

Motor Areas of the Medial Wall: A Review of Their Location and Functional Activation

Our goal in this review is to provide an anatomical framework for the analysis of the motor functions of the medial wall of the hemisphere in humans and laboratory primates. Converging evidence indicates that this region of the frontal lobe contains multiple areas involved in motor control. In the monkey, the medial wall contains four premotor areas that project directly to both the primary motor cortex and the spinal cord. These are the supplementary motor area (SMA) on the superior frontal gyrus and three motor areas buried within the cingulate sulcus. In addition, there is evidence that a fifth motor field, the pre-SMA, lies rostral to the SMA proper. Recent physiological observations provide evidence for functional differences among these motor fields.

In the human, no consensus exists on the number of distinct motor fields on the medial wall. In this review, we summarize the results of positron emission tomography (PET) studies that examined functional activation on the medial wall of humans. Our analysis suggests that it is possible to identify at least four separate cortical areas on the medial wall. Each area appears to be relatively more involved in some aspects of motor behavior than others. These cortical areas in the human appear to be analogous to the pre-SMA, the SMA proper, and two of the cingulate motor areas of the monkey. We believe that these correspondences and the anatomical framework we describe will be important for unraveling the motor functions of the medial wall of the hemisphere.

Views about the structure and function of the motor areas on the medial wall of the hemisphere have undergone dramatic shifts in recent years. In the past, a single motor field, the supplementary motor area (SMA), was placed in area 6 on the medial wall. This area was thought to be preferentially involved in the generation of internally driven movements rather than sensory-guided movements (Goldberg, 1985; Okano and Tanji, 1987; Passingham, 1987; Passingham et al., 1989; Roland, 1987; Mushiake et al., 1991; Tanji, 1994). It is now clear that, in addition to the SMA, the medial wall contains three motor areas buried in the cingulate sulcus (for references and review, see Dum and Strick, 1991a; He et al., 1995). Furthermore, based on anatomical and physiological evidence, the medial portion of area 6 has been subdivided into a rostral region, the pre-SMA, and a caudal region, the SMA proper. Clearly, the medial wall is more functionally differentiated than previously recognized. The specific contributions of each field to motor behavior have yet to be uncovered. However, the presence of multiple motor areas on the medial wall certainly complicates the interpretation of prior studies of medial wall function.

We have turned to the pool of information from functional imaging studies to gain insight into the organization of the motor areas of the medial wall of humans. Most imaging studies with positron emission tomography (PET) have used a common coordinate system to present data. As a consequence, it is possible to make meaningful comparisons among studies. In this selective review, we first present the current evidence from studies in nonhuman primates for multiple motor areas on the medial wall. Next, we review the functional

anatomy of the medial wall derived from human PET investigations. Finally, we interpret the results from PET in relation to the nonhuman primate studies. Our goal is to provide a common frame of reference for studies of medial wall function. Specifically, we sought to determine the relation between sites of activation in various tasks and individual cortical fields.

Motor Areas of the Medial Wall of the Monkey

The Supplementary Motor Area

The original maps of the SMA, derived by electrical stimulation of the cortical surface, placed it in the medial portion of Brodmann's cytoarchitectonic area 6 (Penfield and Welch, 1951; Woolsey et al., 1952). However, based on cyto- and chemoarchitectonic differences, two distinct areas can be distinguished within this region: the SMA proper and the pre-SMA (Table 1A, Fig. 1). The SMA proper is located largely caudal to the level of the genu of the arcuate sulcus (Dum and Strick, 1991a) in area 6α (Vogt and Vogt, 1919) or field F3 (Matelli et al., 1985, 1991). The pre-SMA lies largely rostral to the genu in area 6β or field F6 (Matelli et al., 1991; Matsuzaka et al., 1992).

Like other premotor areas, the SMA proper projects directly to the primary motor cortex and to the spinal cord (Fig. 2A; Dum and Strick, 1991a,b; He et al., 1993, 1995). In contrast, the pre-SMA does not have substantial projections to either region (Dum and Strick, 1991a; Luppino et al., 1993; Tokuno and Tanji, 1993; Lu et al., 1994). Instead, the pre-SMA is interconnected with regions of prefrontal cortex and other nonprimary motor cortical areas (Bates and Goldman-Rakic, 1993; Luppino et al., 1993; Lu et al., 1994). These differences indicate that the SMA has a more direct access to motor effectors than the pre-SMA. As a consequence, the motor functions of the pre-SMA may be more abstract than those of the SMA proper.

The thalamic input to the SMA and pre-SMA is another distinctive aspect of their connectivity. The most substantial input to the SMA originates from parts of the nucleus ventralis lateralis pars oralis (VLo; e.g., Schell and Strick, 1984; Wiesendanger and Wiesendanger, 1985a,b; Rouiller et al., 1994). In contrast, the most abundant input to the pre-SMA appears to originate from parts of the nucleus ventralis anterior pars parvocellularis (VAPc) and area X (Wiesendanger and Wiesendanger, 1985a,b). Based on the subcortical input to these thalamic regions it has been suggested that different portions of the basal ganglia and cerebellum innervate each cortical area (Schell and Strick, 1984; Wiesendanger and Wiesendanger, 1985a,b; Rouiller et al., 1994).

The anatomical differences between the SMA and pre-SMA are echoed at the physiological level (e.g., Macpherson et al., 1982a,b; Hummelsheim et al., 1986, 1988; Wiesendanger, 1986; Alexander and Crutcher, 1990). Intracortical stimulation using conventional parameters often fails to evoke movements from the pre-SMA (F6; Luppino et al., 1991; Matsuzaka

Table 1
Correspondence of the cortical subdivisions of the medial wall

A				
Monkey	Pre-SMA F6	SMA F3		Matsuzaka et al. (1992) Matelli et al. (1991)
Human	Area 6a β	Area 6a α		Vogt and Vogt (1919)
	Area 6a	Area 6p		Sarkisov et al. (1955)
	Superofrontal magnopyramidal region, pars anterior	Superofrontal magnopyramidal region, pars posterior (paraganglionic belt)		Braak (1979, 1980)
B				
Monkey	CMAr Area 24c	CMAv Area 23c	CMA α Area 6c	Dum and Strick (1991a)
Human	Area 24c	Area 24d		Matelli et al. (1991)
	Rostral cingulate zone	Caudal cingulate zone		Picard and Strick
	Anterior	Posterior		
	—	Gigantopyramidal field		Braak (1976, 1980)

et al., 1992). When evoked, movements tend to be slow or tonic, multijoint responses that do not show a somatotopic organization. In contrast, intracortical microstimulation of the SMA (F3) frequently elicits brisk isolated movements of the head, forelimbs, and hindlimbs in a somatotopic order.

The two fields also can be distinguished based on their responsiveness to somatosensory input and their activity during motor tasks. Pre-SMA neurons are poorly responsive to somesthetic stimuli, but frequently show activity changes after the presentation of visual cues in an instructed delay task (Matsuzaka et al., 1992). Conversely, SMA neurons are characterized by their sensitivity to somatosensory stimuli rather than to instructional cues (Matsuzaka et al., 1992). The temporal relation of the neural activity to motor behavior also varies between the two areas. Activity changes time-locked to movement onset are more frequent caudally in the SMA, whereas activity changes during a preparatory period and preceding movement are more common rostrally in the pre-SMA (Alexander and Crutcher, 1990; Rizzolatti et al., 1990; Matsuzaka et al., 1992).

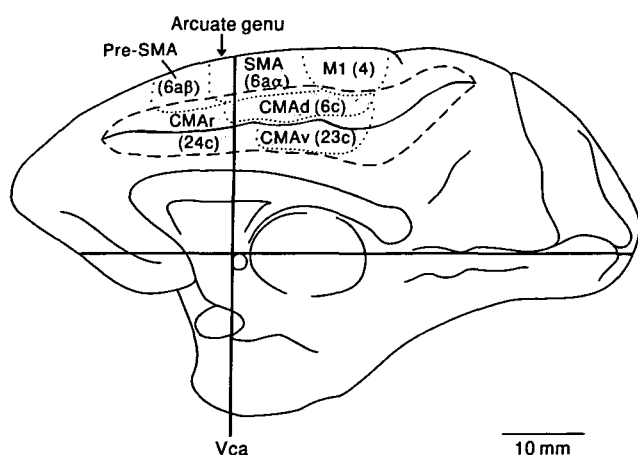


Figure 1. Location of the motor areas of the medial wall of the hemispheres of the monkey. The dashed lines define the extent of the upper and lower banks of the cingulate sulcus that is shown "opened up." The dotted lines show the boundaries of the cytoarchitectonic areas. Shaded areas correspond to the territory of origin of corticospinal projections to cervical and upper thoracic segments. The arrow shows the level of the genu of the arcuate sulcus on the lateral surface of the hemisphere. M1, primary motor cortex; SMA, supplementary motor area; CMAr, rostral cingulate motor area; CMA α , caudal cingulate motor area, dorsal bank; CMAv, caudal cingulate motor area, ventral bank.

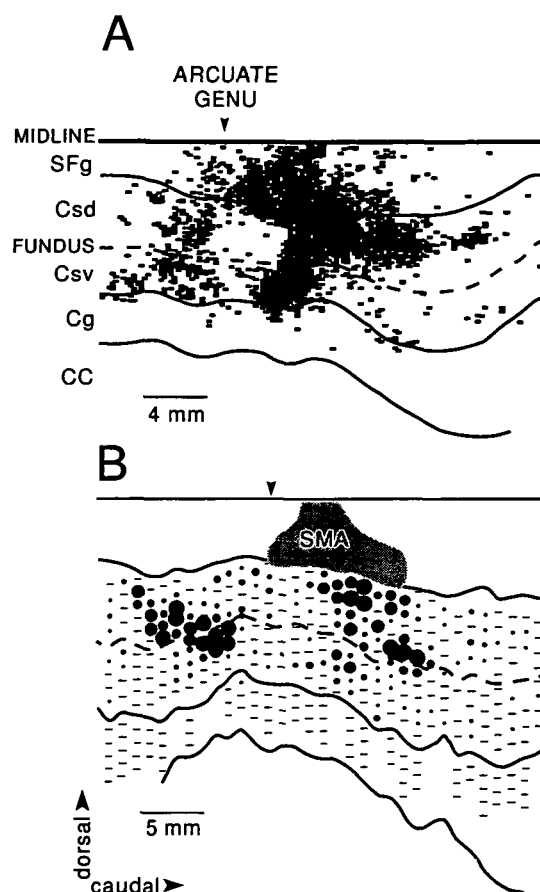


Figure 2. A, This "flattened" reconstruction of the medial wall of the monkey shows the location of corticospinal cells projecting to segments C4–T2 of the spinal cord (adapted from Dum and Strick, 1991a). SFg, superior frontal gyrus; Csd and Csvg, dorsal and ventral banks of the cingulate sulcus; Cg, cingulate gyrus; CC, corpus callosum. B, Filled circles mark the location of active neurons found in monkeys performing key press tasks (adapted from Shima et al., 1991). Circle diameter is proportional to the number of neurons found at each recording site. The rostral group corresponds to the CMAr and the caudal group largely corresponds to the CMA α . The shaded area represents the arm region of the SMA as shown in A.

These differences suggest that the pre-SMA and SMA are involved in distinct aspects of motor control. Pre-SMA function appears to be more closely related to the selection and preparation of movement, whereas that of the SMA proper may be more closely related to motor execution. Thus, the "higher" and "lower" functions, which in the past were ascribed to rostral and caudal portions of the SMA (see Wiesendanger, 1986), may, in fact, pertain to two distinct cortical fields.

The Cingulate Motor Areas

The cingulate motor areas are buried in the cingulate sulcus and do not extend onto the cingulate gyrus. These areas were initially defined by mapping the connections of the medial wall with the primary motor cortex and spinal cord (Fig. 2A; Muakkassa and Strick, 1979; Hutchins et al., 1988; Dum and Strick, 1991a; He et al., 1995). Each motor area corresponds to a different cytoarchitectonic field (Fig. 1, Table 1B). The core of the rostral cingulate motor area (CMAr) is located in area 24c, anterior to the genu of the arcuate sulcus, where it spans both banks of the cingulate sulcus (Dum and Strick, 1991a; He et al., 1995). The other two CMA are located roughly at the same rostrocaudal level as the SMA proper, for instance, caudal to the genu of the arcuate sulcus. The CMA α

is located in a subfield of area 6 (area 6c) on the dorsal bank of the cingulate sulcus, whereas the CMAv is in a subfield of area 23 (area 23c) on the ventral bank (Dum and Strick, 1991a; Morecraft and Van Hoesen, 1992; He et al., 1995). The CMAd and CMAv also differ in their cortical and thalamic connections (for a recent review, see Dum and Strick, 1993). Briefly, the CMAd receives its major input from VLo (Holsapple and Strick, 1989), a target of pallidal efferents (e.g., Kim et al., 1976; DeVito and Anderson, 1982), whereas the CMAv receives its densest input from a caudal portion of the thalamic nucleus ventralis lateralis pars caudalis (VLc), a target of cerebellar efferents (e.g., Percheron, 1977; Stanton, 1980; Kalil, 1981). The CMAd and CMAv are interconnected with largely different regions of the primary motor cortex (Holsapple and Strick, 1991) and the parietal lobe (see Dum and Strick, 1993 for references). In addition, the CMAv (and CMAr), but not the CMAd is interconnected with the prefrontal cortex (Lu et al., 1994; see also Bates and Goldman-Rakic, 1993). These anatomical observations reinforce the separation of the CMAd and CMAv into distinct motor areas, and suggest their differential participation in motor control.

Although to date very few physiological studies have specifically investigated the cingulate motor areas, recent evidence indicates that functional differences complement the anatomical divisions. Luppino et al. (1991) described two areas of the cingulate sulcus where intracortical microstimulation evoked body movements. Relatively low-intensity intracortical stimulation in the CMAd and CMAv (area 24d of Luppino et al., 1991) evoked movement of the fore- and hindlimbs in a topographically organized manner. In contrast, stimulation in the CMAr, area 24c, was only occasionally effective in evoking movements, and responsive sites in the CMAr did not show a clear somatotopic organization. The paucity of motor responses evoked from the CMAr correlates with the comparatively low density of corticospinal neurons found in this area (Dum and Strick, 1991a; He et al., 1995). These observations suggest that, compared to the CMAd and CMAv, the CMAr exerts a relatively weak influence on the spinal cord. The patterns of neural activity recorded in the depth of the cingulate sulcus strengthen the functional differentiation of the cingulate motor areas. Neurons displaying movement related activity were found at two sites within the cingulate sulcus that project to the arm area of the primary motor cortex (Fig. 2B; Shima et al., 1991). The rostral site was comparable to the CMAr, and the caudal site included both the CMAd and CMAv. More neurons related to self-paced movements and displaying "long-lead" activity prior to movement onset (> 1 sec) were found in the rostral site (CMAr) than in the caudal site (CMAd/CMAv). Similar long-lead activity has been reported previously for neurons in the anterior portion of the cingulate sulcus during a spatial delayed response task (Niki and Watanabe, 1976, 1979). The differences between the rostral and caudal cingulate motor areas seen during simple tasks suggest that even more prominent differences will be present for more complex tasks.

Recently, we used the 2-deoxyglucose (2DG) technique to determine the "functional" activity in motor areas when monkeys perform remembered sequences of reaching movements (Picard and Strick, 1994, 1995). The most intense 2DG uptake in the premotor areas on the medial wall was found in a single region, the arm representation of the CMAd. Thus, there is functional, as well as anatomical evidence that the CMAd is distinct from adjacent SMA and CMAv.

Human Functional Anatomy

Functional imaging has provided evidence that the medial wall of humans is involved in multiple aspects of motor control, as well as in attentional processes related to response

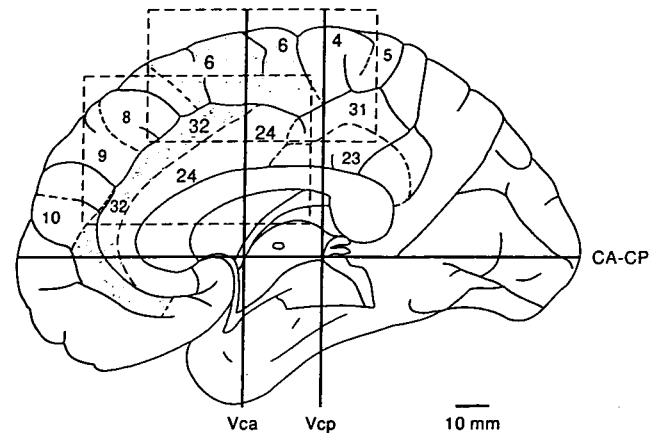


Figure 3. This midsagittal view of the human brain, redrawn from Talairach and Tournoux (1988), illustrates the relation of medial cortical areas to the stereotaxic reference frame. The intersection of the bicommissural line (CA-CP) and a perpendicular line crossing the anterior commissure (Vca) at the midline defines the origin of the Talairach space. Numbers show the approximate location of Brodmann's cytoarchitectonic areas. Boundaries are indicated by dashed lines where they do not course along sulci. Boxes delineate the areas enlarged in Figures 4 and 5.

generation. At this point in time, however, it has not been possible to identify clearly separate motor fields on the medial wall that are comparable to what is seen in the monkey. Yet, there is evidence for some anatomical and physiological heterogeneity of the human medial cortex. In this section, we will attempt to relate the findings of functional imaging studies in humans to the motor areas of the monkey. We believe that this approach, while not definitive, will provide a useful framework for future investigation of the medial wall motor areas.

Direct comparison of activation loci across studies is possible only if a common frame of reference is used. The location of significant rCBF changes identified on PET images is frequently referenced to the standardized coordinate system developed by Talairach and his collaborators (Talairach et al., 1967; Talairach and Tournoux, 1988; Fig. 3). Our review is limited to those PET studies that supply the Talairach coordinates of activation foci. This choice was directed by the widespread use and availability of this atlas, and the need for precise localization beyond global designations like "anterior cingulate." Unfortunately, this choice excluded some studies (e.g., Kawashima et al., 1994; Schlaug et al., 1994), which employed a different atlas for anatomical normalization and localization (Bohm et al., 1986).

Numerous PET studies have demonstrated regional cerebral blood flow (rCBF) changes in the medial wall related to various aspects of motor behavior such as movement execution, response selection, motor learning, and motor planning. As an initial step towards functional differentiation of medial wall areas, we have categorized various tasks as either "simple" or "complex" and compared the distribution of the two types of activation foci. Included in the simple category are tasks that required the most basic spatial or temporal organization of movement, and tasks that are overlearned and highly practiced. An example of a simple task is moving a joystick in a fixed direction after an auditory trigger signal. Conversely, complex tasks are characterized by additional motor or cognitive demands such as the selection of a motor response, and the acquisition of a conditional association. An example of a complex task is moving a joystick in a random, self-selected direction. Clearly, a task classified as complex can be carried out using a relatively simple movement. Classifying tasks rather than movements allows us to examine the aspect

Table 2
Stereotaxic coordinates* of rCBF increases on the medial wall

Reference	Comparisons	C/S*	Superior frontal x, y, z	Cingulate x, y, z
1. Anderson et al. (1994)	Remembered saccades—fixation	S	10, -2, 60	12, 4, 44
	Remembered saccades—reflexive saccades	C	10, 4, 52	8, 4, 44
2. Chollet et al. (1991)	Thumb to finger opposition—rest	S	12, -6, 60	
3. Coghill et al. (1994)	Thermal stimulus (forearm): painful—neutral	S	1, -4, 54	1, 1, 42
	Thermal stimulus (forearm): painful—neutral	S	5, -6, 66	
	Vibratory stimulus (forearm)—neutral thermal	S	5, -19, 47	3, 3, 39
4. Colebatch et al. (1991a)	Thumb to finger opposition—rest	S	5, -3, 52	
	Isolated finger movements—rest	S	2, -8, 57	
	Shoulder flexion—rest	S	1, -7, 47	
	Fist making—rest	S	1, -5, 55	
5. Colebatch et al. (1991b)	Active-passive inspiration	S	4, -29, 48	
6. Deiber et al. (1991)	Random-fixed direction joystick movements	C	2, 14, 52	8, 34, 32
7. Derbyshire et al. (1994)	Thermal stimulus (hand): painful—nonpainful	S		12, 2, 40
	Thermal stimulus (hand): painful—nonpainful	S		18, 38, 24
8. Fox et al. (1985)*	Saccadic eye movements—rest	S	0, -2, 60	
	Fist making—rest	S	0, -10, 60	
9. Frith et al. (1991)	Random-directed finger movements	C		3, 16, 34
	Generate words—repeat words	C		4, 23, 36
10. Grafton et al. (1992b)	Rotor pursuit—rest	S	8, -14, 56	
	Rotor pursuit—rest	S	8, -18, 48	
	Rotor pursuit skill learning: 4th—1st trial	S	2, -14, 52	
11. Grafton et al. (1993)	Tracking (shoulder)—visual tracking	S	3, -13, 50	5, -11, 40
	Tracking (elbow)—visual tracking	S	3, -9, 51	4, -8, 40
	Tracking (wrist)—visual tracking	S	1, -2, 54	4, -9, 40
	Tracking (index)—visual tracking	S	4, -2, 55	5, 1, 38
	Tracking (thumb)—visual tracking	S	2, 7, 60	2, 13, 38
12. Grasby et al. (1993)	Word retrieval from memory—rest	C		8, 22, 28
	Word retrieval from memory—rest	C		8, 18, 32
13. Jenkins et al. (1994)	Learned key press sequence—rest	S	0, -4, 48	0, -2, 44
	New key press sequence—rest	C		4, 22, 28
	New-learned key press sequence	C		6, 30, 28
14. Pardo et al. (1990)*	Stroop task: incongruent—congruent trials	C	7, 10, 50	10, 19, 32
	Stroop task: incongruent—congruent trials	C		7, 17, 32
	Stroop task: incongruent—congruent trials	C		17, 25, 30
	Stroop task: incongruent—congruent trials	C		13, 44, 22
15. Paulesu et al. (1993)	Silent verbal working memory—visual working memory	C	6, 6, 56	4, 4, 48
16. Paus et al. (1993a)	Conditional key press: overpracticed—fixation	S		8, 3, 39
	Conditional key press: reversal—fixation	C		4, 5, 49
	Conditional key press: reversal—overpracticed	C		15, 8, 49
	Directed finger movement—rest	S		5, -7, 49
	Opposite finger movement—rest	C		5, -4, 48
	Opposite-directed finger movement	C		1, 22, 38
	Opposite-directed finger movement	C		5, 10, 45
16. Paus et al. (1993a) continued	Targeted saccades—rest	S	3, -2, 60	
	Conditional saccades: overpracticed—fixation	S	12, -4, 60	
	Conditional saccades: reversal—overpracticed	C		3, 32, 20
	Conditional saccades: reversal—overpracticed	C		7, 27, 29
	Conditional saccades: reversal—overpracticed	C	5, 17, 51*	
	Conditional saccades: reversal—fixation	C		8, 29, 22
	Conditional saccades: reversal—fixation	C		9, 32, 12
	Opposite-targeted saccades	C		1, 10, 42
	Opposite-targeted saccades	C	12, 8, 51*	
	Opposite saccades—rest	C	9, -2, 53*	
16. Paus et al. (1993a) continued	Word association: overpracticed—fixation	S	4, -2, 57	
	Word association: overpracticed—rest	S	1, -1, 60	
	Word association: reversal—rest	C	1, 5, 58	
	Word association: reversal—rest	C		1, 13, 48
	Word association: reversal—rest	C		7, 20, 38
	Word association: reversal—fixation	C		9, 34, 13
	Word association: reversal—fixation	C		4, 15, 49
	Word association: reversal—overpracticed	C		4, 30, 17
	Word association: reversal—overpracticed	C		7, 34, 22
	Word association: reversal—overpracticed	C		1, 22, 49
	Word association: reversal—overpracticed	C		3, 18, 44
	Word association: reversal—overpracticed	C		5, 20, 36

Table 2
Continued.

Reference	Comparisons	C/S*	Superior frontal x, y, z	Cingulate x, y, z
17. Petersen et al. (1988)*	Repeat words—view words	S	2, -1, 54	
	Repeat words—view words	S	2, 3, 56	
	Generate words—repeat words	C		6, 14, 41
	Generate words—repeat words	C		2, 24, 30
	Generate words—repeat words	C		7, 18, 41
	Generate words—repeat words	C		11, 21, 30
18. Petrides et al. (1993a)	Self-ordered pointing—directed pointing	C		7, 34, 26
	Self-ordered pointing—directed pointing	C		3, 29, 29
	Self-ordered pointing—directed pointing	C		9, 24, 40
	Conditional pointing—directed pointing	C		5, 30, 21
19. Petrides et al. (1993b)	Random-externally specified number generation	C	0, 3, 65	
	Random number generation—counting	C		11, 25, 22
20. Playford et al. (1992)	Fixed direction joystick movements—rest	S	2, -3, 52	6, 5, 32
	Fixed direction joystick movements—rest	S		2, 3, 36
	Fixed direction joystick movements—rest	S		2, 3, 40
	Fixed direction joystick movements—rest	S		2, 3, 44
	Fixed direction joystick movements—rest	S		2, -3, 48
	Random joystick movements—rest	C		4, 27, 24
	Random joystick movements—rest	C		2, 25, 28
21. Ramsey et al. (1993)	Active-passive inspiration	S	10, -16, 48	
	Active-passive expiration	S	0, -4, 60	
22. Sergent et al. (1992a)	Playing scales—hearing scales	S	4, -7, 57	
	Playing score—reading and hearing score	C	16, 6, 53	
23. Sergent et al. (1992b)	Letter sound discrimination—object discrimination	C	25, 8, 48	4, 18, 31
24. Talbot et al. (1991)	Thermal stimulation (forearm): painful—warm	S		15, 1, 33
				5, -17, 39
25. Taylor et al. (1994)	Incongruent—congruent letter naming	C		10, 14, 43
26. Weiller et al. (1992)	Thumb to finger opposition—rest (recovered hand after infarction)	NA		0, 22, 20
27. Wise et al. (1991a)	Silent verb generation—rest	C	0, 6, 60	
28. Zatorre et al. (1992)	Alternate key press—rest	C	12, 6, 57	7, 8, 42
	Alternate key press—rest	C	4, -2, 63	
29. Zatorre et al. (1994)	Conditional key press—repetitive key press	C		8, 18, 29
	Conditional key press—repetitive key press	C		1, 24, 42
				5, 36, 26

*The coordinates are in millimeters from the origin of the standard space of Talairach and Tournoux (1988), where *x* indicates the distance from the midline in the coronal plane, *y* indicates the distance from the anterior commissure (Vca line) in the sagittal plane (positive = rostral, negative = caudal), and *z* indicates the vertical distance from a plane crossing both the anterior and posterior commissures (positive = superior to the bicommissural line). The laterality of the responses ($\pm x$) has been omitted for clarity and because of uncertainty in many instances. Each coordinate represents the locus of peak response or a weighted average equivalent to the center of mass of the response. The coordinates from the studies marked with an asterisk (*) originally referred to the brain Hd6 of Talairach et al. (1967). They were converted to the standard of Talairach and Tournoux (1988) by linear transformation with total brain size in each axis as scaling factor.

*Task classification as complex (C) or simple (S). NA: not applicable.

*These data points are included in the superior frontal gyrus group, although they were described as cingulate activation by Paus et al. (1993a). It is our view that activation at this axial level better reflects pre-SMA function. However, because of uncertainty, these data points are plotted both on the superior frontal gyrus and cingulate cortex in Figures 4B and 5B.

of premotor function related to the integration of “rules” and “conditions” into movement production. Obviously, this classification scheme is relative, not absolute.

All the data on which the following analysis is based are presented in Table 2.¹ The relevant references are listed alphabetically and numbered consecutively. The table includes the rating for each task used, simple (S) or complex (C), and the coordinates of the associated activation foci on the medial wall. The activation foci are plotted on standard midsagittal views of the brain (Figs. 4, 5). The foci are numbered according to the reference list in Table 2. To reduce the complexity of figures, the medial wall has been split into two views: superior frontal gyrus (areas 4 and 6; Fig. 4) and the cingulate region (areas 24 and 32; Fig. 5). For clarity, foci related to arm

Figure 4. The location of rCBF increases on the superior frontal gyrus is plotted in Talairach space (from Fig. 3; see Table 2 for coordinates). *Symbol numbers* refer to the studies listed in Table 2. *Circles* designate activations observed during relatively simple tasks, whereas *diamonds* indicate activations related to more complex attributes of motor behavior. Symbols with double borders highlight separate activation foci observed in single studies. For clarity, activation loci related to arm movement tasks, eye movement tasks, and verbal tasks are plotted separately in *A*, *B*, and *C*. In *D*, activations during oculomotor and speech tasks are designated together as *FACE*. Functional groups of activation foci related to simple and complex aspects of movement correspond to the SMA proper caudally and the pre-SMA rostrally.

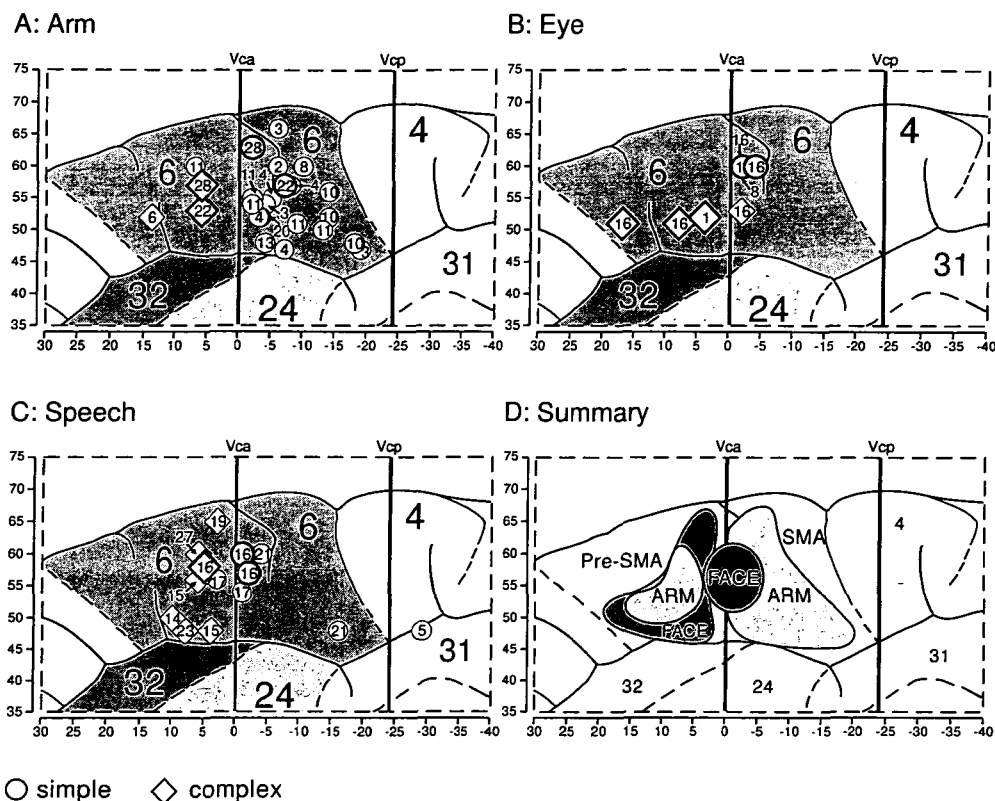
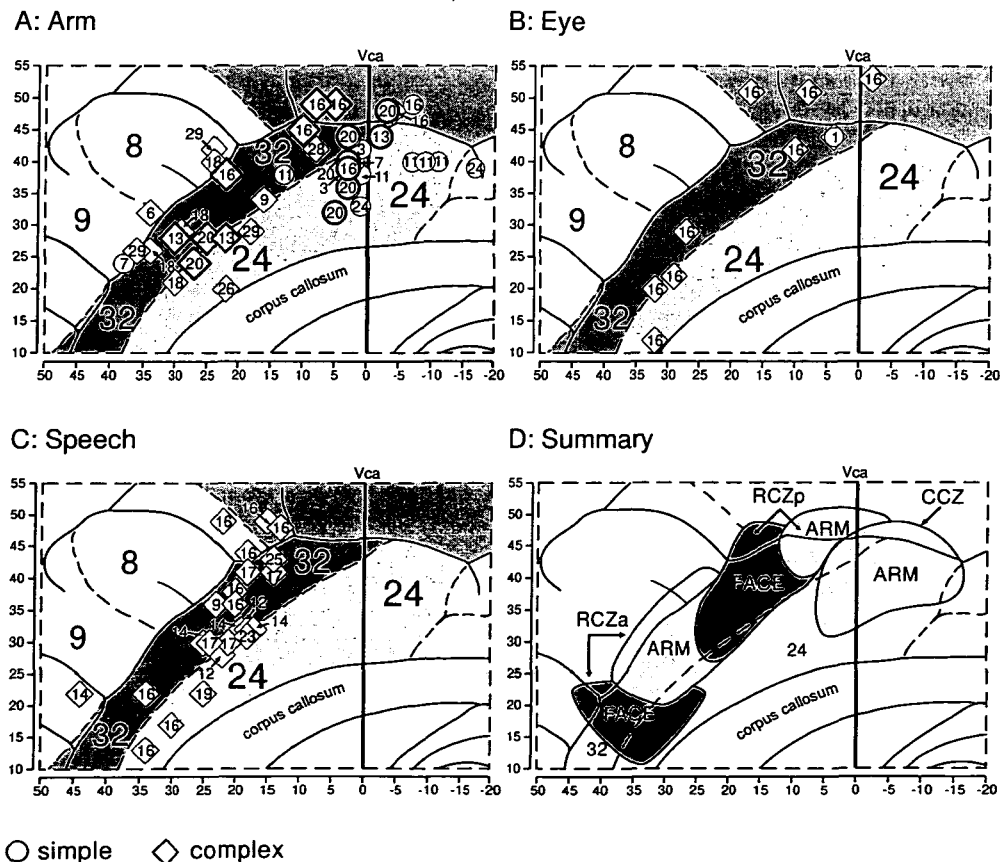


Figure 5. The location of rCBF increases in the anterior cingulate region is plotted in Talairach space (from Fig. 3; see Table 2 for coordinates). *A–C*, Conventions as in Figure 4. *D*, Summary view showing that, rostral to the Vca line, two groups of foci related to oculomotor tasks and speech tasks (shown together as *FACE*) alternate with two groups of foci related to arm movement tasks. This alternation divides the rostral cingulate zone into anterior (*RCZa*) and posterior (*RCZp*) sectors activated in relation to complex tasks. The caudal cingulate zone (*CCZ*) is defined by the activations associated with simple arm movement tasks located just in front and behind the Vca line.



and hand tasks, eye movement tasks, and verbal tasks are separately considered. Overall, our synthesis of the PET data suggests that at least four separate motor areas are located on the medial wall.

The Supplementary Motor Area

Early, nontomographic cerebral blood flow studies supported the concept that the SMA is a functionally distinct premotor area (Orgogozo and Larsen, 1979; Roland et al., 1980). Furthermore, these studies suggested that the SMA operates at a level that is hierarchically superior to that of the precentral motor cortex. One of the most influential observations was that the SMA, not the primary motor cortex, was activated during imagined movements (Roland et al., 1980). This, and the finding that the rCBF over the SMA increased primarily for complex sequential movements and not simple movements, lead to the concept that the SMA is primarily involved in establishing motor programs rather than movement execution (Roland et al., 1980).

Our analysis of PET data suggests that the superior frontal gyrus of humans contains two distinct motor areas like those found in the monkey. With few exceptions, the loci activated during the execution of simple tasks (S in Table 2, circles in Fig. 4), as well as during somatosensory stimulation of the forearm, are located caudal to the level of the anterior commissure (Vca line). In contrast, loci activated during relatively more complex tasks are located more rostrally (C in Table 2, diamonds in Fig. 4). Hence, the Vca line appears to provide a reasonably good anatomical landmark for distinguishing between two functional regions on the medial aspect of the superior frontal gyrus. For consistency, these motor areas will be referred to as the pre-SMA (rostral to the Vca line) and SMA proper (caudal to the Vca line).

Direct support for our hypothesis comes from the topographic shift of activation foci with increasing task complexity found by Sergent et al. (1992a; Sergent, 1993). These authors identified separate rCBF increases associated with the motor execution and planning components of piano playing. Activation associated with playing scales, a highly automatic activity for practiced pianists, was found in the SMA, 7 mm caudal to the Vca line (Table 2, Fig. 4A, double circle 22). In contrast, playing an unfamiliar musical piece produced an rCBF increase that was centered on a portion of area 6 on the lateral surface of the hemisphere, but also included the pre-SMA, 6 mm rostral to the Vca line (double diamond 22; Sergent et al., 1992a; Sergent, 1993). Reading, but not playing the musical score, as well as listening to the piece, and playing scales were not associated with activation of the pre-SMA. These observations suggest that the pre-SMA activation was associated with the cognitive/motor demands of playing an unfamiliar piece.

Two separate foci of activation, on either side of the Vca line, also were noted by Zatorre et al. (1992) in relation to a key press task. The task had the distinctive feature that the subjects responded only to every other trigger signal; hence, we have classified it as complex. The caudal focus was located in the vicinity of activation foci reported for various simple hand tasks (Table 2, Fig. 4A, circle 28; see also Matelli et al., 1993). This activation may reflect the involvement of the SMA proper in the execution of a simple movement. The rostral focus in the pre-SMA was located near activation foci associated with complex movements (Fig. 4A, diamond 28). Such activation may arise from the "choice" aspect of the task (generate or withhold movement). This interpretation is consistent with the observation of Grafton et al. (1992a) that activation of the superior frontal gyrus during a simple visually guided movement of the finger was strongly increased by the addition of a "no go" contingency.

When a task requires movement selection, activation is consistently seen in the pre-SMA. For example, Deiber et al. (1991; Table 2, Fig. 4A, diamond 6) demonstrated increased rCBF in the pre-SMA when subjects were required to select the direction in which to move a joystick. In contrast, activation was only found more caudally, in the SMA, when the joystick movements were made repetitively in a fixed direction (Playford et al., 1992; Table 2, Fig. 4A, circle 20).²

Whether a movement is self-paced or externally cued appears to significantly influence the location of activation on the medial wall. Most studies that have found activation in the SMA used tasks that were externally paced (i.e., triggered by metronome clicks or visual stimuli; Table 2). Similarly, Remy et al. (1994) found that auditory-cued movements produce greater activation in the SMA than self-paced movements (see also Rao et al., 1993). Perhaps the absence of any distinction between pre-SMA and SMA sites of activation in the study of Shibasaki et al. (1993) is due to their use of self-paced movements in all tasks.³

An additional factor that influences the relative amount of activation in the SMA and pre-SMA is the level of skill acquisition. There is growing evidence that practice has an effect on the level of SMA activation in humans (e.g., Lang et al., 1988; Grafton et al., 1992b, 1994; Seitz and Roland, 1992b; Jenkins et al., 1994; Schlaug et al., 1994). For example, Grafton et al. (1992b, 1994) reported that activation in the SMA proper increases as a function of the performance improvement associated with practice on a visuomotor tracking task. Likewise, rCBF in the SMA is relatively low for new sequences of key presses, but increases as the performance becomes more automatic (Jenkins et al., 1994).

On the other hand, Friston et al. (1992) reported that practice on a motor task results in a relative decrease in the activation of what appears to be the pre-SMA. Clearly, additional experiments need to be performed to examine the issue of skill acquisition and activation of the medial wall motor areas. However, present evidence suggests that the SMA and pre-SMA are reciprocally engaged during motor learning and the development of automaticity. Activation in the SMA appears to be enhanced during the automatic performance of learned movements, whereas that in the pre-SMA appears to be greatest during the initial stages of skill acquisition.

The separation of activation loci for simple and complex tasks into different areas on the superior frontal gyrus is true not only for arm movements, but also for eye movements (Fig. 4B). Two studies report activation of the SMA, centered just behind the Vca line, related to the execution of targeted saccades (Fox et al., 1985; Paus et al., 1993a; Fig. 4B, circles 8 and 16). Activation was observed in the pre-SMA when the direction of eye movement was dependent on new sensorimotor associations (Paus et al., 1993a; Fig. 4B, diamond 16). Similarly, Anderson et al. (1994) found activation of the SMA when comparing saccades to remembered targets with visual fixation (Fig. 4B, double circle 1), but found increased activation of the pre-SMA when comparing the remembered saccades task with reflexive saccades to visual targets (Fig. 4B, double diamond 1).

Relatively simple speech tasks also produce rCBF increases on the superior frontal gyrus near or caudal to the Vca line (Fig. 4C). Activation of the SMA was observed in association with the simple repetition of words (Petersen et al., 1988, 1989; Fig. 4C, circles 17), and the production of overpracticed verbal associations (Paus et al., 1993a; Fig. 4C, circles 16). The rCBF modulations observed in these studies appear related to the control of the vocal apparatus during speech. Support for this interpretation comes from the work of Ramsay et al. (1993), who found that volitional expiration leads to SMA activation at sites near those activated during simple speech

tasks (Fig. 4C, circle 21). More complex verbal tasks, like silent verb generation (Wise et al., 1991), oral word production in new conditional associations (Paus et al., 1993a, reversal task), or self-ordered number generation (Petrides et al., 1993b), result in activation of the pre-SMA, ahead of the Vca line (Fig. 4C, diamonds Nos. 27, 16, and 19). The involvement of the pre-SMA in higher order aspects of speech is further suggested by its activation during such tasks as silent rehearsal of a sequence of letters (Paulesu et al., 1993) and phonological discrimination of letter sounds (Sergent et al., 1992b). The pre-SMA activation seen in the latter two tasks may be related to the subvocalization that probably occurred during task performance. It is equally possible that the metabolic responses in the pre-SMA during silent verbal tasks were due in part to the active inhibition of speech production that these tasks required. This view is supported by the results of Pardo et al. (1990), who found activation in the pre-SMA during the Stroop conflict task that requires inhibition of habitual responses as well as motor selection.

To summarize, a consistent finding in the studies we reviewed is that, independent of the body part used, tasks requiring higher order aspects of motor control produce activation rostral to the Vca line in the pre-SMA, whereas more simple motor tasks lead to activation caudal to the Vca line in the SMA proper. The spatial separation of the responses is perhaps best illustrated in those studies that examined activation of the superior frontal gyrus using paradigms that incorporated simple and complex task components (Sergent et al., 1992a; Zatorre et al., 1992; Paus et al., 1993a). In such studies (Fig. 4A–C, double symbols), there is evidence for an activation in the SMA proper associated with the simple component of the task and an activation in the pre-SMA associated with the more complex component.

The Vca line also appears to approximate the boundary between cytoarchitectonic subdivisions of area 6 and to divide the traditional SMA into anatomically distinct regions. Braak (1979, 1980) defined a superior frontal magnopyramidal field on the medial wall of the hemisphere that corresponds to area 6. He considered the caudal portion of this field to be specialized and part of a paraganglionic belt on the medial wall that extends from his ganglionic core (area 4) "anteriorly up to about the level of the anterior commissure" (Braak, 1980; p. 97). Sarkissov et al. (1955) also identified anterior and posterior subdivisions within Brodmann's area 6, which they termed "6a" and "6p." In addition, a survey of sulcal anatomy in a large number of human brains indicated that abrupt changes in the course of the cingulate sulcus frequently occur at the level of the anterior commissure (Tomaiuolo et al., 1993). Significantly, this change in sulcal anatomy was found to be closely related to the location of hand representation in PET images of the medial wall (Paus et al., 1993b). These observations indicate that there is a close correspondence between the anatomical subdivisions of area 6 on the medial wall and the spatial separation of activation sites related to simple and complex tasks. Thus, anatomical and functional evidence support our conclusion that medial area 6 of humans contains two distinct motor areas, the pre-SMA and SMA proper.

Our analysis is consistent with concepts of body representation on the medial wall derived from monkey and human experiments (e.g., Penfield and Welch, 1951; Woolsey et al., 1952; Talairach et al., 1967; Fried et al., 1991; Luppino et al., 1991; Matsuzaka et al., 1992). In PET studies (Fig. 4A–C), the activation sites for eye, face and arm movements tend to be represented in a rostrocaudal sequence within the SMA proper (caudal to the Vca line), whereas they are intermingled in the pre-SMA (rostral to the Vca line; Fig. 4D). Similarly, in monkey experiments, the SMA proper, but not the pre-SMA, is so-

matotopically organized (Luppino et al., 1991; Matsuzaka et al., 1992).

Electrical stimulation of medial area 6 in humans has not resulted in clear distinctions between the pre-SMA and SMA. Movements have been evoked by stimulation of medial wall sites both rostral and caudal to the Vca line (e.g., Talairach et al., 1967; Fried et al., 1991). Fried et al. (1991) did not distinguish between the pre-SMA, SMA and cingulate motor areas, but described a single body map that encompassed the total region. Surprisingly, Talairach et al. (1967) found that most of the sites that were effective in evoking motor responses were located rostral to the Vca line in the pre-SMA. This is not consistent with the results of the monkey studies described above. Nonetheless, both Talairach et al. (1967) and Fried et al. (1991) found that more complex responses (e.g., the "urge" to move, vocalization, naming errors, complex movement synergies) were generally evoked from stimulation sites anterior to the Vca line.

The Cingulate Motor Areas

Focal activation in the cortex adjoining the cingulate sulcus has been seen in a variety of experimental conditions (Table 2, Fig. 5). The cingulate region we have analyzed begins with area 32 at the genu of the corpus callosum and extends caudally up to the posterior border of area 24 (Fig. 3). Our synthesis of PET findings indicates that the simple/complex dichotomy divides activation sites related to arm movement into two spatially separate zones: a large rostral cingulate zone (RCZ) activated in relation to complex tasks and a smaller caudal cingulate zone (CCZ) activated during simpler tasks. Furthermore, within the rostral zone, two separate clusters of sites activated during arm movements alternate with sites activated during eye and face movements. This arrangement suggests that the rostral zone is subdivided into two functional sectors. Thus, as a whole, there is evidence that the cingulate region of humans contains as many as three separate motor areas (Fig. 5D).

Caudal Cingulate Zone (CCZ)

Activation of the CCZ, in area 24 near the Vca line, has been observed in relation to simple tasks similar or identical to those that produce rCBF changes in the SMA proper (Playford et al., 1992, 1993; Zatorre et al., 1992; Grafton et al., 1993; Paus et al., 1993a; Table 2, Fig. 5). These foci can be distinguished from those in the SMA proper because of their much more ventral location. Unlike the SMA proper, activation of the CCZ has not as yet been seen during relatively simple tasks involving face and eye movements, such as in speech production or the execution of targeted saccades. The significance of this observation is unclear, but it may correspond to the apparent absence of a distinct face representation in the caudal cingulate motor area of the monkey (Muakkassa and Strick, 1979; Morecraft and Van Hoesen, 1992; see also Luppino et al., 1991; Dum and Strick, 1993).

It is interesting to note that all but one of the activation sites in cingulate cortex associated with tasks using painful stimuli fall in the CCZ (Talbot et al., 1991; Coghill et al., 1994; Derbyshire et al., 1994; Fig. 5A, circles Nos. 24, 3, and 7). Weak activation of the CCZ is also generated by vibratory stimuli (Coghill et al., 1994). Whether the activation in these studies is truly related to the nature of the somatosensory stimulation, the motor aspects of the tasks, or a combination of the two has not as yet been resolved.

Based on its location, the CCZ in area 24 may correspond, at least in part, to the "gigantopyramidal" field of Braak (1976) located in the cingulate sulcus. This agranular field extends rostrally just beyond the level of the anterior commissure (Fig. 6). According to Braak (1976), this field has the morphological

features of a primordial motor area. This view is consistent with the finding that the CCZ is activated by somatosensory stimulation and during simple motor tasks.

Rostral Cingulate Zone (RCZ)

Imaging studies also provide evidence for additional motor areas in rostral portions of the cingulate cortex of humans. Two studies have reported that complex tasks lead to activation at sites just anterior and somewhat dorsal to the CCZ (Zatorre et al., 1992; Paus et al., 1993a; Fig. 5A, diamonds 28 and 16). For example, Paus et al. (1993a) observed activation in an anterior and dorsal cortical region during a key press task that required reversal of a conditioned association (Fig. 5A, double diamonds 16). In the same study, they found activation in the CCZ associated with a key press movement in a simpler motor task (Fig. 5A, double circle 16). It is our view that the two regions of activation represent different functional areas—one in the posterior portion of the rostral cingulate zone (RCZp), and another in the CCZ. This view should be tested in future studies.

Still further anteriorly in cingulate cortex, there is considerable evidence for another area in the RCZ that is activated in relation to complex aspects of arm movement. Playford et al. (1992, 1993) found two sets of activation foci in cingulate cortex during arm movements. One set was located in the region we term the CCZ and was activated during joystick movements made repetitively in a fixed direction (Fig. 5A, double circles 20). The second set of activation foci was found about 25 mm more anteriorly in the region we term the anterior portion of the rostral cingulate zone (RCZa). Blood flow changes at the anterior sites appeared exclusively when subjects randomly selected the direction of joystick movements, and not when the movements were made in a fixed direction (Fig. 5A, double diamonds 20; see also Deiber et al., 1991; Fig. 5A, diamond 6). Likewise, Jenkins et al. (1994) found separate rostral and caudal sets of activation during arm movement tasks. The activation in the CCZ was present when subjects performed a learned key press sequence (Fig. 5A, double circle 13). The activation in the RCZa appeared when subjects were learning a new sequence (Fig. 5A, double diamonds 13).

In multiple other studies, activation was consistently observed in the RCZa in relation to the internal selection of an aspect of movement (Frith et al., 1991; Zatorre et al., 1992, 1994; Paus et al., 1993a; Petrides et al., 1993a). For example, Frith et al. (1991) examined activation during two tasks requiring movement of one of two fingers. In the control task, the subject was instructed which finger to move. In the internal selection task, the subject decided which finger to move. Compared to the control task, activation in the RCZa was either only present or of greater magnitude during the internal selection task.

In normal subjects, simple motor tasks generally do not lead to activation in the RCZa. However, activation in this region was present during simple movements in subjects who had recovered hand motility after a cerebral infarction (Weiller et al., 1992; Fig. 5A, diamond 26). This observation supports the view that activation in the RCZa is motor in nature. Furthermore, it suggests that RCZa plasticity may contribute to the recovery of motor function seen in some stroke patients.

The activation patterns in patients with Parkinson's disease demonstrate a further functional difference between the RCZa and the CCZ (Playford et al., 1992, 1993). The caudal zone in Parkinson's patients, like that in normal subjects, was activated during repetitive joystick movements made in a fixed direction. In contrast, the RCZa in Parkinson's patients, unlike that in normal subjects, failed to show activation in relation to the random selection of the direction of move-

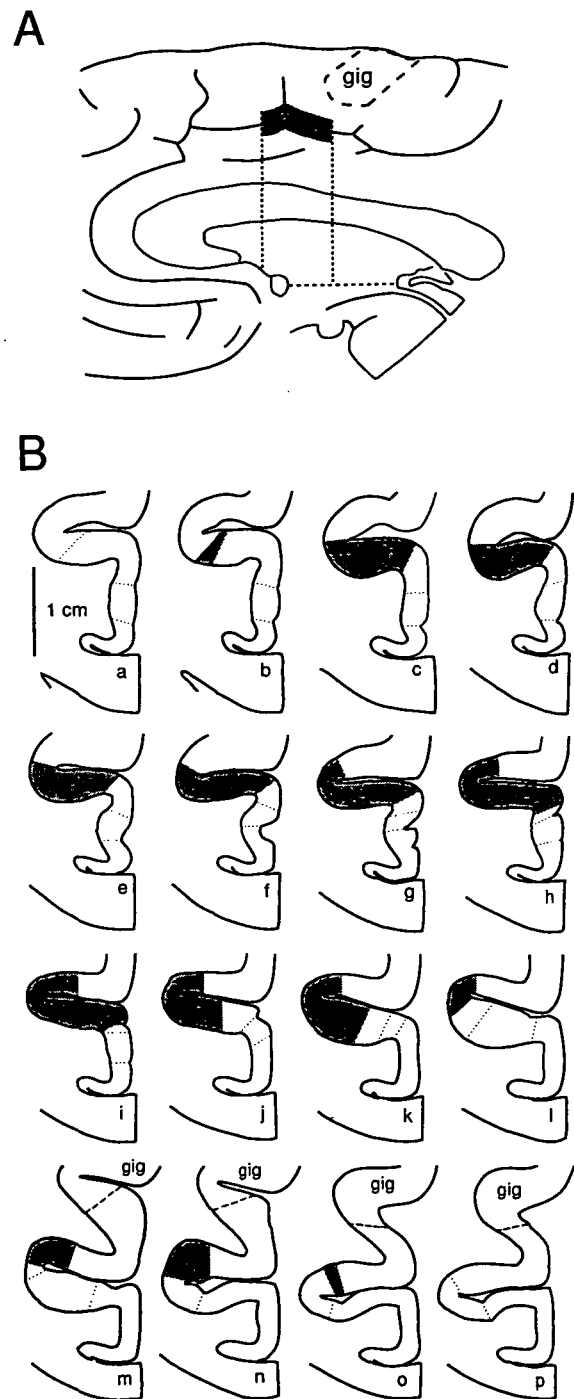


Figure 6. The primitive gigantopyramidal field of the human brain described by Braak (1976) extends roughly from the middle of the bicommissural line to just beyond the level of the anterior commissure (A). The sections shown in B were cut perpendicular to the intercommissural line through the cingulate sulcus from the level of the anterior commissure (a) rostrally to the level of the mammillary bodies (p) caudally. The primitive gigantopyramidal field, indicated by shading, is almost totally buried within the banks of the cingulate sulcus. The dotted lines indicate the borders of paralimbic transition areas. The dashed lines in A and B (sections m to p) represent the border of area gigantopyramidalis (gig, primary motor cortex).

ment. Thus, the activation in the two zones was differentially affected by the disease.

The pattern of blood flow changes observed during eye movement tasks (Fig. 5B) and verbal tasks (Fig. 5C) reinforce the view that the RCZ is involved in higher order aspects of

motor behavior (Table 2, Petersen et al., 1988, 1989; Pardo et al., 1990; Frith et al., 1991; Sergent et al., 1992b; Grasby et al., 1993; Paus et al., 1993a; Petrides et al., 1993b; Taylor et al., 1994). For example, neither the RCZa nor RCZp was activated during a task that required the simple repetition of viewed words (Petersen et al., 1988). Instead, activation in the RCZp was present in relation to the generation of verbs from a list of nouns (Fig. 5C, diamonds 17). This activation disappeared when the list of nouns became familiar and the task was "overpracticed," but reappeared when a new list of nouns was presented (Raichle et al., 1994). In general, the RCZ, in rostral area 24 and area 32, is activated during tasks that require movement selection and willful generation of many different types of motor behavior. In contrast, the CCZ, around and behind the Vca line, appears to be activated even during more rudimentary types of motor tasks.

The RCZa and, in most cases, the RCZp are activated in conjunction with the prefrontal cortex. This association occurs for complex tasks involving eye, face, or arm movements (e.g., Petersen et al., 1988; Deiber et al., 1991; Frith et al., 1991; Playford et al., 1992, 1993; Grasby et al., 1993; Petrides et al., 1993a,b; Zatorre et al., 1994). In contrast, there does not appear to be any association between activation in the CCZ and the prefrontal cortex; prefrontal activation has not been observed during simple motor tasks (Playford et al., 1992; Grafton et al., 1993; Paus et al., 1993a). The association between activation in the RCZ and prefrontal cortex may relate to the finding that, in monkeys, the prefrontal cortex is interconnected with the CMAr and the CMAv, but not the CMAd (Bates and Goldman-Rakic, 1993; Lu et al., 1994).

One surprising outcome of our synthesis of PET data is the demonstration that, within the RCZ, two groups of foci activated in relation to eye and face movements alternate with two groups activated during arm movements (Fig. 5D). For example, Paus et al. (1993a) observed that an eye movement task activated multiple sites in the RCZ. Activation sites were located as far caudally as 10 mm rostral to the Vca line, and as far rostrally as 32 mm rostral to the Vca line. They were separated dorsoventrally by 30 mm. Likewise, Pardo et al. (1990) observed multiple activation foci in the RCZ during a speech task. These foci were located as far caudally as 16 mm rostral to the Vca line, and as far rostrally as 42 mm rostral to the Vca line. The alternation of eye/speech foci of activation with those of the arm is apparent from a comparison of Fig. 5A–C. This alternation is the major reason we have subdivided the RCZ into anterior (RCZa) and posterior (RCZp) portions (Fig. 5D).

Cingulate Zones and CMA Correspondences

Provisionally, we have associated the human cingulate zones defined by imaging studies (RCZa, RCZp, and CCZ) with the three cingulate motor areas of the monkey (CMAr, CMAv, and CMAd; Table 1B). The gigantopyramidal field (Braak, 1976), which probably overlaps with the CCZ (see above), has some similarities with the CMAd (area 6c) of the monkey in terms of its cytoarchitecture and location (Dum and Strick, 1991a). In particular, both areas have a complement of large pyramidal-shaped neurons in layer V which, in the monkey, project to the spinal cord. As described above, the CCZ of humans is activated during simple arm movements. Similarly, neurons in the monkey CMAd are active during a simple key press task (Shima et al., 1991). In addition, of the monkey cingulate motor areas, only the CMAd lacks interconnections with the dorsolateral prefrontal cortex (Lu et al., 1994). This correlates with the observation that, of the human cingulate zones, only activation in the CCZ is dissociated from that of the prefrontal cortex. For these reasons, although their equivalence cannot

be definitively established, we propose that the CCZ of humans corresponds to the CMAd of monkeys (Table 1B).

The correspondence between the two portions of the rostral cingulate zone of humans (RCZa and RCZp) with motor areas in the monkey is much more speculative. In monkeys, it is clear that the cortical motor areas in the cingulate sulcus are quite distinct from the cortical fields on the cingulate gyrus (Dum and Strick, 1993). The cingulate motor areas are intimately related to the motor system, whereas the cingulate gyrus is densely interconnected with the limbic system. At this point, it is unclear whether some, or perhaps all, of the rostral cingulate sites of PET activation lie in the human equivalent of the cingulate gyrus or the equivalent of a cingulate motor area. This uncertainty is due, in part, to the variability in the depth and course of the cingulate sulcus (Ono et al., 1990). The need to average data from groups of subjects in PET studies further compounds the problem of precise localization.

We have tentatively associated the RCZa of humans with the CMAr of monkeys (Table 1B). Neurons in the CMAr of the monkey display activity changes long before the onset of a self-paced movement (Shima et al., 1991). This pattern of activity is often taken to indicate a region's involvement in the initial ("higher order") stages of movement generation. Likewise, the RCZa is activated only during complex motor tasks. Furthermore, both the RCZa of humans and the CMAr of monkeys are located close to the level of the genu of the corpus callosum (Figs. 1, 5D). Thus, the topography of these two areas and their involvement in complex aspects of motor behavior support the association we have made.

A correspondence between one of the cingulate zones of humans and the CMAv of monkeys is difficult to establish. Given the tentative association of the RCZa with the CMAr, the RCZp could, by exclusion, correspond to the CMAv. The CMAv is interconnected with prefrontal cortex (Bates and Goldman-Rakic, 1993; Lu et al., 1994). Similarly, many tasks that activate regions of prefrontal cortex also result in activation in RCZp. However, there are important discrepancies in the location of the two areas. The CMAv of the monkey is located more ventrally than the CMAd, whereas in humans the RCZp, especially the arm region, is slightly more dorsal than the CCZ. Moreover, the CMAv of monkeys lies in area 23c (Dum and Strick, 1991a). The RCZp of humans lies mostly in area 32. On the other hand, it is unlikely that the monkey CMAv in area 23c corresponds to area 23 in humans. In humans, area 23 does not appear to be activated during motor tasks. Rather, activation in area 23 has been observed in relation to somatosensory processes (e.g., Seitz et al., 1991; Seitz and Roland, 1992a). Similarly, intracortical stimulation in the anterior portion of area 23 in humans evokes somesthetic sensations instead of motor responses (Richer et al., 1993). These uncertainties raise the possibility that there are some significant differences between the functional anatomy of motor areas in humans and monkeys. At this point, we can only emphasize the need for further studies to determine the human analog of the CMAv and the monkey analog of the RCZp. Most importantly, the descriptive terminology that we have adopted to designate zones of activation should be replaced once correspondences with the cingulate motor areas of monkeys have been more firmly established.

Interpretational Considerations

For the purpose of the present review we have adopted a scheme of categorization based on a simple/complex task dichotomy. It is obvious that this scheme oversimplifies many aspects of the experimental paradigms used in the studies we examined. The usefulness of this approach is its practical applicability. Arguably, the dichotomy adopted lacks an absolute

operational definition. There is a large variety of ways to categorize experimental tasks (e.g., externally driven vs internally guided, conditional vs fixed associations, etc.) and movements (e.g., single joint, multiple segments, sequential, etc.). We opted for a fairly broad definition to encompass the diverse aspects of the tasks used in the studies reviewed. It is possible that other classification schemes would provide alternate hypotheses of medial wall organization. Importantly, as more paradigms are employed, it will be possible to develop better criteria for comparing and contrasting different regions. Thus, we believe that the ability to differentiate among the motor areas of the medial wall will improve in the future.

There are multiple technical issues that need to be considered when interpreting PET data. Most of these cannot be presented in the limited space appropriate for this review. However, one needs to be emphasized. We have charted sites of peak activation (or, in some instances, an activation's center of mass). This method of charting will underrepresent the spatial extent of activation and potential overlap between sites. Further, our analysis indicates only that, for the tasks examined, there are *relative* differences in the intensity of activation in specific areas. On the other hand, the clustering of activation sites from multiple studies, which underlies our interpretations, is remarkable, given the fact that different mapping algorithms were used by several groups.

The basis for some of the correspondences we have proposed is stronger than for others. Much of the anatomical information about the cingulate motor areas in monkeys has only recently become available. Thus, there is relatively little physiological information about these cortical fields. Similarly, the view that the medial wall contains multiple motor areas is a relatively new concept for human studies. As a consequence, some of the correspondences we have proposed should be considered as provisional. However, without a clear framework, further investigations into the functional contributions of the medial wall would not be productive in terms of generating testable hypotheses. We expect the map of the medial wall to evolve as additional data becomes available and intend this review to initiate this process.

Notes

1. The articles included in this review were published prior to December 1994.

2. Studies involving the use of the nondominant arm have not been included in our maps of activation foci (e.g., Corbetta et al., 1991, 1993). However, the foci on the medial wall in Corbetta et al. (1993) lie at or rostral to the Vca line. Their task may be considered complex because it required a high level of attention, and the most rapid responses possible of the nondominant hand.

3. This study did not provide Talairach coordinates.

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