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Localization of grasp representations in humans by positron emission tomography

2. Observation compared with imagination

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Abstract Positron emission tomography imaging of cerebral blood flow was used to localize brain areas involved in the representation of hand grasping movements. Seven normal subjects were scanned under three conditions. In the first, they observed precision grasping of common objects performed by the examiner. In the second, they imagined themselves grasping the objects without actually moving the hand. These two tasks were compared with a control task of object viewing. Grasp observation activated the left rostral superior temporal sulcus, left inferior frontal cortex (area 45), left rostral inferior parietal cortex (area 40), the rostral part of left supplementary motor area (SMA-proper), and the right dorsal premotor cortex. Imagined grasping activated the left inferior frontal (area 44) and middle frontal cortex, left caudal inferior parietal cortex (area 40), a more extensive response in left rostral SMA-proper, and left dorsal premotor cortex. The two conditions activated different areas of the right posterior cerebellar cortex. We propose that the areas active during grasping observation may form a circuit for recognition of hand-object interactions, whereas the areas active during imagined grasping may be a putative human homologue of a circuit for hand grasping movements recently defined in nonhuman primates. The location of responses in SMA-proper confirms the rostrocaudal segregation of this area for imagined and real movement. A similar segregation is also present in the cerebellum, with imagined and observed grasping movements activating different parts of the posterior lobe and real movements activating the anterior lobe.

Key words Motor control · Positron emission tomography · Cerebral blood flow · Grasp · Imagined movements · Human

Introduction

Previous electrophysiological studies in nonhuman primates as well as functional neuroimaging studies in humans define a diversified set of cortical areas that are active during goal-directed grasping movements. Multiple frontal motor areas involved in hand control can be identified in nonhuman primates (Dum and Strick 1991; Gentilucci et al. 1988; He et al. 1993, 1995; Hepp-Reymond et al. 1994; Kurata 1993; Kurata and Tanji 1986; Luppino et al. 1991; Matelli et al. 1986; Matsuzaka et al. 1992; Matsumura and Kubota 1979; Muakkassa and Strick 1994; Rizzolatti et al. 1988, 1981). Additional sites in parietal and temporal cortex are likely to be essential for spatial representation, visuomotor transformation, and the pragmatic manipulation of objects (see Jeannerod et al. 1995; Milner and Goodale 1995; and Wise and Desimone 1988 for recent reviews). Functional imaging studies are beginning to identify putative human homologues to some of the areas defined in monkey brain (Grafton et al. 1996, 1992; Haxby et al. 1991; Parsons et al. 1995; Tyszka et al. 1994; Watson et al. 1993). An enduring challenge is to define the functionality that each of these cortical sites contributes to movement. Of particular interest in the present study is the problem of localizing where entire movements or gestures are represented in the motor system.

Within the constraints of functional neuroimaging, the localization of areas where movements or gestures are represented can be investigated with at least three ap-

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proaches. First, an executor system can be identified by comparing real grasping behavior with some type of rest condition (Grafton et al. 1996). This comparison typically reveals a limited set of activated brain areas, including primary sensorimotor cortex, anterior cerebellum, superior parietal cortex, and ventrolateral thalamus, with minimal involvement of lateral premotor, prefrontal, or inferior parietal areas (Grafton et al. 1991, 1992). This lack of activity in associative motor areas could be due to insufficient task complexity, insufficient behavioral contrast between the movement and rest task, or possibly inhibition of areas involved in motor preparation during scans dominated by motor execution.

A second approach is to map areas involved in movement planning by requiring subjects to imagine performing grasping movements without actually executing movements. Subjects can usually describe the mental strategy used to complete the task and it has been assumed that this mental process is similar to that used during preparation of real movements. This mapping strategy has been used extensively with positron emission tomography (PET) and magnetic resonance imaging (fMRI) techniques to localize motor "planning" areas. For example, it is well established that the mental task of imagined movement activates lateral premotor cortex and supplementary motor area (SMA; Orgogozo and Larsen 1979; Rao et al. 1993; Roland et al. 1980; Stephan et al. 1995). More recent imaging studies of subjects performing imagined joystick movements and sequential finger tapping suggest that the caudal part of mesial area 6 (SMA-proper) may be functionally subdivided into rostral (SMAr) and caudal (SMAc) planning areas (Stephan et al. 1995; Tyszka et al. 1994). These areas are differentially activated for mental compared with real movements, revealing a functional gradient that changes with task complexity, such that simple movement execution evokes responses in the SMAc and movement planning estimated by imagined movement evokes responses in the SMAr. In the present study we examine further this aspect of SMA-proper functional subdivision by localizing the SMA response for mental representations of grasping and comparing them with our previous studies of motor execution (Grafton et al. 1996). We also sought to determine whether additional premotor areas, such as ventral premotor cortex, are also activated during imagined grasping of real objects.

Finally, areas involved in the planning of movements can be identified by requiring subjects to observe other persons making grasping movements (Jeannerod 1994; Rizzolatti et al. 1996a). We refer to this as a *mirror effect* because the perception of a specific action (grasping) is used to activate a motor area that may be involved in planning a similar action. In a previous PET study using different subjects (Rizzolatti et al. 1996b), we showed that the observation of grasping movements markedly increases the regional cerebral blood flow (rCBF) in two cortical districts: the cortex of left superior temporal sulcus (STS) and the rostral part of Broca's area (area 45). The presence of neurons in the STS region and in the postarcuate region (area F5) of the monkey that become active when an animal observes hand-objects interactions (Rizzolatti et al.. 1987) led us to propose that in both humans and monkeys the inferior frontal gyrus and the STS region are two nodes of a circuit involved in the internal representation of grasping. In the present experiment we further investigated the human functional anatomy of this mirror effect during grasping observation and compared it with that of imagined movements.

Materials and methods

Subjects

Seven subjects participated in the study after informed consent was obtained in accordance with the Institutional Review Board of the University of Southern California. All were normal by medical interview. Their mean age was 22.6 years (range 19–28 years) and the male to female proportion was 5:2. All were right-handed as determined with a standardized inventory (Oldfield 1971).

Behavioral tasks

Subjects lay supine in the PET scanner with their heads immobilized with a foam head restraint (Smithers, Akron, Ohio). In all three behavioral tasks, subjects observed individual familiar objects held in the examiner's hand. A curtain was arranged so that the subject's visual scene was limited to a view of the examiner's hand and an object. This view was interrupted on average very 4.6 s. During the interruption a new object was positioned by the examiner for the subject to view. Objects were randomly selected by the examiner from a total set of 90. Objects were common and ranged in size from small (paper clip, coin, stamp) to large (cup, pretzel, shell).

In the *object viewing* condition (control), subjects were instructed to observe the object being held by the examiner. In the *grasp observation* condition, subjects were instructed to observe each object being grasped by the examiner. In this condition, the examiner used a precision grasp to enclose the object with the fingers. The subject's observation was timed so that only the final enclosure of the examiner's fingers with each object was viewed. Thus, there was minimal observation of limb transport.

In the *imagined grasping* condition, subjects were instructed to imagine grasping each object using a precision grasp. They were told to imagine that the hand was close to the object at the start of each grasp. As a test of subject's imagining, the examiner held a small fraction of objects (approximately every tenth object) in an orientation that would interfere with natural grasp postures of the subject. In post hoc interviews, the subjects could consistently report the objects that were awkward to grasp. Furthermore, they described in great detail the strategies used to grasp these blocked objects, confirming that thoughts of imagined movements were actually being generated.

Subjects practiced the tasks for 5 min prior to each PET scan. Each task was performed in duplicate in counterbalanced order, for a total of six scans obtained in 60 min. The interstimulus interval averaged 4.6 s (SD 0.38) and the number of presentations did not differ between conditions.

Imaging

Images of rCBF were acquired using a modified autoradiographic method (Herscovitch et al. 1983; Raichle et al. 1983). For each scan, a bolus of 35 mCi of $H_2{}^{15}O$ was injected intravenously commensurate with the start of scanning and the behavioral task. A 90-s scan was acquired and reconstructed using calculated attenuation correction, with boundaries derived from each emission scan sinogram. Arterial blood samples were not obtained. Images of radioactive counts were used to estimate rCBF as described previously (Fox et al. 1984; Mazziotta et al. 1985).

PET images of rCBF were acquired with the Siemens 953/A tomograph. The device collected 31 contiguous planes covering a 105-mm field of view. The nominal axial resolution was 4.3 mm at full-width half-maximum (FWHM) and the transaxial resolution was 5.5 mm FWHM as measured with a line source.

Image analysis

Image processing was performed on a SUN SPARC 20 workstation. This processing was accomplished in three steps, spatial normalization, global blood flow normalization, and statistical analysis. For spatial normalization a within-subject alignment of PET scans was performed using an automated registration algorithm (Woods et al. 1992). A mean image of the registered and resliced images was calculated for each subject. The mean PET image from each individual was coregistered to a population-based PET CBF reference atlas centered in Talairach coordinates (Talairach and Tournoux 1988) using an affine transformation with 12 *df* (Grafton et al. 1994; Woods et al. 1993). The parameters to be fit were three translations, three rotations, and three scalars oriented in a direction specified by the last three parameters. This method provides a direct fit of MRI or PET scans from different subjects to each other. The method uses the intrinsic intensity values of the PET CBF images to perform the fitting instead of a surface contour or a limited set of internal or external landmarks. Once the PET scans were coregistered, all images were smoothed to a final isotropic resolution of 18 mm FWHM (as verified with a line source). Previous investigations demonstrate that this smoothing enhances signal detection (Friston et al. 1991; Grafton et al. 1990; Worsley et al. 1992). After stereotactic coregistration, a mask consisting of all pixels for which data was available from all 42 PET scans was generated. For the given degree of image smoothing, the volume of this mask yielded approximately 90 gray matter resolving elements (Worsley et al. 1992).

All 42 smoothed images were normalized to each other using proportionate scaling calculated from the global activity of each scan. Normalization was performed using the common volume mask defined above, to avoid global normalization errors associated with missing data.

A three-way analysis of variance (ANOVA) with planned comparisons of means across task conditions was used to identify significant task effects (Neter et al. 1990; Woods et al. 1996). The three effects (and sources of variance) in this approach based on the general linear model of multivariate analysis were *task*, *repetition*, and *subject*. To account for the intersubject variance, a randomized blocking design was used with *subjects* as a blocking effect. Two planned comparisons of task means were calculated. The first identified a grasp observation effect (grasp observation minus object viewing) and the second identified an imagined grasping effect (imagined object grasping minus object viewing). An image of the resultant t-test values, i.e., a "t-map" image for each of these contrasts was calculated on a pixel-by-pixel basis (df=1,14) and a threshold was set for t=3.326, P<0.005. Peak sites on the t-map above this threshold were localized and maximal t and P-values and mean rCBF values were tabulated. The resultant t-maps were superimposed on a reference MRI atlas from one normal subject centered in Talairach coordinates, using the fitting algorithm described above. To improve the description of response localization with respect to surface brain anatomy, the images of rCBF significance were rendered in three-dimensional perspective on the surface of the MRI reference atlas, using the display software AVS (Advanced Visualization Systems, Waltham, Mass.).

Results

Grasp observation versus object viewing

The comparison between grasp observation and object viewing identifies brain regions demonstrating increased activity during passive observation of precision grasping executed by the examiner. Confirming our previous findings (Rizzolatti et al. 1996b), activation sites were found in left inferior frontal gyrus (area 45) and in the region of the left STS. In addition, activations were observed in the left parietal lobe, right posterior cerebellum, right dorsal premotor cortex, and mesial area 6 (SMA-proper, rostral part). All brain regions significantly activated are summarized in Table 1. The location of the sites with respect to local gyral anatomy are shown in yellow in Fig. 1.

Imagined grasping versus object viewing

The comparison between imagined grasping and object viewing identifies brain regions with response properties that may be related to the active mental operation of

Table 1 Brain regions activated with grasp observation. Locations of maximal differences of blood flow between control (observing objects) and observing objects grasped with a precision grip by the examiner. Locations and Brodman's areas (BA) are referenced to the Talairach atlas. Mean flow values assume a global flow of 50 ml/min per 100 g tissue. Statistical significance was determined with a planned comparison of means by linear contrasts and three-way ANOVA model (df=1,14)

Region	Talairach coordinates			rCBF		Statistical comparison	
	x	y	z	Control	Grasp observation	t	P-value
L mesial frontal gyrus (BA 6): SMA – rostral	– 1	– 7	55	65.3	66.7	3.41	0.004
R superior frontal gyrus (BA 6): lateral premotor	22	–10	55	60.5	61.9	4.16	0.001
L inferior parietal sulcus (BA 40/2): ventrorostral	–55	–24	40	41.4	43.8	5.13	0.0002
R inferior parietal sulcus (BA 40): intraparietal sulcus	46	–39	37	56.0	57.0	5.61	0.00006
L superior occipital gyrus (BA 19)	–16	–84	30	51.7	53.0	4.04	0.001
L parietal operculum (BA 22/40)	–36	–45	21	38.4	39.8	5.73	0.00005
L inferior frontal gyrus (BA 45)	–48	36	12	40.8	42.6	3.76	0.002
L superior temporal sulcus (BA 21/22): fundus	–58	–21	0	46.1	47.7	4.06	0.001
R posterior cerebellum: medial	13	–67	–30	56.6	58.8	4.07	0.001

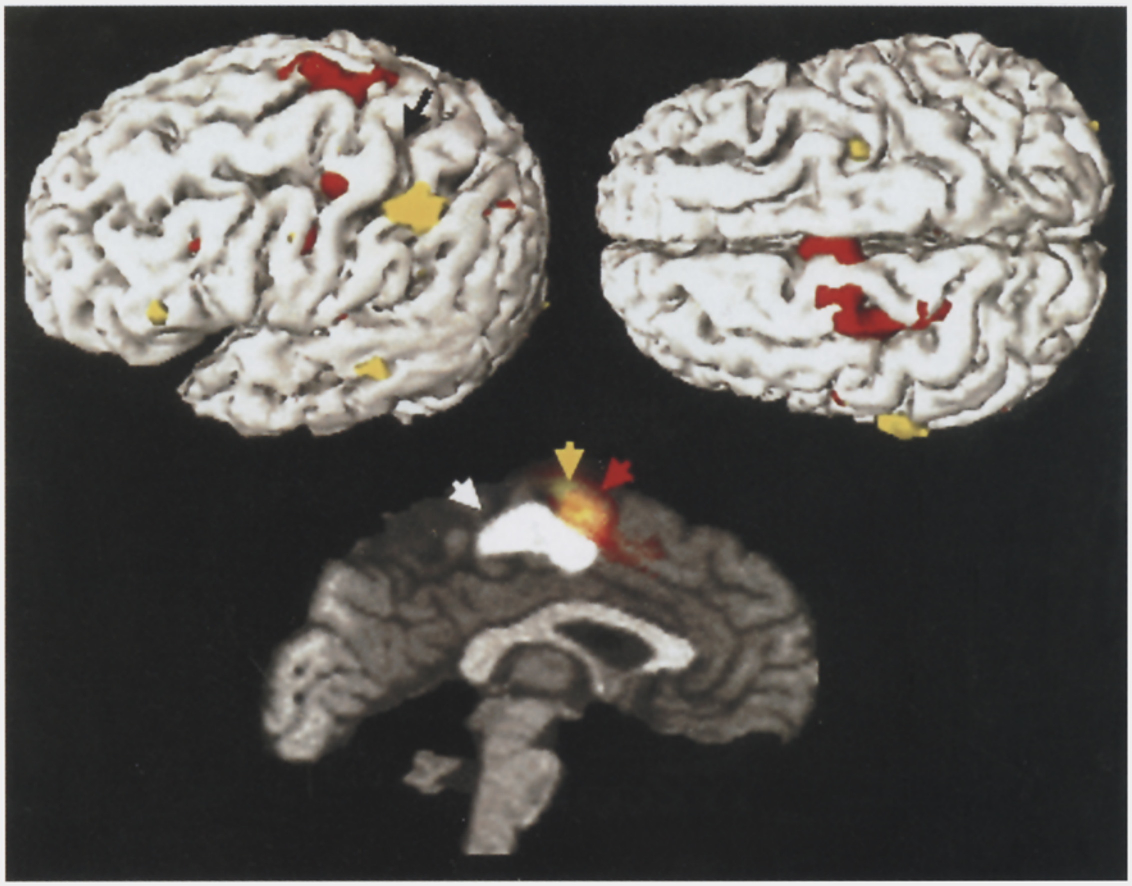

Fig. 1 Localization of significant blood flow changes relative to local cortical anatomy. Significant blood flow changes at a statistical threshold of $P<0.005$ are shown for the grasp observation task (in *yellow*) and the imagined grasping task (in *red*). Both sets are superimposed on a single subject's MRI scan centered in Talairach coordinates (Talairach 1988). The central sulcus is indicated with a *black arrow*. The lateral view of the left hemisphere (*upper left panel*) shows increased activity (*yellow*) during grasp observation located in left inferior frontal cortex, left anterior parietal cortex, and left superior temporal sulcus. Imagined grasping (*red*) activated left premotor cortex at the superior frontal sulcus, left precentral sulcus (maxima located in BA 44), and left parietal cortex. The superior view (*upper right panel*) shows a small focus of increased activity during grasp observation (*yellow*) in the right premotor cortex at the superior frontal sulcus. Imagined grasping (*red*) also activates the supplementary motor area (SMA) extensively. It is noteworthy that both grasp observation and imagined grasping activate primarily the left hemisphere. A parasagittal section 1 mm left of the midline (*lower panel*) shows the localization of peak SMA responses during imagined grasping (*red arrow*), grasp observation (*yellow arrow*), and real grasping (*white arrow*; reported by Grafton et al., 1996). There is a functional gradient between rostral and caudal SMA as a task changes across mental, perceptual, and executor attributes

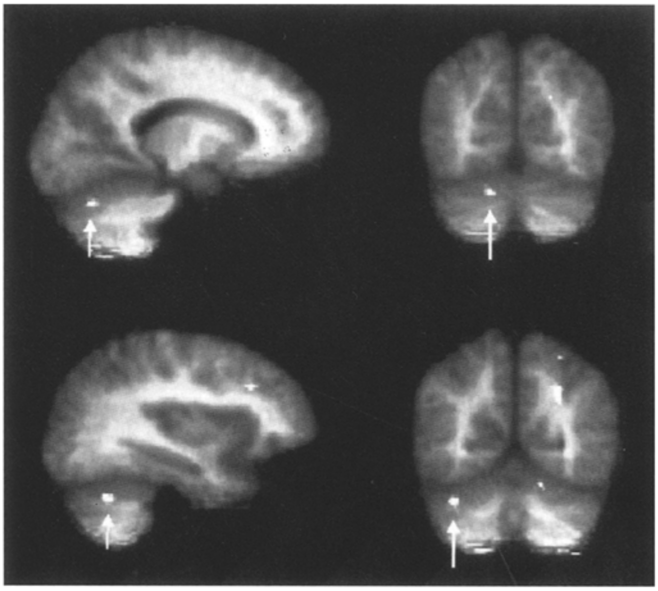

Fig. 2 Localization of posterior cerebellar responses during grasp observation (*upper row*, at coordinates 13, –67, 30) and imagined grasping (*lower row*, at coordinates 33, –58, 31). The two locations differ primarily along the lateral axis

imagined grasping. Table 2 gives a complete list of regions activated in this comparison. Significant changes are identifiable in red in Fig. 1. The most important activated sites were: (a) dorsolateral and mesial area 6 (SMA-proper, rostral part). The SMA activation was very robust, as seen in Fig. 1. The location of maximal change in the rostral SMA was nearly identical for the two task comparisons, as shown in the lower section of Fig. 1. The site for imagined grasping was 6 mm rostral to that for grasp observation. The relative spatial extent of the response was much larger for imagined movement than during grasp observation. (b) Left areas 44 and area 40 (caudal part). Both the inferior frontal and the parietal

Table 2 Brain regions activated with imagined grasping. Locations of maximal differences of blood flow between imagined grasping of objects and control (observing objects). Locations and Brodman's areas (*BA*) are referenced to the Talairach atlas. Mean flow values assume a global flow of 50 ml/min per 100 g tissue. Statistical significance was determined with a planned comparison of means by linear contrasts and a three-way ANOVA model (*df*=1,14)

Region	Talairach coordinates			rCBF		Statistical comparison	
	x	*y*	*z*	Control	Imagined grasp	*t*	*P*-value
L superior frontal gyrus (BA 6): premotor	–6	–7	58	59.9	62.7	6.47	1.5E-05
L precentral gyrus (BA 6/4): premotor/motor	–19	–15	58	56.3	58.2	5.87	0.00004
R precentral gyrus (BA 6/4): premotor/motor	18	–22	54	50.3	51.6	4.18	0.001
L mesial frontal gyrus (BA 6): SMA – rostral	–1	–1	49	67.4	70.5	12.21	7.0E-09
L inferior parietal lobule (BA 40): caudal	–48	–54	37	55.6	57.4	4.36	0.00065
L occipitoparietal sulcus (BA 7/19): fundus	–25	–61	33	47.6	49.3	4.52	0.0005
L occipitoparietal sulcus (BA 19): fundus	–21	–75	31	53.9	55.6	4.76	0.0003
L precentral sulcus (BA 44)	–43	0	30	61.3	64.2	4.78	0.0003
L middle frontal gyrus (BA 9)	–42	25	28	51.4	52.6	5.10	0.0002
R caudate	13	13	12	51.8	54.1	3.90	0.002
L superior temporal gyrus (BA 42)	–48	–12	7	58.6	60.1	4.13	0.001
R posterior cerebellum: lateral	33	–58	–31	61.6	63.6	5.06	0.0002

activation site were located in different parts of the lobule with respect to those observed in the grasp observation condition. (c) Posterior cerebellum. The focus was located more laterally than during grasp observation, as shown in Fig. 2. Note that, during imagined grasping, neither STS region nor area 45 were activated.

Discussion

The findings from this study suggest a differential activation of human cortical areas in two tasks where the representation of grasping movements was evoked with different strategies. In both tasks two main groups of areas were activated. The first group, which we will refer to as the *lateral group*, was formed by the left inferior frontal cortex and left inferior parietal lobule plus, in the case of grasp observation, of the left STS region. The second group, which we will refer to as the *dorsomesial group*, consisted of premotor areas of the mesial and superior frontal gyrus. In the following sections we will compare the activation of lateral and dorsomesial areas in the two experimental conditions. Other activations (cerebellum, prefrontal cortex) will be discussed in less detail.

Lateral cortical areas activated during grasp observation and imagined grasping

Three lateral sites were activated during *observation of grasping movements*. Their locations were the left STS, the left inferior frontal area 45, and the left parietal area 40. The locations of the first two activation sites closely correspond to those found in a previous PET study in which grasping observation was investigated (Rizzolatti et al. 1996b). A minor difference is that in the present experiment the maximum of the activation was located in the dorsal bank of the STS rather than in its ventral bank, as reported in that study. In addition, in the present experiment an activation was found in the rostral part of the left intraparietal sulcus, at the border between areas 40 and 2.

The location of the activated sites during grasping observation in humans corresponds rather well to that of monkey cortical areas containing neurons that selectively discharge during hand action observation. Neurons with such a property have been reported by Perrett et al. (Perrett et al. 1989, 1990) in the STS region and, more recently, by Rizzolatti and his coworkers in area F5 of the inferior premotor cortex (di Pellegrino et al. 1992; Gallese et al. 1994). Although firm evidence of the existence of neurons responding to hand-object interaction in inferior parietal lobule is lacking, some data of Leinonen and coworkers suggest that neurons with such properties could be present also in area 7b (Leinonen and Nyman 1979). Furthermore, anatomical evidence in monkeys shows that the temporal region studied by Perrett et al. (1989) sends projections to area 7b (Seltzer and Pandya 1978; Webster et al. 1994), which, in turn, is heavily connected with F5 (Godschalk et al. 1984; Matelli et al. 1986; Petrides and Pandya 1984). It appears, therefore, that in monkeys and humans a similar cortical circuit is involved in the representation of observed grasping.

A major difference between monkey and human grasping observation network is that in monkey the cortical activation is bilateral, while in humans it is lateralized to the left hemisphere. We previously proposed that the "mirror" neurons represent an ancient recognition system whose basic mechanism consists in matching observed and executed actions (Rizzolatti et al. 1996a). In human evolution the increase of manipulatory abilities has led to a division of labor between the left and right hand. For right-handed subjects the left hand plays mostly a static, supporting role, while the right hand is responsible for the dynamic aspect of the actions (Kimura 1993). Since the recognition of an action is based mostly on its dynamic aspects, it is likely that when the activity of the left hemisphere became dominant for action execution, it became dominant also for action recognition.

The activation sites during *imagined grasping* included parietal and frontal areas. Their location was different from that found in grasping observation. The active parietal site was in the caudal part of area 40 rather than in its rostral sector, and the frontal activation was in area 44 rather than in area 45. The STS activation was absent.

An important issue concerning imagined grasping is whether the cortical areas activated in this condition coincide with those activated during grasping execution. Unfortunately, the available data on areas active during grasping execution are rather disappointing. In experiments devoted to this purpose, no areas specifically related to this action were convincingly identified (Grafton et al. 1996; Rizzolatti et al. 1996b). The activated sites found in those experiments coincided with those activated during other types of hand-arm movements in which no grasping was required (Colebatch et al. 1991; Deiber et al. 1991; Grafton et al. 1991, 1992; Jenkins et al. 1994; Matelli et al. 1993).

Although these negative results might indicate that in humans there are no areas specifically devoted to grasping, this seems to be rather implausible. Firstly, parieto-frontal circuit for grasping exists in monkey. This circuit is formed by parietal area AIP, located in the lateral bank of the intraparietal sulcus, and area F5, located in the rostral most part of inferior area 6 (see Jeannerod et al. 1995). Secondly, computational considerations on the organization of hand-arm movements strongly suggest that grasping movements are organized separately from reaching and other proximal movements (Arbib 1981; Jeannerod 1988; Jeannerod et al. 1995). It is more likely, therefore, that the negative results of the extant functional imaging experiments are due to the fact that the task demands in those experiments were too weak to strongly activate the human grasping circuit rather than to its absence.

Unlike actual grasping, which, typically (if no constraints are added), is an easy, almost automatic action driven by the stimulus, grasping imagining is a cognitive task that requires a conscious, detailed representation of the movement. A "planning representation" may be held longer in an imagined movement than in an actual movement where this representation is promptly "read out" as control of movement proceeds elsewhere. One can posit that mental grasping, in addition to the activation of other areas necessary to retrieve the action, would produce also an intense activation of areas involved in grasping organization and could reveal, therefore, the cortical circuit devoted to it.

In our view, the human grasping circuit (corresponding to that formed by area AIP and F5 in the monkey) would be constituted of the dorsocaudal part of areas 40 and a sector of area 44. Within the limits of interspecies comparisons, the general location of these sites appears to fit rather well that of the areas forming the monkey grasping circuit. The human parietal node of the proposed grasping circuit in area 40 is located at the border between the two major cytoarchitectonic areas of the inferior parietal lobule (PF and PG). In monkey, AIP is also at the border of these two areas. AIP, however, has a more dorsal location than the possible equivalent human site and is mostly buried inside the lateral bank of the intraparietal sulcus (Gallese et al. 1994). More straightforward is the homology between human area 44 and monkey F5 (Passingham 1993; Petrides and Pandya 1994). Human area 44 is agranular, belongs to the set of areas that collectively form area 6, and constitutes the rostralmost part of inferior are 6 (Bailey and von Bonin 1951; Campbell 1905; von Economo 1929; for a recent review of cytoarchitectonic details, see Petrides and Pandya 1994). Functionally the homology between 44 and F5 was drawn considering essentially that both areas are involved in laryngobuccal movements. Recent PET data showed, however, that, as F5, human area 44 is not devoted exclusively to control of laryngobuccal movements. Activation in this area is present also during hand movements, either actually executed (Bonda et al. 1994) or mentally thought about (Parsons et al. 1995).

In conclusion, during imagined grasping movements, a circuit is activated that is anatomically and functionally similar to that which, in the monkey, mediates visuomotor transformation for selecting hand grip according to the object's intrinsic properties (see Jeannerod et al. 1995), whereas during grasping observation the activation concerns areas homologous to those which in non-human primates are active during grasping observation. Monkey's F5 is involved in both these functions. A sector of it selects grasping movements according to the physical properties of the object, another sector codes them on the basis of the observed action. It is likely that in humans this dual function of F5 is represented in two anatomically distinct areas: area 44 for object-related grasping, area 45 for action recognition. Arguments for a possible development of areas 44 and 45 from the same precursors from which developed the various sectors of F5 were presented in a previous paper and will be not discussed here (Rizzolatti et al. 1996a).

Medial and dorsal cortical areas activated during grasp observation and imagined grasping

Anatomical and physiological data indicate that in the monkey, mesial area 6 (SMA) constitutes two separate areas, F3 (SMA-proper) and F6 (pre-SMA; Luppino et al. 1991; Matelli et al. 1991; Matsuzaka et al. 1992). Recent anatomical data in humans confirmed this subdivision and showed that the border between these two areas corresponds approximately to a coronal plane passing across the anterior commissure and orthogonal to the AC-PC horizontal plane (Zilles et al. 1996). PET studies functionally confirmed this subdivision. Simple movements such as single-joint contractions activate SMA-proper (Colebatch et al. 1991; Grafton et al. 1991; Matelli et al. 1993), whereas more complex types of movements are required to activate pre-SMA (see Deiber et al. 1991; Matelli et al. 1993; Picard and Strick 1996; Sergent et al. 1992; Zatorre et al. 1992).

In addition to the subdivision of mesial area 6 into SMA-proper and pre-SMA, it was recently demonstrated that different sectors of SMA-proper became active during movement execution and movement imaging. Tyszka et al. showed that during motor imaging of finger tapping there was an activation restricted to the rostral part of the SMA-proper, whereas the activation extended to the caudal part of SMA-proper when the subjects actively executed the same movements (Tyszka et al. 1994). A similar activation pattern was observed by Stephan et al. in a task involving imagined and real movements of a joy-stick (Stephan et al. 1995).

The present findings confirm these data. During grasping imaging, the SMA-proper activation was more rostral than that observed in experiments in which subjects had to execute real grasping movements (Grafton et al. 1996). Furthermore, the present data indicate that not only intransitive imagined movements (e.g., finger tapping), but also transitive (object-directed) imagined movements activate SMA-proper. While this finding is in good agreement with the general notion that mesial area 6 plays an important role in imagined movements (Orgogozo and Larsen 1979; Rao et al. 1993; Roland et al. 1980; Stephan et al. 1995), it is in contrast with some data reported by Decety et al., who did not observe an activation of mesial area 6 in imagined grasping of virtual objects (Decety et al. 1994). The most likely interpretation of this discrepancy is that the virtual objects used by Decety et al. in their experiments were insufficient to evoke a motor image such as to activate the medial cortical areas. This image was instead evoked with the real objects.

An increase, although smaller, of activity in SMA-proper (rostral part) was also detected during grasping observation. One interpretation of this finding is that the SMA-proper contains a subpopulation of neurons that respond selectively to the observation of hand-object interactions. The absence, however, of evidence in this sense as well the anatomical and physiological characteristics of SMA-proper renders this possibility rather unlikely (Weisendanger 1986; Tanji 1994). Another interpretation is that the SMA is involved in the higher level analysis of hand orientation, irrespective of grasping. For example, Parsons and colleagues recently showed that SMA-proper is active when subjects are required to distinguish pictures of right and left hands displayed in unusual orientations (Parsons et al. 1995). The most parsimonious explanation, however, is that the observed SMA-proper activation in our study was not specifically related to hand-object interaction, but rather to an unspecified motor set determined by the observation of grasping movements. Worth noting is that, although the activation site during grasping observation almost coincided with that during imagined grasping, the extent and intensity of activation was much stronger during imagined grasping. It is likely that this occurred because a greater effort was necessary to create and maintain the motor set for internally generating grasping movement than for maintaining it on the basis of an observed external movement.

Other activations

Among other activated sites found during representation of grasping movements, there are two that are of particular interest. The first is that of the middle frontal gyrus. It is likely that this activation, which was present only during imagined grasping, reflects the active character of this task. In line with current ideas on prefrontal lobe functions (Fuster 1995; Goldman-Rakic 1987), we posit that this activation was necessary for internally generating activity in the parietal-premotor circuit responsible for grasping movements. In contrast, this intervention was not required in the case of grasping observation. In this case the mental representation was evoked by the occurrence of an action that directly activated the STS-parietofrontal circuit involved in hand-object interaction.

A second activation of great interest was that found in the cerebellum. Previous data showed that the cerebellum becomes active during various mental tasks not requiring overt movements. Examples are word generation, silent counting, and tennis training movements (Decety et al. 1990; Peterson et al. 1988; Thach 1996). The present data show that cerebellum became active also during observation of grasping movements and during the internal generation of the same movements. The activation sites varied, however, in the two conditions and, in turn, their locations differed from those found during real, active grasping (Rizzolatti et al. 1996b). The activations during imagined grasping and grasp observation were both located in the posterior lobe. During imagined grasping the activation was located laterally, while during grasp observation it was located in a paravermian position. In contrast, the activation during real, executed grasping was in the anterior lobe. An approximately similar rostral location was found also by Stephan et al. during execution of a joy-stick movement (Stephan et al. 1995).

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