JL, Phillips JG (1996) Movement-related potentials associated with movement preparation and motor imagery. *Exp Brain Res* 111:429–436.

Day BL, Dressler D, Maertens de Noordhout A *et al.* (1989) Electric and

magnetic stimulation of the human motor cortex: surface EMG and single motor unit responses. *J Physiol* 412:449–473.

Decety J (1996) Do imagined and executed actions share the same neural substrate? *Cogn Brain Res* 3:87–93.

Decety J, Grezes J, Costes N, Perani D, Jeannerod M, Procyk E, Grassi F, Fazio F (1997) Brain activity during observation of actions. Influence of action content and subject's strategy. *Brain* 120:1763–1777.

Evarts EV (1965) Relation of discharge frequency to conduction velocity in pyramidal tract neurons. *J Neurophysiol* 28:16–228.

Evarts EV, Fromm CH (1977) Sensory responses in motor cortex neurons during precise motor control. *Neurosci Lett* 5:267–272.

Fadiga L, Fogassi L, Pavesi G, Rizzolatti G (1995) Motor facilitation during action observation: a magnetic stimulation study. *J Neurophysiol* 73:2608–2611.

Feige B, Kristeva-Feige R, Rossi S, Pizzella V, Rossini PM (1996) Neuro-magnetic study of movement-related frequency changes. *Brain Res* 734:252–260.

Fischer MA (1992) H reflexes and F waves: physiology and clinical indications. *Muscle Nerve* 15:1223–1233.

Gandevia SC, Rothwell JC (1987) Knowledge of motor commands and the recruitment of human motoneurons. *Brain* 110:1117–1130.

Gandevia SC, Wilson LR, Inglis JT, Burke D (1997) Mental rehearsal of motor tasks recruits alpha-motoneurons but fails to recruit human fusimotor neurones selectively. *J Physiol* 505:259–266.

Garcia-Larrea L, Batsujii H, Mauguiere F (1991) Mapping study of somatosensory evoked potentials during selective spatial attention. *Electroencephalogr Clin Neurophysiol* 80:201–214.

Hari R, Salmelin R (1997) Human cortical oscillations: a neuromagnetic view through the skull. *Trends Neurosci* 20:44–49.

Henneman E, Somjen G, Carpenter DO (1965) Functional significance of cells size in spinal motoneurons. *J Neurophysiol* 28: 560–580. .

Henneman E, Clamann HP, Gillies JD, Skinner RD (1974) Rank-order of motoneurons within a pool: law of combination. *J Neurophysiol* 37:13–38.

Houk J (1974) Feedback control of muscle: a synthesis of the peripheral mechanisms. In: *Medical physiology* (Mountcastle VB, ed.), pp. 668–677. St Louis: Mosby.

Izumi SI, Findley TW, Ikai T, Andrews J, Dum M, Chino N (1995) Facilitatory effect of thinking about movement on motor-evoked potentials to transcranial magnetic stimulation of the brain. *Am J Phys Med Rehab* 74:207–213.

Kasai T, Toyoda Y, Yahagi S (1997) Motor evoked potentials (MEPs) and H-reflexes are not equally sensitive to voluntary motor commands. *Brain Res* 764:273–276.

Kiers L, Fernando B, Tomkins D (1997) Facilitatory effect of thinking about movement on magnetic motor evoked potentials. *Electroencephalogr Clin Neurophysiol* 105:262–268.

Kimura J (1983) *Electrodiagnosis in diseases on nerve and muscle: principles and practice*. Philadelphia: Davis.

Kristeva-Feige R, Rossi S, Pizzella V *et al.* (1996) A neuromagnetic study of movement-related somatosensory gating in the human brain. *Exp Brain Res* 107:504–514.

McCloskey DI (1981) Corollary discharges: motor commands and perception. In: *Handbook of physiology, the nervous system* (Brooks VB, ed.), Vol. 2. pp. 1145–1147. Bethesda: American Physiological Society.

Mercuri B, Wassermann EM, Manganotti P, Ikoma K, Samii A, Hallett M (1996) Cortical modulation of spinal excitability: an F-wave study. *Electroencephalogr Clin Neurophysiol* 101:16–24.

Merton PA, Morton HB, Hill DK, Marsden CD (1982) Scope of a technique for electrical stimulation of human brain, spinal cord and muscle. *Lancet* 2:587–600.

Niedermeyer E (1987) The normal EEG of the waking adult. In: *Electroencephalography* (Niedermeyer E, Lopes da Silva F, eds), pp. 97–117. Baltimore: Urban and Schwarzenberg.

Oishi K, Kimura M, Yasukawa M, Yoneda T, Maeshima T (1994) Amplitude reduction of H-reflex during mental movement simulation in elite athletes. *Behav Brain Res* 62:55–61.

Panayiotopoulos CP, Chroni E (1996) F-waves in clinical neurophysiology: a review, methodological issues and overall value in peripheral neuropathies. *Electroencephalogr Clin Neurophysiol* 101:365–374.

Pascual-Leone A, Dang N, Cohen LG, Brasil-Neto J, Cammarota A, Hallett M (1995) Modulation of muscle responses evoked by transcranial stimulation during the acquisition of new fine motor skills. *J Neurophysiol* 74:1037–1045.

- Patton HD, Amassian VE (1954) Single and multiple unit analysis of cortical stage of pyramidal tract activation. *J Neurophysiol* 29: 547-564.
- Ravnborg M, Blinkenberg M, Dahl K (1991) Standardization of facilitation of compound muscle action potentials evoked by magnetic stimulation of the cortex: results in healthy subjects and in patients with multiple sclerosis. *Electroencephalogr Clin Neurophysiol* 81:195-201.
- Rossi S, Pasqualetti P, Tecchio F, Pauri F, Rossini PM (1998a) Corticospinal excitability modulation during mental simulation of wrist movements in human subjects. *Neurosci Lett* 243:1-5.
- Rossi S, Pasqualetti P, Tecchio F, Sabato A, Rossini PM (1998b) Modulation of corticospinal output to human hand muscles following deprivation of sensory feed-back. *NeuroImage* 8:163-175.
- Rossini PM, Rossi S (1998) Clinical applications of motor evoked potentials. *Electroencephalogr Clin Neurophysiol* 106:180-194.
- Rossini PM, Di Stefano E, Stanzione P (1985) Nerve impulse propagation along central and peripheral fast conducting motor and sensory pathways in man. *Electroencephalogr Clin Neurophysiol* 60:320-334.
- Rossini PM, Caramia MD, Zarola F (1987) Central motor tract propagation in man: studies with non-invasive, unifocal, scalp stimulation in man. *Brain Res* 66:88-100.
- Rossini PM, Zarola F, Stalberg E, Caramia MD (1988) Pre-movement facilitation of motor evoked potentials in man during transcranial stimulation of the central motor pathways. *Brain Res* 458:20-30.
- Rossini PM, Desiato MT, Lavaroni F, Caramia MD (1991) Brain excitability and electroencephalographic activation: non invasive evaluation in healthy humans via transcranial magnetic stimulation. *Brain Res* 567:111-119.
- Rossini PM, Barker AT, Berardelli A *et al.* (1994) Non-invasive electrical and magnetic stimulation of the brain, spinal cord and roots: basic principles and procedures for routine clinical application. *Electroencephalogr Clin Neurophysiol* 91:79-92.
- Rossini PM, Caramia MD, Iani C, Desiato MT, Sciarretta G, Bernardi G (1995) Magnetic transcranial stimulation in healthy humans: influence on the behavior of upper limbs motor units. *Brain Res* 67:314-324.
- Rossini PM, Caramia MD, Bassetti MA, Pasqualetti P, Tecchio F, Bernardi G (1996a) Somatosensory evoked potentials during ideation and execution of individual finger movements. *Muscle Nerve* 19:191-203.
- Rossini PM, Tecchio F, Sabato A, Finazzi-Agrò A, Pasqualetti P, Rossi S (1996b) The role of cutaneous inputs during magnetic transcranial stimulation. *Muscle Nerve* 19:1302-1309.
- Rossini PM, Babiloni F, Babiloni C, Ambrosini A, Onorati P, Urbano A (1997) Topography of spatially enhanced human short-latency somatosensory evoked potentials. *NeuroReport* 8:991-994.
- Roth M, Decety J, Raybaudi M, Massarelli R, Delon-Martin C, Segebarth C, Morand S, Gemignani A, Decorsp M, Jeannerod M (1996) Possible involvement of primary motor cortex in mentally simulated movement: a functional magnetic resonance imaging study. *NeuroReport* 17:1280-1284.
- Rothwell JC, Thompson PD, Day BL, Boyd S, Marsden CD (1987) Motor cortex stimulation in intact man. I. General characteristics of EMG responses in different muscles. *Brain* 110:1173-1190.
- Schnitzler A, Salenius S, Salmelin R, Jousmaki V, Hari R (1997) Involvement of primary motor cortex in motor imagery: a neuromagnetic study. *NeuroImage* 6:201-208.
- Smania N, Bazoli F, Piva D, Guidetti G (1997) Visuomotor imagery and rehabilitation of neglect. *Arch Phys Med Rehab* 78:430-436.
- Soso MJ, Fetz EE (1980) Responses of identified cells in postcentral cortex of awake monkeys during comparable active and passive joint movements. *J Neurophysiol* 43:1090-1110.
- Starr A, Caramia MD, Zarola F, Rossini PM (1987) Enhancement of motor cortical excitability in humans by non-invasive electrical stimulation appears prior to voluntary movement. *Electroencephalogr Clin Neurophysiol* 70:26-32.
- Tomberg C, Caramia MD (1991) Prime mover muscle in finger lift or finger flexion reaction times: identification with transcranial magnetic stimulation. *Electroencephalogr Clin Neurophysiol* 81:319-322.
- Wassermann EM, McShane LM, Hallett M, Cohen LG (1992) Noninvasive mapping of muscle representations in human motor cortex. *Electroencephalogr Clin Neurophysiol* 85:1-8.
- Yu G, Cole KJ (1992) Strength increases from the motor program: comparison of training with maximal voluntary and imagined muscle contraction. *J Neurophysiol* 67:1114-1123.