Functional Somatotopy of Finger Representations in Human Primary Motor Cortex

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Abstract: To assess the degree of fine-scale somatotopy within the hand area of the human primary motor cortex (M1), functional mapping of individual movements of all fingers was performed in healthy young subjects ($n = 7$) using MRI at $0.8 \times 0.8 \text{ mm}^2$ resolution and 4 mm section thickness. The experimental design comprised both a direct paradigm contrasting single digit movements vs. motor rest and multiple differential paradigms contrasting single digit movements vs. the movement of another digit. Direct mapping resulted in largely overlapping activations. A somatotopic arrangement was only recognizable when considering the mean center-of-mass coordinates of individual digit representations averaged across subjects. In contrast, differential paradigms revealed more segregated and somatotopically ordered activations in single subjects. The use of center-of-mass coordinates yielded inter-digit distances ranging from 2.0 to 16.8 mm, which reached statistical significance for pairs of more distant digits. For the middle fingers, the functional somatotopy obtained by differential mapping was dependent on the choice of the digit used for control. These results confirm previous concepts that finger somatotopy in the human M1 hand area emerges as a functional predominance of individual digit representations sharing common areas in a distributed though ordered network. *Hum. Brain Mapping* 18:272–283, 2003.

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Key words: functional MRI; primary motor cortex; finger somatotopy; human

INTRODUCTION

More than 100 years ago, Jackson postulated distinct cortical representations for different types of movement, based on the observation of isolated convulsive movements occurring in epilepsy patients [Jackson, 1863/1931]. This fundamental concept was further

strengthened by direct electrical cortical stimulation in animals [Ferrier, 1875; Fritsch and Hitzig, 1870; Woolsey et al., 1952] and humans [Foerster, 1936; Penfield and Boldrey, 1937] and finally resulted in the well-known schematic illustrations of Penfield's homunculus [Penfield and Rasmussen, 1950] and Woolsey's simiusculus [Woolsey et al., 1952]. Although a gross somatotopy of movement representations in the primary motor cortex (M1) has been well established for the functional organization of major body parts, the degree of fine-scale somatotopy, especially in the M1 hand area, remains an unresolved and controversial issue. In fact, there is emerging evidence from animal studies that the cortical representations of movements of smaller body parts are widely distributed and over-

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Received 23 April 2002; Accepted 11 November 2002
DOI 10.1002/hbm.10084

TABLE I. Outline of differential mapping experiments

D1 vs. D2	D1 vs. D3	D1 vs. D4	D1 vs. D5
	D2 vs. D3	D2 vs. D4	D2 vs. D5
		D3 vs. D4	D3 vs. D5
			D4 vs. D5

lapping. The underlying principles of convergence, divergence, and horizontal connections were recently reviewed by Schieber [2001].

The advent of noninvasive mapping techniques such as magnetic resonance imaging (MRI) facilitates a thorough reexamination of the functional organization of the M1 hand area in healthy human subjects. Previous MRI studies of the cortical representation of finger movements either support the concept of a distributed organization with substantial overlap [Indovina and Sanes, 2001; Rao et al., 1995; Sanes et al., 1995] or, at least in part, provide evidence for a somatotopic arrangement [Beisteiner et al., 2001; Hlustik et al., 2001; Kleinschmidt et al., 1997; Lotze et al., 2000]. This somewhat surprising situation may have resulted from a number of undesirable—and with respect to MRI also unnecessary—limitations. Corresponding pitfalls include the use of insufficient spatial resolution, inadequate volume coverage, suboptimal section orientation, or motor paradigms that may have biased the functional responses toward either spatially distributed or segregated representations. The purpose of this work was to reevaluate the issue of fine-scale finger somatotopy in the human M1 hand area by combining direct and differential mapping of individual finger movements for all five digits of the dominant hand using functional MRI with high spatial resolution.

SUBJECTS AND METHODS

Subjects

Nine healthy volunteers (six men, three women; mean age 27 ± 5 years) were recruited and gave informed written consent before all examinations. Pro-

Figure 1.

Top left: Coronal T1-weighted MR image depicting the section orientation selected for functional mapping of the left-hemispheric M1 hand area and **(top right)** corresponding oblique image (section 3, A = anterior, L = lateral, M = medial, P = posterior). **(1–4: left)** T1-weighted FLASH images showing a magnified view of the M1 hand area (Ω) and **(right)** corresponding T2*-weighted multi-echo FLASH images used for functional mapping. The central sulcus is indicated by arrows.

Figure 2.

Functional mapping of individual finger movements of the dominant right hand using a direct paradigm (i.e., D1 to D5 each vs. motor rest) in four consecutive sections covering the left-hemispheric M1 (single subject). The overlap of activated areas within the M1 hand area reveals no clear somatotopy.

cedures were approved by the local ethical committee. All subjects were right-handed as determined by the Edinburgh Inventory [Oldfield, 1971].

MRI

All studies were conducted at 2.0 Tesla (Siemens Magnetom Vision, Erlangen, Germany) using the standard imaging headcoil. Coronal and sagittal T1-weighted 3D gradient-echo (FLASH) images were employed to define the orientation of oblique transverse-to-sagittal sections that tangentially cover the left-hemispheric primary motor hand area. As demonstrated in Figure 1, such sections cut perpendicular through the depth of the central sulcus and, therefore, allow an easy identification of the hand area in accordance with established anatomic landmarks. In particular, the “hand knob” has been reported to

appear in 90% of the cases as an inverted omega and in 10% of the cases as a horizontal epsilon corresponding to the “middle knee” of the central sulcus [Yousry et al., 1997]. Here, the two shapes were seen equally often (5 subjects with an omega, 4 subjects with an epsilon). For simplicity, the figures use the symbol Ω to indicate the position of the M1 hand area.

In each subject, functional mapping by blood oxygenation level dependent MRI started with a multi-slice EPI sequence at $2.0 \times 2.0 \text{ mm}^2$ resolution (16 sections of 2-mm thickness) to identify the full extent of the M1 hand area. In all cases, a properly adjusted 16-mm volume in the transverse-to-sagittal orientation was sufficient to encompass the hand area in the posterior portion of the precentral gyrus. Subsequently, a more detailed mapping of individual finger representations was performed at $0.78 \times 0.78 \text{ mm}^2$ resolution (interpolated from $1.56 \times 0.78 \text{ mm}^2$) in four

Figure 3.

Functional mapping of individual finger movements of the dominant right hand using a differential paradigm (all possible combinations shown, e.g., D5 vs. D4, D5 vs. D3, D5 vs. D2, etc.) in a selected section (section 2, as in Fig. 2) of the left-hemispheric M1 (same subject as in Fig. 2). The exact location of an individual finger representation strongly depends on the control digit used. Nevertheless, a somatotopic arrangement is recognizable.

consecutive sections of 4-mm thickness. High-resolution mapping was accomplished with the use of a multi-slice multi-echo FLASH sequence (repetition time 344 msec, 5 echoes per excitation, mean echo time

43 msec, flip angle 20 degrees) previously developed for studying human ocular dominance columns [Dechent and Frahm, 2000]. Coverage of a 125×200 mm² rectangular field-of-view by a 80×256 acqui-

Figure 4.

Functional mapping of individual finger movements of the dominant right hand using a differential paradigm (selected combinations refer to D5 vs. D2, D4 vs. D1, D3 vs. D1, D2 vs. D3, and D1 vs. D5) in four consecutive sections covering the left-hemispheric M1 (same subject as in Figs. 2 and 3). The segregation of individual finger representations reveals a somatotopic order.

tion matrix resulted in a temporal resolution of 5.5 sec (4 sections). The achievable quality of the T2*-weighted multi-echo FLASH images used for functional mapping is demonstrated in Figure 1 for all sections studied and in direct comparison with corresponding T1-weighted anatomic FLASH images.

Motor Paradigms

Each subject was examined twice on different days. Subjects were asked to place their dominant right hand in a comfortable position on the hip. The arm was supported by foam pads beneath the elbow and the wrist. While lying in the magnet, the finger paradigm to be performed next was announced via a microphone prior to each experiment. During the actual scanning procedure, visual instruction commands (*Movement* and *Rest* in German language) were projected onto a display system mounted atop the head-coil within the magnet. The commands were identical for all motor paradigms to preclude differential visual stimulations. Their timing was computer-controlled and synchronized with the MRI data acquisition.

Each examination started with a sequential finger-to-thumb opposition task to characterize the M1 hand area using low-resolution EPI. After selecting appropriate sections, all other experiments were carried out using the high-resolution multi-echo FLASH technique. Two distinct finger paradigms were conducted for all fingers. Direct mapping involved tapping of a single finger (22 sec or 4 images) vs. motor rest (33 sec or 6 images), whereas differential mapping contrasted the tapping of a single finger (22 sec) with that of a different digit (22 sec). Each protocol comprised six cycles of movement and control condition yielding a total duration of 5.5 or 4.5 min for the direct and differential paradigm, respectively.

Mapping the full extent of M1 representations for each finger by a direct paradigm required five experiments per subject. The differential paradigm was designed to map the functional predominance of each digit (D) vs. each other digit, for example, D1 (thumb) vs. D2, D3, D4, and D5 in separate experiments. Because such experiments can be analyzed with respect to either of the two movements performed, the 10 differential experiments listed in Table I were sufficient to characterize all combinations. The total of 15 direct and differential paradigms carried out by each volunteer was distributed over the two sessions in a pseudo-randomized way to avoid any systematic effects. Prior to the examination, the subjects were allowed to briefly practice respective movements. Dur-

ing scanning, proper task execution at a self-paced frequency of 2–3 Hz was controlled via a video monitor.

Data Analysis

Two male volunteers showed considerable head movement while performing the motor tasks and were excluded from further analyses. Processing of the data of the remaining subjects included 2D motion correction (Brain Voyager 4.3, Brain Innovation, The Netherlands) as well as 1-2-1 temporal and spatial filtering. The latter smoothing reduced the effective in-plane resolution from 0.61 mm² to approximately 0.91 mm². Significantly activated pixels were identified by cross-correlation with the use of a reference function reflecting the respective motor activation shifted by one image (5.5 sec) to account for hemodynamic latencies. Activation maps were obtained by a statistical analysis using an error probability of $P \leq 0.001$ for activation centers, which were complemented iteratively by directly neighboring pixels with $P \leq 0.0075$ [adapted from Kleinschmidt et al., 1995]. The analysis of the direct and differential experiments yielded a total of 100 activation maps per subject. To avoid inaccuracies with anatomic overlays, the activation maps were superimposed onto the original T2*-weighted multi-echo FLASH images, i.e., the functional raw images.

For display purposes only, visual inspection of finger-specific activation patterns was greatly facilitated by using the inflated cortex of single subjects (Brain Voyager 4.3, Brain Innovation). The procedure involved a segmentation of the anatomic 3D MRI data at the gray-white matter boundary and a subsequent inflation of the left hemisphere with overlaid activations for direct and differential paradigms.

Quantitative evaluations of a possible somatotopic arrangement within the M1 hand area were based on distances between the geographic centers of activations (center-of-mass coordinates) of individual finger representations. To realign the results from the two separate examinations, the sagittal anatomic MRI scans were referenced to the AC–PC line providing sufficient accuracy. After transformation of the original activation maps to $1 \times 1 \times 1$ mm³ isotropic resolution (Brain Voyager 4.3, Brain Innovation), the derivation of a center-of-mass coordinate was restricted to activations within the anatomically and functionally characterized hand knob of M1. The procedure ensured elimination of putative contributions from premotor and/or somatosensory activation. If the fin-

ger-specific representation within M1 consisted of more than one cluster of activated pixels, then the center-of-mass referred to the average value of individual clusters weighted by their functional effect size, that is the number of activated pixels per cluster.

In comparison with a re-scaling transformation of the MRI data into a normalized space, the mere use of Talairach coordinates retains the individual convolution of the cerebral cortex and, therefore, prevents the intersubject smearing of a possible individual somatotopic arrangement. It directly yields coordinates in single subjects in a standardized coordinate system and, therefore, allows for a group analysis of individual results. Whereas direct paradigms resulted in five digit-specific center-of-mass coordinates per subject, corresponding values for differential paradigms were obtained by averaging all four center-of-mass coordinates experimentally determined for a particular digit. For example, a center-of-mass value for D3 was averaged from the respective coordinates obtained for the differential representations of D3 vs. D1, D3 vs. D2, D3 vs. D4, and D3 vs. D5. In an alternative approach, the analysis was restricted to differential experiments with directly neighboring digits only, that is D3 vs. D2 and D3 vs. D4.

Distances were calculated as Euclidean distances between the center-of-mass coordinates of directly neighboring digits, that is between D1–D2, D2–D3, D3–D4, and D4–D5. Distances between more distant digits were represented as the sum of distances between all intermediate digits. For example, the D2–D5 distance was obtained by adding the D2–D3, D3–D4, and D4–D5 distances. Such values correspond to more relevant cortical distances than through-space distances as they take the curvature of the M1 hand area into account.

Statistical Analyses

For the group results of the center-of-mass coordinates, a statistical evaluation of finger somatotopy was performed using repeated measures one-way analysis of variance (ANOVA) with individual spatial orientations in medial-lateral, anterior-posterior, and inferior-superior direction as dependent variables and digit movements as within-subject factor. Conditional on a significant main effect, Tukey's least square difference tests were calculated for post-hoc identification of significantly different locations of individual digit representations. The significance threshold adopted throughout was $P < 0.05$.

Figure 5.

A: Surface reconstruction of the left hemisphere (same subject as in Figs. 2–4), which partially hides the M1 hand area (Ω) due to the convolution of the cerebral cortex. **B:** Segmented cortex at the level of the gray-white matter boundary. **C:** Inflated visualization of the segmented cortex with former convex structures (“gyri”) shaded in light gray and former concave structures (“sulci”) shaded in dark gray. The white box corresponds to the region magnified in Figure 6; arrows indicate the central sulcus.

Figure 6.

Individual finger representations in the left-hemispheric M1 hand area on magnified views of the inflated cortex (same subject and same data as in Figs. 2 and 4, but without premotor and somatosensory activations). **Top:** Direct mapping of individual finger movements (i.e., D1 to D5 each vs. motor rest) results in activa-

tion areas with considerable overlap. **Bottom:** Differential mapping (selected combinations refer to D5 vs. D2, D4 vs. D1, D3 vs. D1, D2 vs. D3, and D1 vs. D5) yields more segregated and somatotopically arranged representations.

RESULTS

Individual Subjects

Although finger tapping resulted in activation of various brain regions including the primary motor cortex, supplementary motor area, premotor cortex, and somatosensory cortex in all subjects, the present analysis of fine-scale somatotopy entirely focused on the M1 hand area. As demonstrated in Figure 2 for a single subject, direct mapping of single finger movements vs. motor rest activated large portions of the M1 hand area for all digits. Because of the considerable overlap of cortical representations, a clear somatotopic arrangement was not discernible from these experiments. In contrast, differential mapping resulted in more segregated activations for individual digits. To indicate the variability of an individual finger representation in dependence on the digit used for control, Figure 3 displays all digit representations determined in a selected section (section no. 2) for the same subject. Figure 4 shows the full spatial extent of differential finger representations over all four examined sections using only one selected differential experiment per digit. Whereas movements of the little finger (D5)

led to medial activations in the superior sections, representations of the thumb (D1) occurred throughout all sections, but mainly in the inferior part and mostly in the lateral portion of the M1 hand area. The observation of intermediate activation foci for movements of D2 to D4 further supported the existence of an underlying somatotopic order.

To clarify this assumption, the activation data obtained for direct and differential mapping were projected onto the subject's inflated left hemisphere. Figure 5 outlines the procedure involving gray-white matter segmentation and subsequent inflation of the anatomic 3D MRI data. The appreciation of the cortical representations of single digit movements is then largely facilitated in Figure 6 showing magnified views of the M1 hand area without its complex convolution. In analogy to the original activation maps shown in Figures 2 and 4, respectively, direct mapping of a particular digit movement resulted in considerable overlap of associated representations (Fig. 6, top), while differential mapping caused smaller activation clusters with significantly reduced overlap (Fig. 6, bottom). Moreover, the foci of differential representations were arranged in a somatotopic order ranging from a lateral-anterior-inferior location representative of D1

Figure 7.

Somatotopic arrangement of individual finger representations in the left-hemispheric M1 hand area viewed in a **(left)** posterior-anterior and **(right)** inferior-superior projection (A = anterior, I = inferior, L = lateral, M = medial, P = posterior, S = superior). The coordinates (in mm) refer to mean center-of-mass activations (Table II) obtained for **(A)** a direct paradigm, **(B)** differential paradigms using all other digits, and **(C)** differential paradigms using directly neighboring digits only.

to a medial-posterior-superior position for D5. These qualitative results from visual inspection of inflated cortical maps were quantitatively confirmed when analyzing the mean distances of finger-specific representations averaged across subjects.

Group Results

Quantitative analyses were based on center-of-mass coordinates for cortical finger representations in individual Talairach space. Figure 7 shows the mean re-

sults for all subjects obtained for direct (Fig. 7A) and differential mapping with all fingers (Fig. 7B) as well as for differential mapping with directly neighboring digits only (Fig. 7C). It turns out that even direct mapping yields a mild somatotopic arrangement when the extended activation volumes are condensed into a single center-of-mass position (Fig. 7A). The existence of finger somatotopy becomes much more evident for center-of-mass coordinates derived from differential mapping experiments (Fig. 7B). The foci of respective digit representations are well separated in all three spatial dimensions and the convolution of the hand knob may be recognized by interconnecting the individual center-of-mass coordinates. The absolute spatial separation becomes even more pronounced, in particular in the inferior-superior direction, if the analysis is restricted to the paradigms involving directly neighboring digits only (Fig. 7C).

Table II summarizes the mean locations and sizes of finger-specific representations. Typically, direct mapping resulted in center-of-mass coordinates located close to each other centered at -37 mm (medial-lateral), -29 mm (anterior-posterior), $+48$ mm (superior-inferior) with maximum displacements of 1 to 2 mm. In contrast, differential mapping revealed clearly separated coordinates with extensions ranging from -35 to -40 mm (medial-lateral), -26 to -33 mm (anterior-posterior), and $+51$ to $+44$ mm (superior-inferior), respectively. These values were further increased for analyses restricted to directly neighboring digits. The cortical distances given in Table III substantiate the picture of somatotopically ordered representations of individual finger movements in the M1 hand area. Using the data of Table II, the distances of directly neighboring digits for finger representations obtained by direct mapping decreased from 2.8 mm for D1–D2 to 0.8 mm for D4–D5 yielding a maximum (summed) distance of 6.6 mm for D1–D5. Differential mapping uniformly increased cortical distances of inter-digit representations causing D1–D5 values of 11.8 and 16.8 mm for the two analyses using either all or only directly neighboring digits. Based on the one-way ANOVA results shown in Table II, statistical significance was mainly achieved for pairs of more distant digits.

The different spacings for direct and differential finger representations are paralleled by corresponding findings for respective activation volumes. For example, the overlapping nature of directly mapped finger activations was based on 4 to 8 times larger activation volumes as obtained by differential approaches that tend to subtract areas of shared representation (see Table II). In either case, the volumes for individual

TABLE II. Location and size of individual finger representations in M1[†]

Paradigm	Digit	Spatial coordinates/mm			Volume/mm ³
		M - L	P - A	I - S	
Direct	D1	-37.4 ± 2.5	-27.0 ± 6.3	46.5 ± 5.7	830 ± 441
	D2	-38.5 ± 4.3	-28.4 ± 2.1	48.7 ± 5.6	465 ± 296
	D3	-36.8 ± 3.5	-29.7 ± 4.3	48.5 ± 3.8	766 ± 481
	D4	-36.7 ± 3.2	-30.6 ± 3.3	48.5 ± 3.4	767 ± 362
	D5	-36.3 ± 3.8	-30.1 ± 3.9	49.0 ± 3.5	786 ± 498
Differential ^a		M - L	P - A*	I - S	
	D1	-38.1 ± 3.2	-25.9 ± 5.3	44.4 ± 3.9	201 ± 129
	D2	-39.5 ± 2.1	-28.6 ± 3.9	46.1 ± 4.2	109 ± 69
	D3	-37.6 ± 2.5	-30.6 ± 4.5	47.0 ± 4.3	140 ± 147
	D4	-36.7 ± 2.9	-32.0 ± 3.1	48.8 ± 3.7	230 ± 174
	D5	-34.9 ± 3.8	-32.7 ± 3.2	51.1 ± 4.9	167 ± 152
Differential ^b		M - L*	P - A	I - S*	
	D1	-36.9 ± 3.8	-26.7 ± 5.6	43.5 ± 4.2	233 ± 174
	D2	-39.8 ± 1.6	-28.7 ± 4.2	46.6 ± 4.1	109 ± 82
	D3	-36.6 ± 3.4	-30.7 ± 4.7	47.6 ± 3.5	128 ± 151
	D4	-36.9 ± 3.3	-31.5 ± 3.7	49.4 ± 5.4	117 ± 76
	D5	-32.0 ± 2.4	-33.2 ± 5.7	52.8 ± 5.7	98 ± 104

[†] Values refer to center-of-mass coordinates and volumes of activations (mean ± SD, $n = 7$). Individual coordinates refer to medial-lateral (M-L), posterior-anterior (P-A), and inferior-superior (I-S) orientations with larger values corresponding to more medial, more anterior, and more superior locations, respectively.

^a Mean of differential representations with all other digits.

^b Mean of differential representations with directly neighboring digits only.

* $P < 0.05$ one-way ANOVA.

digits were rather similar with the exception of D2 (index finger) showing markedly reduced activation volumes in comparison to other digits. Sequential finger-to-thumb opposition vs. motor rest resulted in a mean activation volume of $2,129 \pm 557 \text{ mm}^3$ ($n = 7$), so that the functional representation of the entire M1 hand area amounts to about the three-fold volume obtained for individual fingers.

Reversible Somatotopy

For a differential movement paradigm, the precise location of a single finger representation was found to be dependent on the “control” digit used. As a consequence, it was possible to create a reversed somatotopic order for one of the middle fingers in 6/7 subjects by selecting a suitable combination of differential experiments. Figure 8 (top) illustrates this situation for D3 and D4 in a single subject by comparing the representations obtained for D3 vs. D2 with D3 vs. D5 as well as for D4 vs. D3 with D4 vs. D5. In either case, the activations shifted from a medial to a more lateral position when replacing the control digit D2 or D3 with D5, respectively. When referencing the different

D3 (or D4) activations against the representation of D2 (or D3), Figure 8 (bottom) reveals either a conventional or reversed somatotopic order. For example, the representation of D4 (green) occurs more medial to that of D3 (yellow) when contrasting D4 against D3 in correspondence with a conventional somatotopy, whereas this arrangement becomes reversed when using D5 as a control digit for D4.

DISCUSSION

The present results may be summarized into three major findings. First, direct mapping of finger-specific activations vs. motor rest resulted in largely overlapping representations covering large portions of the M1 hand area. Under these circumstances, a somatotopic arrangement with small inter-digit distances was only recognizable when restricting the analysis to center-of-mass coordinates of individual digit representations and comparing mean values averaged across subjects. In contrast, differential paradigms contrasting a single finger movement with tapping of another finger revealed more segregated and somatotopically ordered activations in single subjects. The use of cen-

TABLE III. Distances between individual finger representations in M1[†]

Paradigm	Digit	D1	D2	D3	D4
Direct	D1				
	D2	2.8			
	D3	4.9	2.1		
	D4	5.8	3.0	0.9	
	D5	6.6	3.8	1.7	0.8
Differential ^a	D1				
	D2	3.5			
	D3	6.4*	2.9		
	D4	8.8*	5.3*	2.4	
	D5	11.8*	8.3*	5.5	3.0
Differential ^b	D1				
	D2	4.8			
	D3	8.6	3.8		
	D4	10.6*	5.8	2.0	
	D5	16.8*	12.0*	8.2*	6.2*

[†] Values refer to distances (in mm) between mean center-of-mass coordinates of finger-specific activations as obtained from Table II. Distances between the representations of distant digits represent the sum of all intermediate distances between directly neighboring digits.

^a Mean of differential representations with all other digits.

^b Mean of differential representations with directly neighboring digits only.

* $P < 0.05$ Post-hoc Tukey's least square difference.

ter-of-mass coordinates yielded pronounced inter-digit distances that reached statistical significance for pairs of more distant digits. And finally, the somatotopic arrangement of middle fingers as obtained by differential mapping was found to be dependent on the choice of the digit used for control.

Taken together, these observations do not support the prevalence of a classic somatotopy with spatially separated and monotonously ordered finger representations that refer to independent finger-specific subdivisions of the M1 hand area. Instead, such representations are widely distributed and their spatial extent causes considerable overlap. This is in line with observations of redundant motor representations of different body parts in M1 using electric stimulation in monkeys [McKiernan et al., 1998; Schieber and Hibbard, 1993] and awake patients [Penfield and Boldrey, 1937]. On the other hand, the unambiguous delineation of a monotonously ordered arrangement of differential finger representations provides clear evidence for the implementation of a somatotopic principle that refers to a relative quantitative predominance of individual finger representations. This con-

cept of functional somatotopy maps the residual differential representations of two (or more) finger movements after subtracting shared neuronal populations. It, therefore, also explains the possible reversal of a particular somatotopic order when comparing selected pairs of differential representations for the same finger, for example, when using a control digit on either side of one of the middle fingers. In this case, the shift of a particular finger representation emerges as a natural consequence of the subtraction of its neuronal population with the overlapping though different distributions of neuronal populations subserving neighboring fingers.

The present work redefines fine-scale somatotopy in the human M1 hand area as the presence of distributed and overlapping representations for individual digits, which nevertheless reveal a somatotopic gradient in agreement with the order established by electrophysiologic means [Penfield and Rasmussen, 1950]. It, therefore, not only reconciles previous conflicting reports, but also matches the manifold requirements for fine-scale coordinated movements. For example, in an intuitive manner, the observed cortical layout of digit representations supports hand tasks such as grasping that involve common movements of multiple fingers as well as tasks such as playing a musical instrument that require independent movements of individual fingers.

In a more general sense, the observation of a functional somatotopy in the human M1 hand area, which accommodates both coordinated common movements and independent individualized movements, fits the emerging model of a functional organization of M1 comprising convergence, divergence, and horizontal connections [Schieber, 2001]. Convergence can be demonstrated by cortical stimulation at various sites that all may lead to a contraction of a single muscle [Donoghue et al., 1992; Schieber and Hibbard, 1993]. Consequently, the M1 areas projecting via the spinal level to different muscles of, for example, the hand, reveal extensive overlap. Divergence reflects the fact that a large fraction of M1 neurons projects onto multiple muscles [McKiernan et al., 1998], which destroys the simple picture of a point-to-point relationship between cortical representation and executing muscle. Furthermore, the existence of horizontal connections in M1, which include the neural representations of individual digits [Huntley and Jones, 1991], contradicts its spatial organization into finger-specific or muscle-specific subunits as the correlate of a classic fine-scale somatotopy. This view is also supported by the fact that a partial inactivation of M1, either through intra-cortical injections of muscimol [Schieber

Figure 8.

Reversible somatotopy of D3 and D4 finger representations in magnified views of the inflated cortex covering the left-hemispheric M1 hand area (different subject as in Fig. 6). **Top:** Shifted activations obtained by differential mapping with neighboring fingers on either side (i.e., D3 vs. D2 and D3 vs. D5 as well as D4 vs.

D3 and D4 vs. D5). **Bottom:** When referencing these activations against the representations of D2 (or D3), D3 (or D4) shows either a conventional (**left**) or reversed (**right**) somatotopic order.

and Poliakov, 1998] or small infarcts [Schieber, 1999], always affects more than just one digit.

CONCLUSION

The human M1 hand area presents as a physiologically synergetic and anatomically interconnected area, with fine-scale somatotopy implemented as a quantitative predominance of individual digit representations sharing common areas. In this situation, it is to be expected that direct mapping of finger representations does not lead to a classic somatotopic scheme of spatially distinct sub-divisions of the hand area, but results in considerable overlap of extended activations. On the other hand, differential mapping subtracts shared neuronal populations and respective activation areas, and thereby unravels a functional somatotopy that relates to mean differential representations of individual digits that follow the somatotopic arrangement expected from electrophysiology. Moreover, when selecting specific differential representations for individual digits, pertinent activations may be shifted to such a degree that the quantitatively defined somatotopy appears as reversed.

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