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Functional overlap between hand and forearm motor cortical representations during motor cognitive tasks

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Abstract

Objective: The aim of this study was to verify whether motor imagery (MI) and observation of a movement (MO) enhanced cortical representations of the hand/forearm muscles not primarily involved in the task. We also explored the existence of functional overlaps in the upper-limb cortical representations during the aforementioned tasks.

Methods: Focal transcranial magnetic stimulation (TMS) was used to map out the cortical representation of the opponens pollicis (OP, target muscle) and other hand and forearm muscles at rest and during MI and MO.

Results: The MI and MO tasks induced similar changes in the area and volume of both the OP and synergic muscles. No significant changes were observed in the cortical excitability of the remaining muscles. The superimposition of different muscle maps revealed extensive functional overlaps in the hand/forearm cortical territories.

Conclusions: This study demonstrates that neither the MI nor MO changes single muscle motor responses and that the hand/forearm muscle maps extensively overlap during motor cognitive tasks.

Significance: The data reported in this study support the notion that the basic unit of cortical output is not the mere activation of a given muscle. This flexible organization may have important implications in motor learning and plasticity.

Keywords: Motor cortex; Transcranial magnetic stimulation; Motor imagery; Overlap; Mapping

1. Introduction

One of the most important advances in cognitive neuroscience in the past 10 years is the demonstration that the motor system is involved not only in producing movements, but also in higher-order cognitive motor functions, such as mental representations, recognition and the understanding of actions (for reviews see Georgopoulos, 2000; Rizzolatti and Wolpert, 2005). Motor imagery (MI) and observation of a movement (MO) performed by others are cognitive tasks which refer, respectively, to the internal reproduction and recognition of visually presented movements, with no overt motor output. Recent data have revealed the existence of a widely distributed, overlapping network for movement execution (Stephan et al., 1995; Porro et al., 1996), motor imagery (Decety et al., 1994; Roland and Gulyas, 1995; Jeannerod and Frak, 1999) and action observation (Decety et al., 1997; Grezes and Decety, 2001; Nelissen et al., 2005). Furthermore, some studies in which transcranial magnetic stimulation (TMS) was used described a modulation of primary motor cortex (M1) during imagery (Pascual-Leone et al., 1993, 1995; Beisteiner et al., 1995; Abbruzzese et al., 1996; Kasai et al., 1997; Rossi et al., 1998; Hashimoto and Rothwell, 1999; Fadiga et al., 1999; Rossini et al., 1999; Vargas et al., 2004) and action observation (Fadiga et al., 1995; Hari et al., 1998; Strafella and Paus, 2000; Clark et al.,

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2004). However, while the authors of some of these studies reported that excitability changes induced by these motor cognitive tasks occurred specifically in the "prime mover" muscle (Rossini et al., 1999; Strafella and Paus, 2000; Facchini et al., 2002; Maeda et al., 2002; Clark et al., 2004; Fourkas et al., 2006), others found that the modulation during action observation (Fadiga et al., 1995) and motor imagery (Fadiga et al., 1999) involved both the target and agonist muscles. In addition, data obtained from imaging (see Sanes and Donoghue, 1997, for a review) and TMS (Wassermann et al., 1992; Devanne et al., 2002, 2006; Gentner and Classen, 2006) studies suggest that the hand and arm muscles are not strictly segregated. Interestingly, Gentner and Classen (2006) recently demonstrated that TMS activation can mimic the natural activation of the M1 and that TMS-evoked finger movements showed modular properties.

Within this framework, we investigated whether the cortical representations of the hand and forearm muscles not primarily involved in the task are modulated differently by cognitive motor tasks. Secondly, we explored the possible existence of functional overlaps of the upper-limb cortical maps during motor imagery and movement observation tasks.

To our knowledge, few TMS studies (Wassermann et al., 1992; Devanne et al., 2006; Gentner and Classen, 2006) have used multi-muscle recording in different experimental conditions to address these issues.

2. Materials and methods

2.1. Subjects

Eight healthy subjects (four women and four men; mean age: 36.1 ± 15.0 years) were enrolled for the TMS experiments. They were all right-handed, as confirmed by the Edinburgh Handedness Inventory Scale (Oldfield, 1971). None were aware of the aim of the study and all gave their written informed consent to participate. The experimental procedures were approved by the Local Ethical Committee and were performed according to the Declaration of Helsinki. Subjects were comfortably seated in an armchair with both hands/forearms placed on a pillow in a pronated position and relaxed totally. They were asked to focus on a fixed point on the wall in front of them and were unable to see the equipment display.

2.2. Transcranial magnetic stimulation

TMS mapping of the right (RH) and left (LH) hemispheres was performed using a magnetic stimulator (Magstim 200, Magstim company, Dyfed, UK) connected to a figure-of-eight-shaped coil (7 cm internal diameter). An adherent, inelastic cap was placed over the participant's head, and the reference to an anatomical landmark (intersection of the interaural line and the nasion–inion connection, *Cz*, in the 10–20 International System) was taken. The coil was placed tangentially over the skull, with the handle pointing backwards and perpendicular to the presumed direction of the central sulcus, ~45° to the midline, to evoke anteriorly directed current in the brain. The optimal location (hot spot) for eliciting motor-evoked potentials (MEPs) from the opponens pollicis (OP), i.e. the target muscle, was identified in each individual and marked to ensure stability in the coil position and orientation throughout the session. Motor responses were simultaneously obtained from the first dorsal interosseous (FDI), the abductor digiti minimi (ADM), the extensor digitorum communis (EDC) and the flexor digitorum superficialis (FDS) (see inset in Fig. 1). The motor threshold at rest (rMT) was determined at the optimal scalp position for activating the

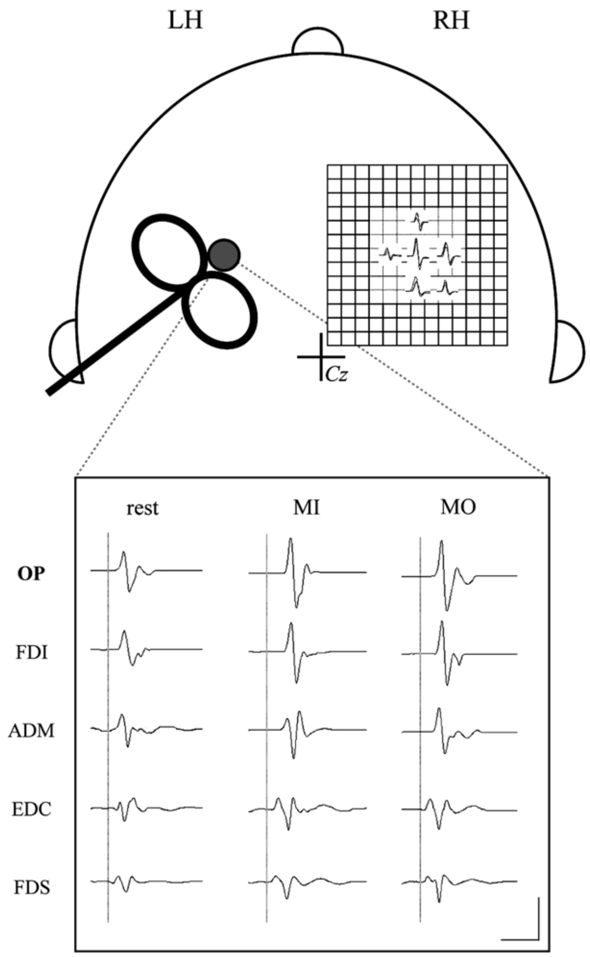

Fig. 1. Schematic head over which the stimulation grid and the original MEPs from the OP muscle at rest are superimposed on the right hemisphere (RH) of a representative subject. The *Cz* represents the intersection of the interaural line and the nasion–inion connection. The inset below shows data acquired from the hot spot (grey circle) of the left hemisphere (LH) in the same subject. The motor responses are obtained from several muscles (OP, FDI, ADM, EDC, FDS) at rest, during motor imagery (MI) and vision of movement (MO). The MEP amplitude increases during MI and MO when compared with the rest condition; this increase is significant in the OP and FDI muscles. Each trace is the average of three trials. The vertical dotted line indicates differences in latency between the hand and forearm muscles. Calibration bar: 1 mV, 20 ms.

aforementioned muscles. The rMT was defined as the lowest TMS intensity of magnetic stimulation required to evoke MEPs larger than 50 µV in at least 50% of the trials (Rossini et al., 1994). In order to map out the muscle representations, a grid of 49 positions, spaced 1.5 cm along both the medio-lateral and antero-posterior axes, was fixed on the subject's head (Fig. 1). Once these procedures were completed, the maps for each muscle were obtained by stimulating each point of the grid lying over the motor strip. For each scalp position, we recorded the muscular responses evoked by four stimulations at 110% of the rMT. The mean of the peak-to-peak MEP amplitude recorded from each excitable scalp site was calculated, as were the area (number of scalp positions from which the MEPs were elicited) and volume (the sum of the averaged MEP amplitudes for each excitable scalp site) for all the cortical maps. Furthermore, we developed a function for the two-dimensional (2-D) reconstruction and superimposition maps (Matlab 7.0, The MathWoks, Inc.) to identify overlaps between the various motor cortical representations. Two different maps were developed: (a) an overlap map, which superimposes all the muscle representations of a single task (called "topographical", see Fig. 5), and (b) a second map that superimposes the single muscle maps obtained across different tasks (referred to as "functional", see Fig. 6). Lastly, to quantify the spatial overlap between the various muscle cortical representations ("topographical" overlap maps, Fig. 5), we calculated, for each condition, a partial overlap (*p-ov*) index, which provided the size (as a percentage) of the area in which at least two muscles were represented. We were unable to apply this index to the "functional" overlap maps owing to a lack of data.

2.3. EMG recordings

A surface EMG was recorded from the OP, FDI, ADM, EDC and FDS muscles with silver–silver chloride electrodes taped in a belly tendon montage. During the recording, which required EMG silence, muscular activity was constantly monitored. EMG signals were amplified with gain set at 3000 (Digitimer D360 amplifier; Digitimer Ltd., Welwyn Garden City, Herts, UK), band-pass filtered (30 Hz–2 kHz), then recorded by a computerusing SIGNAL software (Cambridge Electronic Design, Cambridge, UK) with a sampling rate of 5 kHz per channel. An audio-feedback was used to ensure that total relaxation was maintained. Trials with voluntary EMG activity that might confound MEP measurements were excluded from the analysis.

2.4. Experimental procedures

Motor-evoked potentials (MEPs) were recorded from the OP, i.e. the target muscle, and simultaneously from the FDI, ADM, EDC and FDS (see inset in Fig. 1). The MEPs and cortical maps of the aforementioned muscles were obtained bilaterally (recording first from the right, then from the left hand/forearm) in all the subjects under the following experimental conditions: (1) "rest" – the subjects were completely relaxed, both mentally and muscularly; (2) voluntary contraction (CTR) – the subjects elicited a voluntary contraction (an opposition of the thumb toward the base of the little finger); (3) motor imagery of the same movement (MI) – the subjects were instructed to imagine the movement in a first person perspective by recalling the feelings and sensations they experienced when they had performed the movement, using the same force, speed and repetition rate (about 0.3 c/s), upon the verbal command "imagine the movement"; (4) observation of the same movement performed by others (MO) – the subjects were instructed to look at a panel through which only the hand of an experimenter was visible; when the verbal command "watch the movement" was given, the experimenter's hand started moving in the same way as in the movement executed by the subjects in the CTR condition; lastly (5), counting backwards mentally ("counting") – this was used as a control task.

Before testing started, subjects practiced until they felt confident with the motor imagery task. The imagined movement was controlled by asking participants to physically perform the task and so as to obtain an internal representation to ensure that a first person perspective was maintained. Only when subjects were able to do this were they asked to retain the same imagery pattern and to perform it mentally. Magnetic stimuli were delivered upon a verbal command by the experimenter. Using dedicated software (PsyScope), a PC triggered the Magstim 200 unit with a random delay ranging between 500 and 1500 ms (in steps of 250 ms) following the experimenter's verbal command given through a headphone microphone (Plantronics Audio 320 Stereo PC Multimedia Headset). The subjects were asked not to think about any movement during the interval between the stimuli.

2.5. Data analysis

The following neurophysiological parameters were studied in all the participants.

1. Mean motor threshold at rest (rMT).
2. Mean map area, defined as the number of scalp positions whose stimulation evoked MEPs in that muscle. The motor map area for each muscle was defined as the number of "active" sites of all the participants divided by the number of participants.
3. Mean map volume. First, the mean MEP amplitude for each scalp site was calculated, then the amplitudes of all the positions were summed up to obtain the volume map. Finally, the mean value of each site was calculated and averaged for all the participants; a site was only included in the map if present in all the subjects.

A parametric statistical analysis, which took into account all the sources of variations, was used. We used an analysis of variance (ANOVA) for repeated measures as the main statistical procedure, in which factors were always considered as within-subject. Three-way ANOVA (*hemisphere* × *condition* × *muscle*) was used to investigate whether there were any differences in the area and volume of the muscle maps between the hemispheres and across tasks. *Post-hoc* comparisons (Tukey's test) were performed when the interaction was statistically significant. The assumption of sphericity, which was checked by means of Mauchly's test, was not significant; no correction was applied to the degrees of freedom. Student's *t*-test was used only when two means were compared. Throughout the statistical analysis, the *p* value level of significance was set at 0.05.

3. Results

The hot spot location on the scalp (*x*/*y* coordinates averaged across subjects) proved to be symmetrically positioned between the two hemispheres (LH: lateral 3 ± 0.4; anterior 2.6 ± 0.4/RH: lateral 3.2 ± 0.5 anterior $2.4\ \text{cm} \pm 0.7$, relative to *Cz*). In addition, the mean values of the rMT obtained from the hot spot of the LH and RH were $40 \pm 4.8\%$ and $42.1 \pm 5.2\%$ of the maximum stimulator output, respectively. A comparison revealed that the rMT was significantly lower ($p < 0.05$) in the left than in the right hemisphere. Two general results emerged from the statistical analyses: (1) both hemispheres were symmetrical at rest and during the voluntary contraction; (2) as expected, the voluntary contraction induced, in all the muscles studied, a significant enlargement of the map areas (Fig. 2a), as well as the largest increase in MEP amplitudes (volume), if compared with the remaining conditions (Fig. 2b). In particular, the three-way ANOVA performed on the map areas revealed significant differences for the main factor *condition* ($F = 18.20$; $p < 0.05$) as well as for the interaction *condition* × *muscle* ($F = 3.45$; $p < 0.05$). In addition, the *post-hoc* analysis showed that, during contraction, the map areas of the OP and FDI were enlarged to a greater extent than those of all the other muscles ($p < 0.05$) (Fig. 2a). Similarly, ANOVA performed on the map volumes showed significant differences for the factor *condition* ($F = 18.23$; $p < 0.05$) and for the interaction *condition* × *muscle* ($F = 4.59$; $p < 0.05$), and *post-hoc* comparisons revealed that the OP and FDI map volumes were enhanced to a greater extent than those of the other muscles ($p < 0.05$) (Fig. 2b). The reasons for these two results have been explained in detail elsewhere (see Rossini et al., 1999).

Lastly, although the data are presented as group averages, the same findings were evident in the maps of the individual subjects.

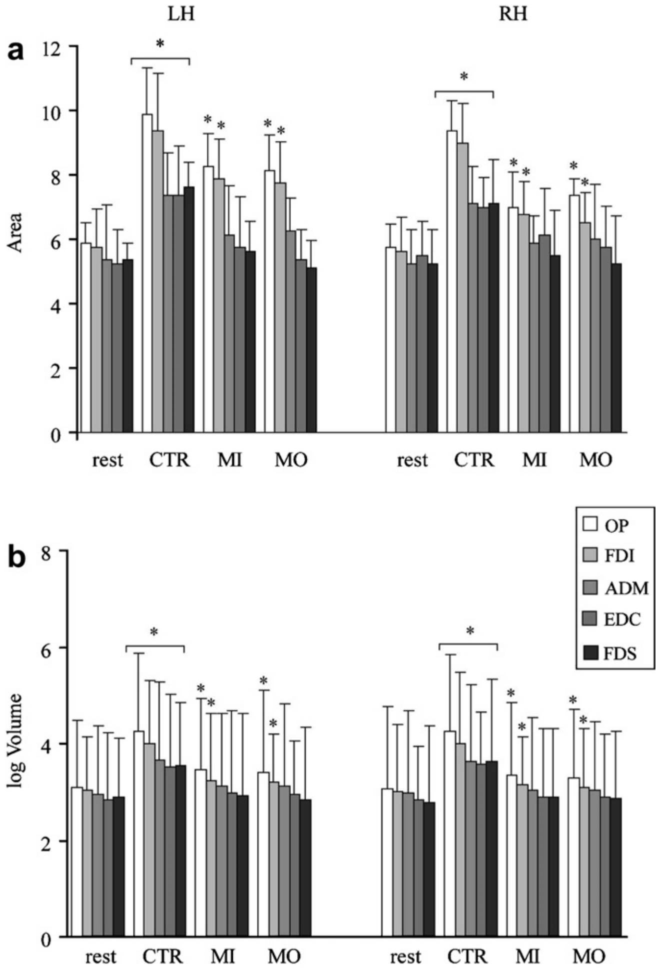

Fig. 2. Histograms (mean values and error bars) of the muscle map areas (a) and volumes (b), in both hemispheres and across tasks. Motor imagery (MI) and movement observation (MO) tasks significantly increase both map area and volume of the OP and FDI muscles, in both the LH and RH. The voluntary contraction (CTR) induces, in all the muscles, a significant enlargement of the map area and the greatest increase in volume when compared with the other conditions.

3.1. *Effects of motor imagery and movement observation on the area and volume of the cortical representation of the target versus non-target muscles*

A three-way ANOVA (*hemisphere* × *condition* × *muscle*) was performed to evaluate the effects of MI and MO on the cortical area and volume of the target and non-target muscle maps. As regards the map area, we found significant differences in the two main factors, *condition* ($F = 47.24$; $p < 0.001$) and *muscle* ($F = 6.94$; $p < 0.05$), as well as in the interaction term *condition* × *muscle* ($F = 5.69$; $p < 0.05$). As revealed by the *post-hoc* comparisons, MI and MO tasks increased the area of the OP ($p < 0.001$) and FDI muscles in both hemispheres (Figs. 2a and 3), though the effect was significantly more marked in the left hemisphere (LH versus RH; $p < 0.05$) (Fig. 2a). By contrast, these tasks had no effect on the area of the remaining hand and forearm muscles (Figs. 2a and

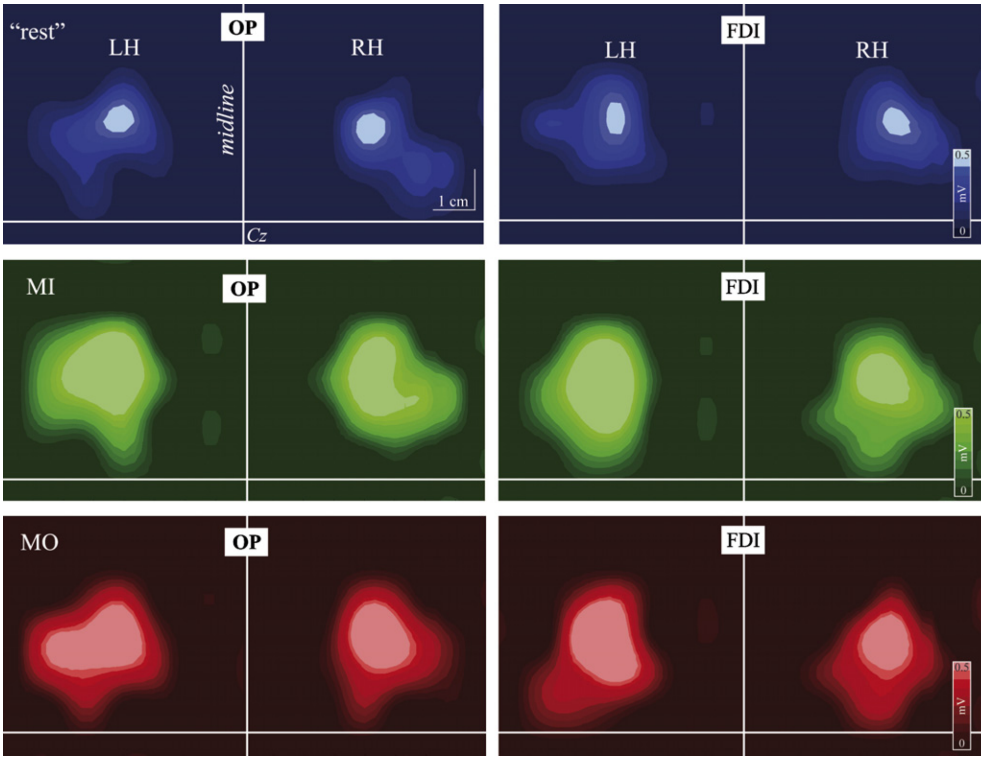

Fig. 3. Two-dimensional (2-D) maps of the OP and FDI muscles, during rest, MI and MO. The RGB (red, green, blue) color mode is used to identify the different tasks. The palettes always range from dark (0 mV) to light (0.5 mV) colors. Both the area and volume increase significantly in the OP and FDI muscles during both MI and MO when compared with rest. These modulations in motor responses are observed in both hemispheres, though the increase is more significant in the LH than in the RH. The scale bar used is 1 cm for both x/y axes.

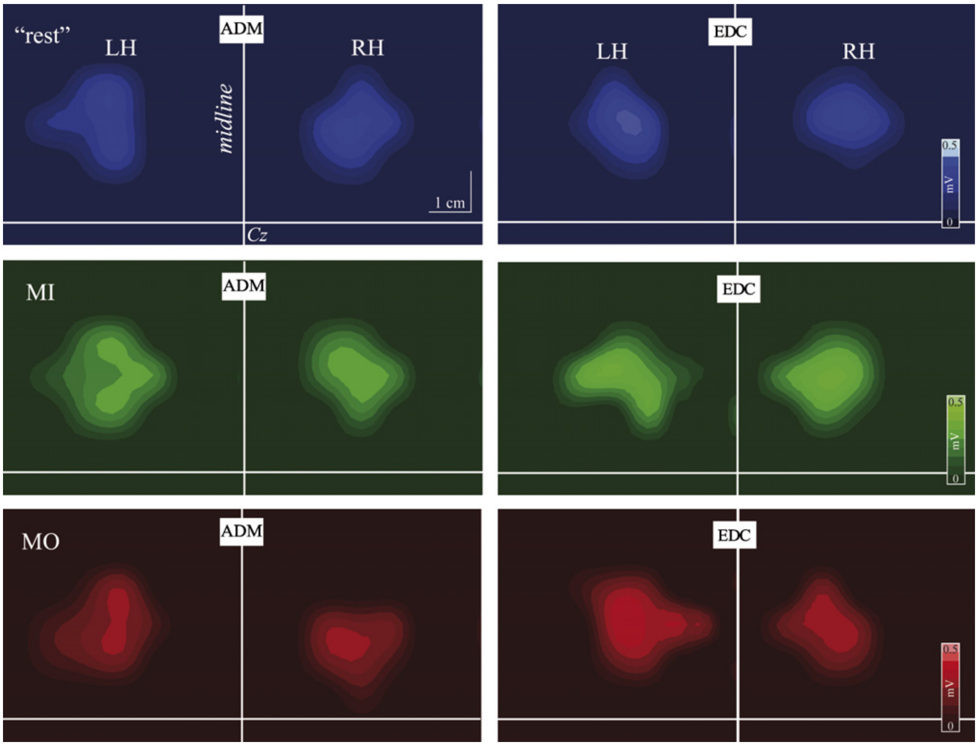

Fig. 4. Same 2-D maps as in Fig. 3, relative to the ADM and EDC muscles. There is no significant difference for either ADM or EDC in the area and volume during MI and MO when compared with rest. The other conventions are the same as those in Fig. 3.

4). No modifications in the map area were observed in any of the muscles during "counting". A separate three-way ANOVA (*hemisphere* × *condition* × *muscle*) was performed to evaluate the effects of MI and MO tasks on map volume. The results revealed significant differences in the main factors *hemisphere* ($F = 6.17$; $p < 0.05$), *condition* ($F = 212.80$; $p < 0.001$) and *muscle* ($F = 80.70$; $p < 0.001$), as well as in the interaction term *condition* × *muscle* ($F = 69.20$; $p < 0.001$). The *post-hoc* comparisons revealed that the MI and MO tasks modulated cortical excitability in both hemispheres, when compared with the rest condition, in the target OP ($p < 0.001$) as well as in the FDI ($p < 0.05$) muscles (Figs. 2b and 3). Moreover, MI and MO increased the OP and FDI map volume to a greater extent in the LH than in the RH ($p < 0.05$; see green and red maps in Fig. 3). No significant cortical excitability modulation was

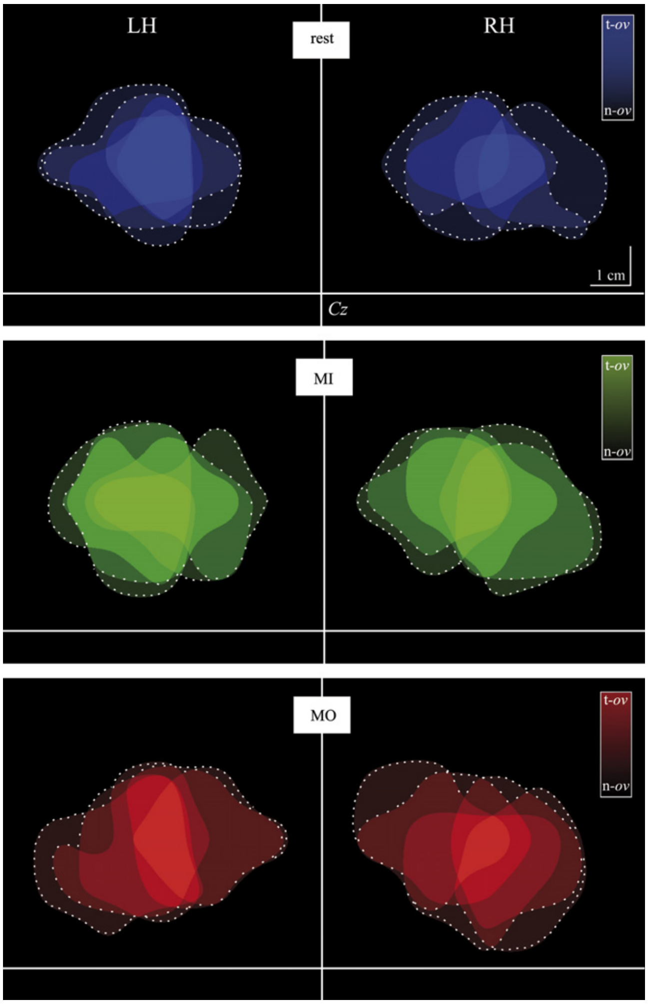

Fig. 5. Two-dimensional "topographical" overlap maps in which the cortical representations of the various muscles (OP, FDI, ADM, EDC, FDS) are superimposed in each task (rest, MI and MO). A transparence code is added to indicate the degree of overlap between the different maps. The external tight-dotted line (n-*ov* in the palette) shows the peripheral map zones in which only one muscle is present. The internal wide-dotted line region represents the partial overlap (at least two muscles), while the full colors in all the tasks (central) correspond to the total (five muscles) overlapped territory (t-*ov*, in the palette). Most of the cortical territory is, in all the conditions, covered by the representation of at least two muscles, which is in agreement with the high *p-ov* index values obtained (see Section 3).

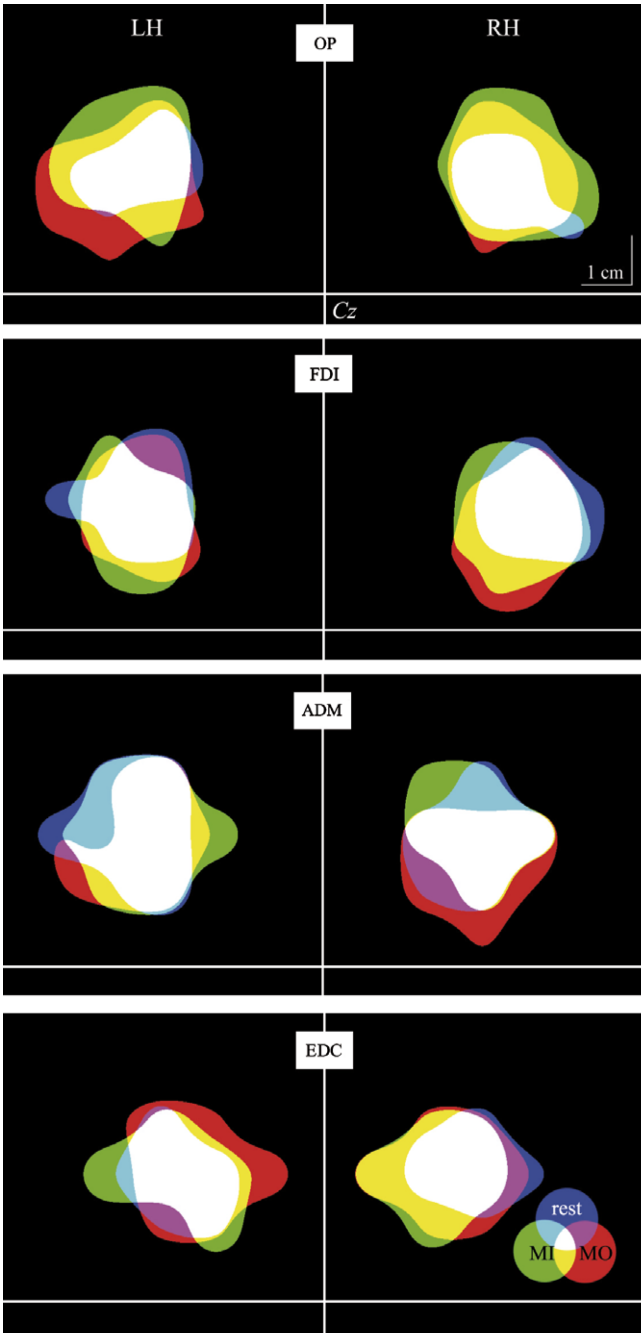

Fig. 6. Two-dimensional "functional" overlap maps obtained by overlapping the cortical representations (OP, FDI, ADM, EDC) for each muscle during rest, MI and MO. Given the similarity of the pattern displayed by the two forearm muscles, the FDS has been removed. Full colors indicate that a motor map is present in one condition alone: *blue* at rest; *green* during MI and *red* during MO. Largely functional overlaps are disclosed in these maps by means of the "additive" properties typical of the RGB system (see the circular palette). In particular, *cyan* indicates rest plus MI, *magenta* indicates rest plus MO, *yellow* indicates MI plus MO and, lastly, *white* represents the total overlap across tasks. Extensive "functional" overlaps emerge, as indicated by the predominance of white in all the maps.

observed in the ADM, EDC (Fig. 4) and FDS during either MI or MO, if compared with rest. Finally, there were no statistical differences either between MI and MO, which produced similar MEP amplitude increases, or between the "counting" (control) task and rest.

3.2. Overlaps between the hand and forearm muscle cortical representations during cognitive tasks

In this study, we also investigated the overlaps between the different cortical maps. During different conditions (rest, MI and MO), the two-dimensional (2-D) maps in Fig. 5 show that all the cortical representations (OP, FDI, ADM, EDC and FDS) coalesced into one large territory in both hemispheres. Indeed, all the tasks totally overlapped in the central part of these maps (Fig. 5), with a very small peripheral zone showing the representation of one muscle alone (tight-dotted line, n-*ov*). Most of the cortical territory in all the conditions was covered by the representation of at least two muscles (see the large region inside the wide-dotted line, Fig. 5). Accordingly, the *p-ov* index values in the LH were 80% at rest, 79% for the MI and 72% for the MO tasks, while those in the RH were 74% at rest, 81% for the MI and 69% for the MO. As expected, the hand muscles covered more lateral cortical territory, while the forearm muscles mainly occupied a more medial position over the motor strip. Similarly, by overlapping the cortical maps (OP, FDI, ADM, EDC) obtained for each muscle at rest, we found that the MI and MO conditions were highly concordant, as the predominance of white in all the 2-D maps (Fig. 6). A similar tendency to converge toward the centre was observed in all the hand (OP, FDI, ADM) and forearm (EDC and FDS) muscles, together with a selective task-dependent modulation on the periphery of all the maps. The medio-lateral trend was the same as that shown in Fig. 5.

4. Discussion

In the present study, we found that motor imagery and observation of a movement performed by others enhanced the area and volume in both the target (OP) and synergic muscles (FDI). The facilitation pattern induced by these motor cognitive tasks was more marked in the left than in the right hemisphere. By contrast, the two hemispheres were symmetrical at rest and during voluntary contraction, and the facilitation observed in the MEP amplitude was not observed during the control task ("counting").

4.1. Are motor cognitive tasks target-muscle focused?

Our observations are in agreement with those of Fadiga et al. (1995), who observed that the MEP amplitude increased in both the target and synergic muscles during action observation of a hand movement requiring activation of the same group of muscles. Moreover, those authors revealed that a greater degree of facilitation was obtained when the imagery involved a muscle acting as an agonist in a given task than when the imagery involved the same muscle as an antagonist (Fadiga et al., 1999). In our study, we found that the effect of motor imagery and movement observation was not focused exclusively on the "prime mover" muscle (OP), but also involved a functionally related muscle (FDI). Indeed, the second muscle modulated most significantly by the motor cognitive tasks after the OP, i.e. the FDI, worked in synergy with the target muscle in hand-closing as well as in the precision grip. By contrast, most previous studies have shown that the excitability changes induced by imagery and movement observation are specific to the muscle primarily involved in these tasks (Rossini et al., 1999; Strafella and Paus, 2000; Facchini et al., 2002; Maeda et al., 2002; Clark et al., 2004; Fourkas et al., 2006), no significant modulation being reported for the other muscles. This finding may be due to the fact that most of the aforementioned studies recorded fewer muscles because they had different experimental aims.

4.2. A complex level of output from the primary motor cortex: evidence of gradient-like functional organization

The overlap observed in the cortical representation of different muscles across the tasks described in this study is in agreement with recent works on the functional organization of both human and non-human primary motor cortex (see Rossini and Pauri, 2000; Schieber, 2001, 2004).

Studies using anatomical (Shinoda et al., 1981) and physiological techniques in monkey (Buys et al., 1986; Cheney and Fetz, 1985) have shown that single M1 neuron output diverges to the motoneuronal pools of different muscles and engages them at different strengths (Fetz and Cheney, 1987). More recently, Rathelot and Strick (2006) demonstrated that cortico-motoneuronal cells to different muscles extensively overlapped in M1. Therefore, the current vision on motor cortical organization is that cortical representations of different muscles extensively overlap and that the movements of different body parts are not so strictly somatotopically controlled (see Schieber, 2001 for a review). Imaging studies have strongly contributed to this vision by showing how finger and forearm movements activate a wide and overlapping expanse of motor cortical territory (Sanes et al., 1995; Sanes and Donoghue, 1997; Kleinschmidt et al., 1997; Lotze et al., 2000; Hlustik et al., 2001; Indovina and Sanes, 2001). More recently, the results of various TMS studies have suggested that the cortical overlaps observed between muscle representations in M1 cannot merely be ascribed to the spreading of magnetic stimuli (Devanne et al., 2006; Malcolm et al., 2006). Moreover, Gentner and Classen (2006) demonstrated that the TMS can reproduce features of natural activation of the M1, thereby revealing the modular properties of TMS-evoked finger movements. Not only our findings are in agreement with this vision, but they extend earlier findings by mapping out several muscles during motor imagery and observation of a movement performed by others. Indeed, we found that the "overlap index", introduced as a quantitative measure, was high in all the conditions, thereby indicating that the different hand/forearm maps all coalesced into one large territory with a "somatotopic-gradient" of representation. Moreover, the "functional" overlap maps were characterized by a high proportion of shared functional properties in the centre that progressively decreased as they moved towards the periphery of the maps, thus pointing to the existence of a "functional-gradient" in the hand/forearm cortical representations. The data reported here therefore indicate that the different hand/forearm muscle representations in M1 are not topographically focused during motor cognitive tasks, and the territory controlling a single hand or forearm muscle overlaps extensively with the territories controlling other muscles. This implies that the overlapping nature of the muscle representation is a genuine feature of human motor cortical organization. Moreover, it is noteworthy that a higher number of additional sites and increased map volume were observed in the left hemisphere than in the right hemisphere in both the target and agonist muscle representations. These results are in agreement with previous findings showing that the left hemisphere is modulated to a greater extent than the right hemisphere by motor cognitive tasks (Beisteiner et al., 1995; Fadiga et al., 1999; Aziz-Zadeh et al., 2002; Stinear et al., 2006). These data are also highly consistent with the observation that patients with "ideomotor apraxia" very often have a left hemispheric lesion (see Zadikoff and Lang, 2005, for a review).

In conclusion, this study demonstrates that motor cognitive tasks do not change individual muscle motor responses, thus supporting the notion that the basic unit of cortical output is not the mere activation of a given muscle. In addition, our data show that the hand/forearm region of the human motor cortex consists of converging territories even during motor cognitive tasks. This flexible organization may have important implications in motor learning and plastic reorganization, which may in turn lead to recovery of motor function following a brain lesion.

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References

Abbruzzese G, Trompetto C, Schieppati M. The excitability of the human motor cortex increases during execution and mental imagination of sequential but not repetitive finger movements. Exp Brain Res 1996;111:465–72.

Aziz-Zadeh L, Maeda F, Zaidel E, Mazziotta J, Iacoboni M. Lateralization in motor facilitation during action observation: a TMS study. Exp Brain Res 2002;144:127–31.

Beisteiner R, Hollinger P, Lindinger G, Lang W, Berthoz A. Mental representations of movements. Brain potentials associated with imagination of hand movements. Electroencephalogr Clin Neurophysiol 1995;96:183–93.

Buys EJ, Lemon RN, Mantel GW, Muir RB. Selective facilitation of different hand muscles by single corticospinal neurones in the conscious monkey. J Physiol 1986;381:529–49.

Cheney PD, Fetz EE. Comparable patterns of muscle facilitation evoked by individual corticomotoneuronal (CM) cells and by single intracortical microstimuli in primates: evidence for functional groups of CM cells. J Neurophysiol 1985;53:786–804.

Clark S, Tremblay F, Ste-Marie D. Differential modulation of corticospinal excitability during observation, mental imagery and imitation of hand actions. Neuropsychologia 2004;42:105–12.

Decety J, Perani D, Jeannerod M, Bettinardi V, Tadary B, Woods R, et al. Mapping motor representations with positron emission tomography. Nature 1994;371:600–2.

Decety J, Grezes J, Costes N, Perani D, Jeannerod M, Procyk E, et al. Brain activity during observation of actions. Influence of action content and subject's strategy. Brain 1997;120:1763–77.

Devanne H, Cohen LG, Kouchtir-Devanne C, Capaday N. Integrated motor cortical control of task-related muscles during pointing in humans. J Neurophysiol 2002;87:3006–17.

Devanne H, Cassim F, Ethier C, Brizzi L, Thevenon A, Capaday C. The comparable size and overlapping nature of upper limb distal and proximal muscle representations in the human motor cortex. Eur J Neurosci 2006;23:2467–76.

Facchini S, Muellbacher W, Battaglia F, Boroojerdi B, Hallett M. Focal enhancement of motor cortex excitability during motor imagery: a transcranial magnetic stimulation study. Acta Neurol Scand 2002;105:146–51.

Fadiga L, Fogassi L, Pavesi G, Rizzolatti G. Motor facilitation during action observation: a magnetic stimulation study. J Neurophysiol 1995;73:2608–11.

Fadiga L, Buccino G, Craighero L, Fogassi L, Gallese V, Pavesi G. Corticospinal excitability is specifically modulated by motor imagery: a magnetic stimulation study. Neuropsychologia 1999;37:147–58.

Fetz EE, Cheney PD. Functional relations between primate motor cortex cells and muscles: fixed and flexible. Ciba Found Symp 1987;132:98–117.

Fourkas AD, Avenanti A, Urgesi C, Aglioti SM. Corticospinal facilitation during first and third person imagery. Exp Brain Res 2006;168:143–51.

Gentner R, Classen J. Modular organization of finger movements by the human central nervous system. Neuron 2006;52:731–42.

Georgopoulos AP. Neural aspects of cognitive motor control. Curr Opin Neurobiol 2000;10:238–41.

Grezes J, Decety J. Functional anatomy of execution, mental simulation, observation, and verb generation of actions: a meta-analysis. Hum Brain Mapp 2001;12:1–19.

Hari R, Forss N, Avikainen S, Kirveskari E, Salenius S, Rizzolatti G. Activation of human primary motor cortex during action observation: a neuromagnetic study. Proc Natl Acad Sci 1998;95:15061–5.

Hashimoto R, Rothwell JC. Dynamic changes in corticospinal excitability during motor imagery. Exp Brain Res 1999;125:75–81.

Hlustik P, Solodkin A, Gullapalli RP, Noll DC, Small SL. Somatotopy in human primary motor and somatosensory hand representations revisited. Cereb Cortex 2001;11:312–21.

Indovina I, Sanes JN. On somatotopic representation centers for finger movements in human primary motor cortex and supplementary motor area. Neuroimage 2001;13:1027–34.

Jeannerod V, Frak M. Mental imaging of motor activity in humans. Curr Opin Neurobiol 1999;9:735–9.

Kasai T, Kawai S, Kawanishi M, Yahagi S. Evidence for facilitation of motor evoked potentials (MEPs) induced by motor imagery. Brain Res 1997;744:147–50.

Kleinschmidt A, Nitschke MF, Frahm J. Somatotopy in the human motor cortex hand area. A high-resolution functional MRI study. Eur J Neurosci 1997;9:2178–86.

Lotze M, Erb M, Flor H, Huelsmann E, Godde B, Grodd W. fMRI evaluation of somatotopic representation in human primary motor cortex. Neuroimage 2000;11:473–81.

Maeda F, Kleiner-Fisman G, Pascual-Leone A. Motor facilitation while observing hand actions: specificity of the effect and role of observer's orientation. J Neurophysiol 2002;87:1329–35.

Malcolm MP, Triggs WJ, Light KE, Shechtman O, Khandekar G, Gonzalez Rothi LJ. Reliability of motor cortex transcranial magnetic stimulation in four muscle representations. Clin Neurophysiol 2006;117:1037–46.

Nelissen K, Luppino G, Vanduffel W, Rizzolatti G, Orban GA. Observing others: multiple action representation in the frontal lobe. Science 2005;310:332–6.

Oldfield RC. The assessment and analysis of handedness: the Edinburgh inventory. Neuropsychologia 1971;9:97–113.

Pascual-Leone A, Cammarota A, Wassermann EM, Brasil-Neto JP, Cohen LG, Hallett M. Modulation of motor cortical outputs to the reading hand of braille readers. Ann Neurol 1993;34:33–7.

Pascual-Leone A, Nguyet D, Cohen LG, Brasil-Neto JP, Cammarota A, Hallett M. Modulation of muscle responses evoked by transcranial magnetic stimulation during the acquisition of new fine motor skills. J Neurophysiol 1995;74:1037–45.

Porro CA, Francescato MP, Cettolo V, Diamond ME, Baraldi P, Zuiani C, et al. Primary motor and sensory cortex activation during motor performance and motor imagery: a functional magnetic resonance imaging study. J Neurosci 1996;16:7688–98.

Rathelot JA, Strick PL. Muscle representation in the macaque motor cortex: an anatomical perspective. Proc Natl Acad Sci 2006;103:8257–62.

Rizzolatti G, Wolpert DM. Motor systems. Curr Opin Neurobiol 2005;15:623–5.

Roland PE, Gulyas B. Visual memory, visual imagery, and visual recognition of large field patterns by the human brain: functional anatomy by positron emission tomography. Cereb Cortex 1995;5:79–93.

Rossi S, Pasqualetti P, Tecchio F, Pauri F, Rossini PM. Corticospinal excitability modulation during mental simulation of wrist movements in human subjects. Neurosci Lett 1998;243:147–51.

Rossini PM, Pauri F. Neuromagnetic integrated methods tracking human brain mechanisms of sensorimotor areas 'plastic' reorganization. Brain Res Rev 2000;33:131–54.

Rossini PM, Barker AT, Berardelli A, Caramia MD, Caruso G, Cracco RQ, et al. Non-invasive electrical and magnetic stimulation of the brain, spinal cord and roots: basic principles and procedures for routine clinical application. Report of an IFCN committee. Electroencephalogr Clin Neurophysiol 1994;91:79–92.

Rossini PM, Rossi S, Pasqualetti P, Tecchio F. Corticospinal excitability modulation to hand muscles during movement imagery. Cereb Cortex 1999;9:161–7.

Sanes JN, Donoghue JP. Static and dynamic organization of motor cortex. Adv Neurol 1997;73:277–96.

Sanes JN, Donoghue JP, Thangaraj V, Edelman RR, Warach S. Shared neural substrates controlling hand movements in human motor cortex. Science 1995;268:1775–7.

Schieber MH. Constraints on somatotopic organization in the primary motor cortex. J Neurophysiol 2001;86:2125–43.

Schieber MH. Motor control: basic units of cortical output? Curr Biol 2004;14:353–4.

Shinoda Y, Yokota J, Futami T. Divergent projection of individual corticospinal axons to motoneurons of multiple muscles in the monkey. Neurosci Lett 1981;23:7–12.

Stephan KM, Fink GR, Passingham RE, Silbersweig D, Ceballos-Baumann AO, Frith CD, et al. Functional anatomy of the mental representation of upper extremity movements in healthy subjects. J Neurophysiol 1995;73:373–86.

Stinear CM, Fleming MK, Byblow WD. Lateralization of unimanual and bimanual motor imagery. Brain Res 2006;1095:139–47.

Strafella AP, Paus T. Modulation of cortical excitability during action observation: a transcranial magnetic stimulation study. Neuroreport 2000;11:2289–92.

Vargas CD, Olivier E, Craighero L, Fadiga L, Duhamel JR, Sirigu A. The influence of hand posture on corticospinal excitability during motor imagery: a transcranial magnetic stimulation study. Cereb Cortex 2004;14:1200–6.

Wassermann EM, McShane LM, Hallett M, Cohen LG. Noninvasive mapping of muscle representations in human motor cortex. Electroencephalogr Clin Neurophysiol 1992;85:1–8.

Zadikoff C, Lang AE. Apraxia in movement disorders. Brain 2005;128:1480–97.