

Research report

# Functional organization of the lateral premotor cortex: fMRI reveals different regions activated by anticipation of object properties, location and speed

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## Abstract

Previous studies have provided evidence that the lateral premotor cortex (PMC) is involved in representations triggered by attended sensory events. However, while the functional specificity of subregions of this large cortical structure has been intensively investigated in the monkey, little is known about functional differences within human lateral premotor areas. In the present study, functional magnetic resonance imaging was used to investigate if attending to object-specific (O), spatial (S), or temporal (T) properties of the same sensory event, i.e. moving objects, involves different premotor areas. We found a frontoparietal ‘prehension network’ comprising the pre-supplementary motor area (preSMA), the ventral PMC, and the left anterior intraparietal sulcus (aIPS) to be activated independently of the attended stimulus property, but most intensively during object-related attention. Moreover, several areas were exclusively activated according to the attended stimulus property. Particularly, different PMC regions responded to the Object (O) task (left superior ventrolateral PMC), the Spatial (S) task (dorsolateral PMC), and the Timing (T) task (frontal opercular cortex (FOP)). These results indicate that the representation of different stimulus dimensions engage distinct premotor areas and, therefore, that there is a functional specificity of lateral premotor subregions. © 2001 Elsevier Science B.V. All rights reserved.

*Theme:* Motor systems and sensorimotor integration

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## 1. Introduction

The premotor cortex (PMC) is involved in a broad variety of behavioral functions, including the preparation, imagination and control of movement, the processing of sequential information, the representation of tool use, and, more generally, action schemas. In contrast to the medial PMC, which is associated with self-generated movement [36], the lateral PMC appears to be especially engaged in sensory triggered and sensory guided action [23,45,46,78,85,116,125,127]. The responsiveness of our actions to external stimulation is a fundamental function in everyday life, where we have to adapt our body’s posture and motion to objects and spatial settings. This is par-

ticularly important when objects are in motion, because then we are facing a time window we have to cope with in order to react fast and appropriately to situations, i.e. opportunities and dangers.

Confronted with moving objects, three types of information have to be processed. (1) *Object information:* The moving object must be recognized as a continuous unit, although its visual dimensions such as colour and shape varies with the spatial relation between object and observer. (2) *Spatial information:* The movement direction of the element and its relative distance must be referenced to the body, head and eye of the observer in order to be predictable in its subsequent spatial course. (3) *Timing information:* The speed of the object movement must be determined precisely in order to adapt the timing of the observer’s own movement to the target movement.

With regard to *object information*, the visual presentation of objects was found to be associated with responses

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of the ventrolateral PMC (vPMC) in monkey [76,94]. The same area was activated in man when object features had to be retained in working memory [75]. Some of the responses of this area, which is involved in hand/arm representation [23], are sensory, i.e. definitely not related to motor preparation [29]. This finding has led to the interpretation that the visual dimensions of attended objects are, regardless of any intention to grasp, translated into a potential grasping action in the observer [76].

With regard to the *spatial information*, cerebral activations during pointing at fixed locations in space indicated a dorsolateral premotor region (dPMC), posteriorly adjacent to the frontal eye field (FEF), to be engaged in arm movements guided by a spatial reference [41,54,56,73]. However, in the absence of any reaching requirement, the same area was found to be also involved during the directional expectation of a moving target pattern [108]. These findings suggest that this dPMC region might be generally engaged in spatially referenced target representations, as required during reaching.

Finally, the processing of *timing information* involves the frontal opercular cortex (FOP/BA44), anteriorly adjacent to the most inferior vPMC. Imaging studies indicate a FOP activation when we have to synchronize our movement to a sensory event [92] or time the perceptual anticipation of a sensory event [89,106]. Located on the transition from premotor to prefrontal areas, this area exposes prefrontal properties, since it receives sparse input from the mediodorsal thalamus to its dysgranular layer IV [37], but it also resembles the PMC [88].

Taken together, these findings suggest that different areas of the lateral PMC are involved in the processing of object, spatial and timing properties of sensory events, either in sensory triggered motor preparation or in perceptual anticipation. However, since these different functions have not yet been investigated within the same experimental context, and paradigms used to investigate these functions differ markedly, there is to date no clear anatomical dissociation of these representations within the lateral PMC.

The present study is the first to investigate premotor involvement in the representation of object, spatial, and timing information within the same experimental paradigm. fMRI was used to analyse brain activations when subjects performed in an object movement monitoring task. Since we wanted to investigate sensory triggered activation without a preparation of movement towards the sensory event, we employed an experimental paradigm that allows to investigate the anticipation of certain features of moving objects without inducing object-related motor preparation. Moreover, a specific presentation mode was used in order to allow physically identical stimulation in fundamentally different tasks.

Subjects had to attend to the object properties, the spatial properties, or the timing properties of visual stimulus sequences. These stimulus sequences consisted of

objects that differed slightly in the color distribution on their surface (=manipulation of *object information*). They were presented pairwise on a virtual circle and varied their position on that circle only gradually from screen to screen, resulting in a rotation motion (=manipulation of *spatial information*). Each picture was presented for a certain duration, resulting in a non-isochronous motion speed pattern (=manipulation of *temporal information*). Within a trial, the stimulus sequences were repeated several times, so that subjects were able to set up an expectation about the stimulus train and to monitor this train for deviants in the attended task-relevant stimulus dimension. Depending on the attended stimulus property, i.e. object features, spatial locations, or temporal durations, we expected differential premotor areas to be activated.

## 2. Materials and methods

### 2.1. Participants

Twelve healthy right-handed subjects (four male and eight female, aged 19–27 years, mean age 23.6) participated in the study. Informed consent was obtained from each subject before testing. All experiments complied with German legal requirements. Immediately prior to the functional imaging session, subjects spent 20 min in the scanner, so that they could acclimate to the confinement and sounds of the MR environment. The subject's hands were carefully stabilized with the right index finger positioned on the response button in order to prevent postural adjustments.

### 2.2. Stimuli

Twelve objects were used in the experiment, each composed of a 25-mm circle ( $0.14^\circ$  of visual angle) and a slightly smaller geometrical form placed in its centre (see Fig. 1). In six objects, this was a 14-mm square, and a 10-mm circle in the six other objects. The big circle and the small form were coloured red, yellow, or blue, respectively, so that objects were always two-coloured. On each screen, two identical objects were presented at opposite locations on a virtual circle, at  $3.1^\circ$  of visual angle to the screen centre, resulting in  $6.2^\circ$  of visual angle for the entire circle. On the virtual circle, there were 32 possible locations at constant gaps of  $11.25^\circ$ , starting at  $5^\circ$  clockwise. The screen centre was marked with a small fixation cross to facilitate constant visual fixation. Each picture was presented for 300, 600, 900, 1200, 1500, or 1800 ms (800 ms mean duration per picture).

### 2.3. Tasks

Forty-two trials were presented per task, and tasks were presented in randomized order. Each trial lasted 9.6 s and

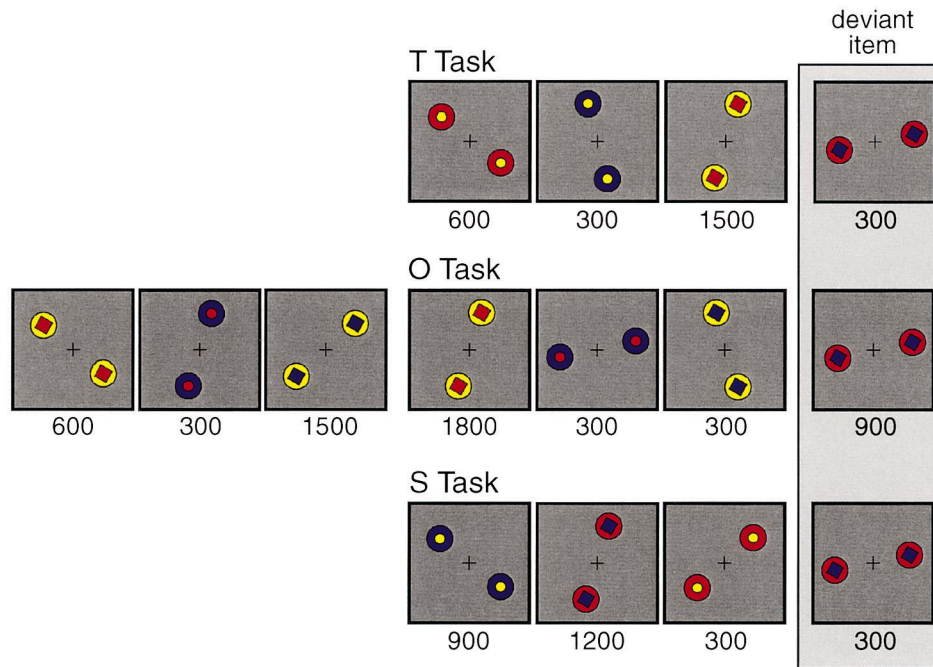


Fig. 1. Examples for the beginning of a trial of the Timing (T), Object (O), and Spatial (S) Task, starting from the left side (for the control condition (C), see text). The first three pictures are the set that has to be memorized with regard to the relevant stimulus dimension. The first presentation of the second repetition shows a deviant item in the task relevant dimension, i.e. a different duration in the T task (300 instead of 600 ms), a different object in the O task (red circle with blue square instead of yellow circle with a red square), and a different spatial location in the S task ( $+80^\circ$  instead of  $-40^\circ$ ).

was preceded by a short visual cue that announced the task to be performed next. The intertrial interval was 6.4 s. As shown in Fig. 1, 12 pictures were presented subsequently in such a way that objects were perceived as rotating clockwise or counterclockwise, each in 50% of the trials, around the screen centre. Three successive presentation durations always added up to 2400 ms, building one out of 18 different rhythm types, like 300–600–1500, 300–1500–600, 600–600–1200, 1800–300–600, etc.

Within each trial, one out of three stimulus dimensions (object, location, or duration) was task-relevant, the other two were task-irrelevant. The two irrelevant dimensions always varied randomly from picture to picture. In contrast, the task-relevant stimulus dimension always varied orderly: each third picture of the trial was identical with respect to the task-relevant property. Subjects had to attend only to the task-relevant stimulus dimension in the following way: encode the task-relevant features of the first three stimuli, i.e. the starting sequence, and look if they recurred in the proper order within the same trial.

In order to control that subjects did attend to the task-relevant information, performance was tested in a go/no-go response mode. In 38% of the trials, one of the pictures was transferred from its proper place to the end of the trial, so that the sequential order was violated *in the task-relevant dimension*. In these trials (go-trials), all stimuli following the missing picture immediately moved up, so that no gap was perceived. Subjects had to indicate these missing pictures immediately by button press (right index

finger). Within a go-trial, the omission occurred between the 4th picture (at the earliest) and 11th picture (at the latest), and on average 6 s after trial onset.

In the Object (O) task, subjects had to attend to the three *objects* presented in the starting sequence, and indicate the omission of one of the objects in the subsequent repetitions.

In the Spatial (S) task, subjects had to attend to the *spatial locations* of the objects in the starting sequence, and indicate omission of spatial locations in the subsequent repetitions.

In the Timing (T) task, subjects had to attend to the temporal durations of the starting sequence, i.e. the motion rhythm, and indicate omission of temporal durations (=rhythm violations) in the subsequent repetitions.

In the Control (C) task, subjects had to attend only to the fixation sign. Subjects were instructed that the sign was small in pictures 1–3 and 7–9, and slightly bigger in pictures 4–6 and 10–12. The task was to indicate if the sign changed in size out of turn, i.e. earlier or later than in pictures 4, 7, or 10.

#### 2.4. Scanning procedure

Imaging was performed at 3 T on a Bruker Medspec 30/100 system equipped with the standard bird-cage head coil. Subjects were supine on the scanner bed, and cushions were used to reduce head motion. Slices were positioned parallel to the bicommissural plane (AC–PC),

with 16 slices (thickness 5 mm, spacing 2 mm) covering the whole brain. A set of two-dimensional anatomical images was acquired for each subject immediately prior to the functional experiment, using a MDEFT sequence (256×256 pixel matrix). Functional images in plane with the anatomical images were acquired using a single-shot gradient EPI sequence (TE=30 ms, 64×64 pixel matrix, flip angle 90°, field of view 192 mm) sensitive to BOLD contrast. During each trial, eight images were obtained from 16 axial slices each at the rate of 2 s per image (=16 slices).

In a separate session, high-resolution whole brain images were acquired from each subject to improve the localization of activation foci using a T1-weighted three-dimensional segmented MDEFT sequence covering the whole brain.

### 2.5. Data analysis

The fMRI data were processed using the software package LIPSIA [64]. In the preprocessing, low-frequency signals (frequencies due to global signal changes like respiration) were suppressed by applying a 1/130 Hz high-pass filter. This filter length was calculated in the following way: twice the length of one complete oscillation, i.e. minimal gap between two trials of the same experimental condition =  $2 \times 64 \text{ s} \approx 130 \text{ s}$ . Because low frequencies were removed, temporal filtering also effected a signal baseline correction. The increased autocorrelation caused by the filtering was taken into account during statistical evaluation by the adjustment of the degrees of freedom. A spatial smoothing was performed using a Gaussian filter kernel with a  $\sigma$  of 0.8. To correct for the temporal offset between the slices acquired in one image, a sinc-interpolation algorithm based on the Nyquist–Shannon Theorem was employed. To correct for movements, the images of the fMRI time series were geometrically aligned using a matching metric based on linear correlation.

The anatomical registration was done in three steps: First, the anatomical slices geometrically aligned with the functional slices were used to compute a transformation matrix, containing rotational and translational parameters, that register the anatomical slices with the three-dimensional reference T1 data set. In a second step, each individual transformation matrix was scaled to the standard Talairach brain size ( $x=135$ ,  $y=175$ ,  $z=120$  mm) [113] by applying a linear scaling. Finally, these normalized transformation matrices were applied to the individual functional raw data. Slice-gaps were scaled using a trilinear interpolation, generating output data with a spatial resolution of  $3 \text{ mm}^3$ .

The statistical analysis was based on a least-squares estimation using the general linear model (GLM) for serially autocorrelated observations (random effects model) [1,30,126,129,130]. For each individual subject, statistical

parametric maps were generated, and were averaged over all subjects afterwards [7]. The design matrix was generated with a boxcar function model and a response delay of 6 s. For each condition, the brain activations during the whole sequence presentation of each trial, starting from the cue, were analysed (10 s). The design matrix and the data were linearly smoothed by convolving it with a matrix representing the hemodynamic response function, a Gaussian kernel of dispersion of 4 s full width at half maximum. The model adjusts the degrees of freedom to include the effects of temporal autocorrelation. The contrasts between the different conditions were calculated using the  $t$  statistic. Subsequently,  $t$  values were converted to  $Z$  scores. As the individual functional datasets were all aligned to the same stereotactic reference space a group analysis of fMRI-data was performed by averaging individual  $z$ -maps and multiplying each mean value with  $\text{sqr}(N)$  ( $N$ =number of subjects) [7].  $Z$ -maps were thresholded at  $Z \geq 8$ .

## 3. Results

### 3.1. Behavioral performance

Behavioral performance (see Fig. 2, left) was assessed by a modified version of the Discrimination index  $P_r$  [110], which is the difference between hit rate and false alarm rate. Since the  $P_r$  is an index for binary decisions, it was modified to assess performance in the present Go/No-go-paradigm in the following way. The hit rate was defined as correctly indicated Go-trials relative to all Go-trials, and the false alarm rate as falsely indicated No-go-trials relative to all No-go-trials. A repeated-measures analysis

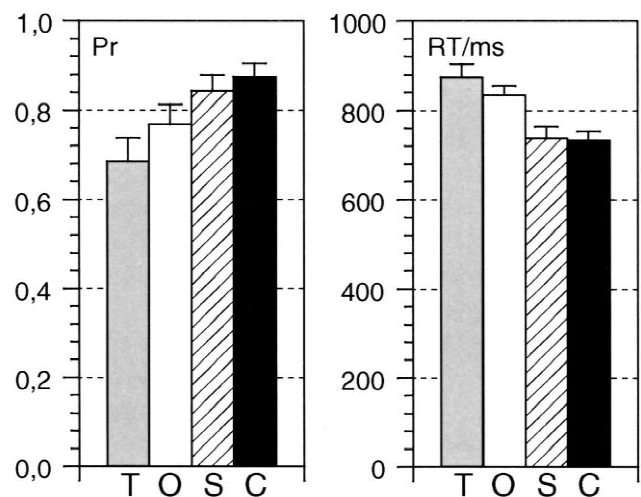


Fig. 2. Behavioral performance of the Timing task (T), Object task (O), Spatial task (S) and the Control task (C), indicated by a modified discrimination index  $P_r$  (chance level=0.25) [97] (left), and reaction times of the correctly answered Go-trials (right).

of variance with the four level factors TASK (O, S, T, C) indicated a main effect ( $F(3,33)=13.2$ ,  $P<0.003$ ). Single  $t$ -tests revealed that both the T task ( $F(1,11)=18.3$ ,  $P<0.001$ ) and the O task ( $F(1,11)=11.3$ ,  $P<0.006$ ) were significantly more difficult than the control condition (C), and that the T task was significantly more difficult than the S task ( $F(1,11)=10.4$ ,  $P<0.007$ ). The reaction times of the correctly answered Go-trials confirmed these results (see Fig. 2, right).

### 3.2. MRI data

Brain areas with significantly higher BOLD response in the movement monitoring tasks (O, S, T) than in the Control task (C) are listed in Table 1 and shown in Fig. 3. Relative to C, all tasks elicited activations in the pre-supplementary motor Area (preSMA), the lateral PMC, the frontal eye fields (FEF), the left anterior intraparietal sulcus (aIPS), and the right fusiform gyrus (FG). Additionally, other frontal as well as parietal areas were activated by single tasks versus baseline, including the SMA, the left superior vPMC (PMC<sub>2</sub>), the frontal opercular cortex (FOP), the inferior frontal sulcus (IFS), the posterior intraparietal sulcus (pIPS), the left FG, the motion area (MT), the calcarine sulcus (CaS), and the basal ganglia (BG).

In order to differentiate these activation patterns, direct task comparisons between O, S, and T task were computed (Fig. 4 and Table 2). To this end, the activations of one task were contrasted against the activations of the two other tasks. With respect to the premotor areas, significantly higher activations during the O task were present in

the preSMA and the left vPMC inferior and superior (PMC, PMC<sub>2</sub>). In contrast, the S task led to higher activations bilaterally in a dPMC area posteriorly adjacent to the FEF (dPMC). Finally, the T task showed higher activation in the SMA and bilaterally in the frontal opercular cortex (FOP). Other brain areas were also activated specifically according to the task. The left aIPS was more activated during the O task, whereas the right aIPS was more activated during the S task. Both the O task and the S task lead to activations in the pIPS, but their foci were different. The activations elicited by the O task were located at the lateral banks of the pIPS (pIPSlat), whereas the S task activations were located medially (pIPSmed), spreading into the precuneus. Areas exclusively activated in the direct task contrasts were the IFS, the FG, and the CaS (all bilaterally) for the O task, the right MT and the right superior occipital gyrus (sOG) for the S task, and finally the right caudate nucleus (BG) for the T task.

To summarize, our results revealed both a general network underlying the processing of moving objects as well as brain areas with specific contributions to the processing of object, spatial, and timing information. In contrast to the neutral baseline (C), the preSMA, the PMC, the FEF, the left aIPS, and the right FG were activated during attentively observing moving targets, regardless whether object, spatial, or timing information had to be processed. With the exception of the right lateral PMC, which was equally activated in each task, all these areas were most activated during the O task, as revealed by direct task comparison. Additionally, a set of areas were exclusively activated by the O, S, or the T task alone.

Table 1

Attending to object, spatial, or temporal features versus control: mean location [100] and Z-score of peak activations from group average data ( $n=12$ )

Anatomical area	Object–Control				Space–Control				Timing–Control				
		x	y	z	Z-score	x	y	z	Z-score	x	y	z	Z-score
PRESMA		–8	12	47	21.9	1	12	47	10.1	–5	18	43	13.8
SMA										–5	1	53	17.5
FEF	L	–26	–2	48	19.7	–26	–1	51	22.9	34	0	42	11.9
	R	22	0	44	12.8	22	–1	53	14.4	–26	–2	48	11.5
vPMC <sub>2</sub>	L	–41	0	42	19.5								
vPMC	L	–47	–9	31	23.3	–47	4	23	12.2	–44	3	21	16.7
	R	34	6	32	12.8	43	4	23	11.1	43	8	14	15.1
FOP	L									–47	6	8	13.4
	R									43	16	–1	12.6
IFS	L	–38	27	18	21.3					–41	33	17	14.7
	R	40	25	22	14.5								
aIPS	L	–41	–40	42	18.6	–44	–29	36	13.4	–41	–48	49	11.6
	R					49	–24	32	11.7				
pIPS	L	–26	–64	44	28.8	–14	–62	52	22.2				
	R	22	–61	43	21.3	13	–66	50	21.6				
FG	L	–32	–81	–1	20.6								
	R	28	–75	–2	23.3	19	–87	0	17.6	19	–91	9	11.7
MT	R					43	–53	–1	12.8				
CaS	L	–11	–76	9	19.2	–11	–79	7	11.8				
	R	7	–71	14	20.7								
BG	R									16	7	11	8.8

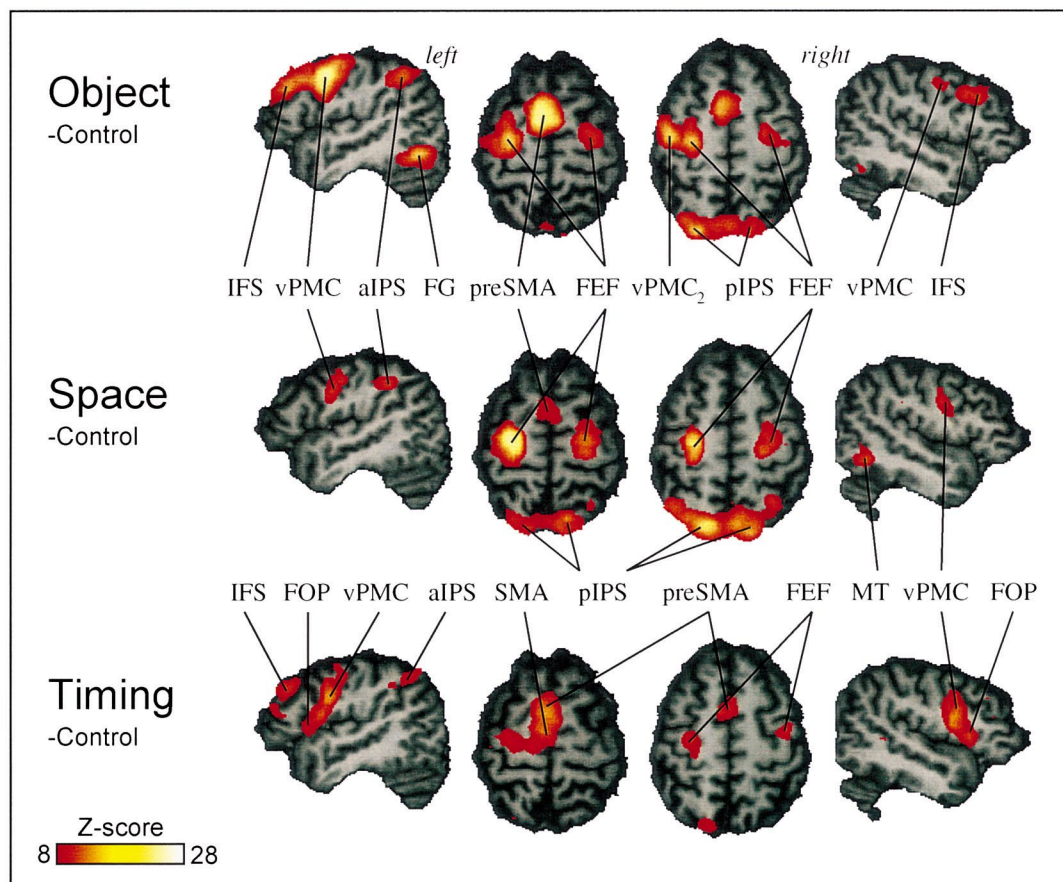


Fig. 3. Group ( $n=12$ ) averaged activation pattern in the O, S, and T task relative to C (baseline contrasts), displayed on an individual brain. Z-maps are thresholded at  $Z \geq 8$ . The left hemisphere is shown on the left side, right on the right; two different top views are shown in the middle. Anatomical areas abbreviated as follows: basal ganglia (BG), frontal eye field (FEF), frontal opercular cortex (FOP), fusiform gyrus (FG), anterior/posterior Intraparietal sulcus (aIPS, pIPS), inferior frontal sulcus (IFS), ventral premotor cortex (vPMC), superior vPMC (vPMC<sub>2</sub>), motion area (MT), (pre-) supplementary motor area (preSMA, SMA).

#### 4. Discussion

The discussion of the present findings focuses on frontal activations and is organized as follows. First, it will deal with the data obtained from the baseline contrasts that gives information about which areas are involved in object movement monitoring independently from the attended stimulus domain (Section 4.1). Second, data from direct task comparisons will be discussed, revealing areas specifically involved in the processing of the attended stimulus domain (Sections 4.2–4.5). Finally, possible implications of the present and related findings for the functional differentiation of the lateral PMC will be investigated (Section 4.6).

##### 4.1. A 'prehension network' activated independently of attended stimulus dimension

Three areas prominent in prehension — the preSMA, the vPMC and the aIPS — were activated when moving objects were observed, independently of the attended stimulus dimension. These activations were marked in the

left hemisphere, as one would expect in right-handed subjects during a grasp representation. The co-activation of these areas reflect the strong reciprocal connections that exist between the preSMA and the vPMC [65,67] and between the aIPS and the vPMC [71,72]. The way these projections cooperate in prehension has been investigated intensively in monkeys, but recent imaging studies now appear to confirm these findings in man.

The fact that the preSMA is found to be involved in both object grasping [8,115] and reaching-like slow spatial displacements of the arm [66] indicates a global control function over reaching–grasping actions in this region [97,98]. The anatomically restrictive projection pattern between preSMA and vPMC gave rise to the assumption that the goal selection of a movement, functionally realized in the preSMA, is strongly bound to the target selection, i.e. the selection of the appropriate grip, functionally realized in the vPMC [23]. On a more general level of functional description, studies of the human brain confirm a central role of the human preSMA in motor selection and control [22,23,44,90,111,120].

The vPMC, in contrast, was found to be involved

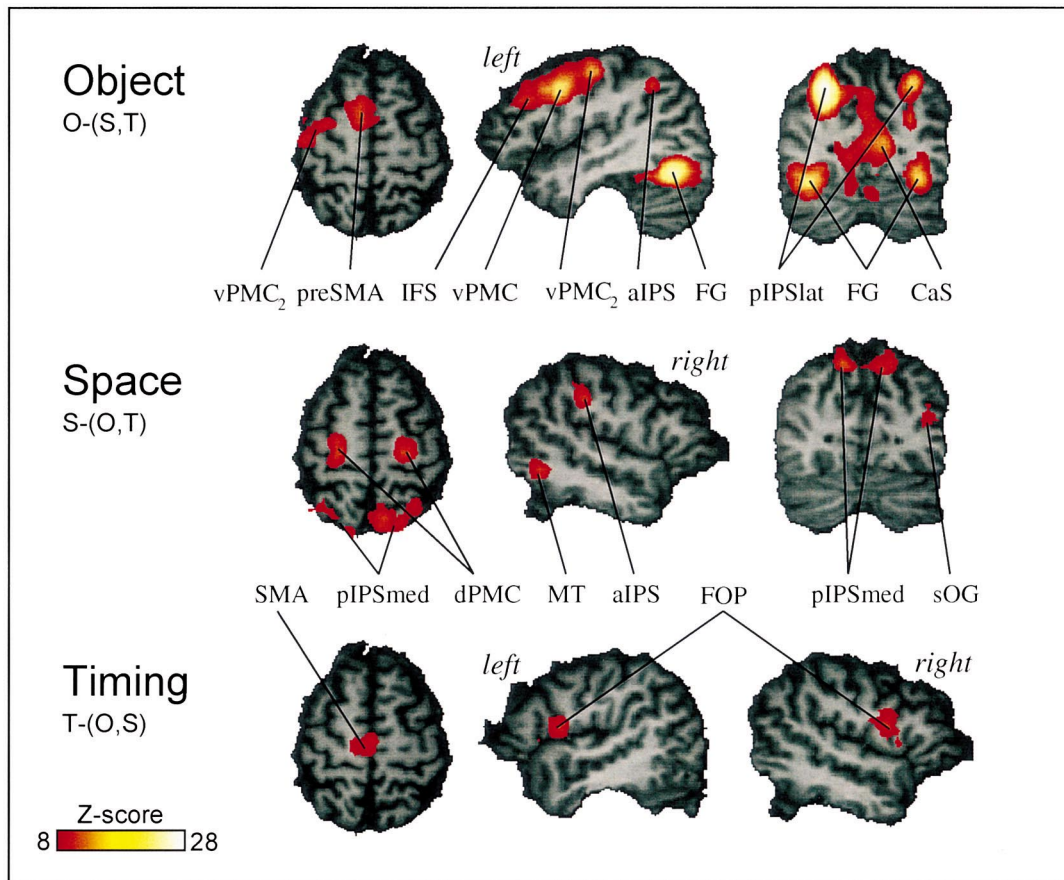


Fig. 4. Group ( $n=12$ ) averaged activation pattern in direct task contrasts (activation dominant in one relative to the two other tasks). Left and right hemisphere views are indicated. Anatomical areas abbreviated as follows: calcarine sulcus (CaS), dorsal premotor cortex (dPMC), posterior intraparietal sulcus lateral/medial (pIPSlat, pIPSmmed), superior occipital gyrus (sOG). For other abbreviations, see Fig. 3.

Table 2  
Attending to object, spatial, or temporal features: direct task comparisons

Anatomical area	Object-(Spa/Tim)				Space-(Obj/Tim)				Timing-(Obj/Spa)				
	x	y	z	Z-score	x	y	z	Z-score	x	y	z	Z-score	
PRESMA	-8	12	47	12.4									
SMA									-5	-3	57	14.8	
dPMC					-23	-10	52	12.3					
					22	-11	50	12.1					
vPMC													
	L	-41	-3	42	17.4								
	R	-38	11	28	21.8								
FOP													
	L								43	7	11	13.7	
	R								-44	9	5	11.7	
IFS													
	L	-38	27	18	17.4								
	R	40	22	22	10.8								
aIPS													
	L	-41	-40	42	12.6								
	R					49	-20	34	13.3				
pIPS													
	L	-26	-64	44	29.4	-14	-62	52	13.6				
	R	22	-56	42	22.5	13	-66	50	13.0				
FG													
	L	-41	-63	-2	25.3								
	R	25	-74	0	17.2								
MT													
	R					43	-53	1	12.7				
CaS													
	L	-7	-71	16	15.7								
	R	7	-71	16	15.7								
sOG													
	R					31	-75	26	12.2				
BG										16	7	11	9.6

selectively in specific types of movement [32]. Thus, most of the vPMC (monkey area F5) neurons sensitive to grasp actions are selective for one of three main grip types, and in particular for the precision grip [52]. Moreover, graspable objects were found to cause vPMC responses regardless from the possibility to grasp the perceived object later on [76,95]. These findings are confirmed also in the human vPMC, which is found to be activated in imaging studies specifically during grasping [73], during imagining grasping ([39] ( $x=-43$ ,  $y=0$ ,  $z=30$ ); [21] (several bilateral foci)), during the generation of manual object-related action words [69], during looking at man-made tools [40] ( $x=-48$ ,  $y=-2$ ,  $z=29$ ), and during memorizing graspable, manipulable objects [43]. Recently, it has been proposed that the specific contribution to the vPMC in prehension is the selection of a certain movement (prehension) type [27].

Finally, the aIPS is the parietal area which supply the vPMC and other frontal areas with higher order visual input [102]. Monkey studies suggest that the cortical banks surrounding the aIPS and the vPMC are together responsible for the transformation of intrinsic object properties into hand action, regardless of the intention to act [76,77,96,101,112]. In humans, patient studies confirm that successful prehension depends on an intact aIPS. Lesions including this area often cause a prehension deficit ('optic ataxia'), reflected by the patient's inability to appropriately adapt the hand's orientation and the finger grip to an object they are reaching for [6,51,87].

The FEF were also activated in all tasks relative to baseline (mean:  $x=\pm 26$ ,  $y=-1$ ,  $z=47.6$ ; in line with a review by Paus [86]:  $x=\pm 31.5$ ,  $y=-2$ ,  $z=46.5$ ). The FEF belongs to a neural network that supports both saccade generation as well as covert spatial attention, as indicated by studies in monkeys [2,9,12,31,104,105] and imaging studies in humans [5,13,16,18,20,79,131]. This dual function has led to the so-called *premotor theory of attention* [94,99]. According to that view, spatial attention is a consequence of an activation of brain areas which are also involved in the transformation of spatial information into action. Applied to our findings, the FEF activation is caused by the same prehension-preparatory situation as the 'prehension network'. Accordingly, the intensity of FEF activation appears to reflect the amount of spatial attention required in each of the three tasks. In the T task the FEF activation was weakest. In this task, spatial information could be ignored, but might still have attracted some attention. In the O task, spatial information was also task-irrelevant, but since objects to be visually analyzed appeared on random spatial positions on a fixed circle, covert shifts of spatial attention were required in the moment of each stimulus onset. Accordingly, the FEF activation was much higher than in the T task, but still weaker than in the S task. The highest FEF activation was found in the S task, where spatial information was task-relevant, and subjects anticipated the appearance of items on certain spatial positions.

Finally, the right FG was the only non-frontal area to be activated by all tasks relative to baseline. The FG is prominent in the processing of faces in contrast to other body parts [53], objects [107], or locations [48]. Moreover, an MEG study recently showed that the FG region responds equally strong to both faces and eyes [123]. This is important to consider for the present study, because our stimulus material, i.e. pairwise presented round objects with a discrete inlay, actually resembled eyes. Therefore, we considered the task-unspecific right FG activation to be a by-product of the stimulus presentation which might disappear in a non-eye-like stimulus presentation mode. Preliminary data from two succeeding fMRI studies confirm this suggestion, showing that FG activation is absent in both a wallpaper-like and in a central single object presentation mode.

#### 4.2. Object (O) task

All areas of the 'prehension network' found to be activated by all tasks relative to baseline were most intensively activated by the O task, as revealed by direct task comparisons. Furthermore, the left vPMC showed an additional activation at a slightly more superior focus. We therefore suggest that grasp representation was dominant in the condition in which subjects attended neither to the object's position nor to their motion speed, but to the objects themselves. Provided that the vPMC activation reflects some kind of grasp selection related to the objects, the additional left PMC activation indicate that the O task made the highest demands on this premotor function. This interpretation considers the perceptually triggered grasp selection to be one component of the representation of attended objects, as suggested by other authors [19,76].

Additional evidence for this interpretation comes from the bilateral IFS activation also dominant in the O task. Damage of the dorsolateral PFC (dPFC) including the IFS were found to impair response inhibition in the monkey [103]. Imaging studies confirm this interpretation by the finding that the IFS is dominant in inhibitory mechanisms, e.g. response inhibition [11,55] and inhibition of set shifting [57,58]. On the basis of this approach, we suggest specific motor inhibitory requirements to cause the IFS dominance in the O task. Accordingly, since the O task, in the absence of any real grasp requirements, causes the 'prehension network' to be activated more strongly than in the other tasks, a higher activation of areas related to motor (grasp) inhibition seems plausible. Furthermore, the IFS is known to target specifically and directly the vPMC [65]. Thus, the fact that the IFS dominance co-occurs with a double activation focus in the left vPMC in the O task also suggests an inhibitory function.

#### 4.3. Spatial (S) task

The location of the human FEF reported by different studies vary considerably along the medio-lateral dimen-



sion, but only minor with respect to the  $y$ -axis and  $z$ -axis [86]. Therefore we suggest that the dPMC activation in the vicinity of the FEF observed during the S task ( $x = \pm 22.5$ ,  $y = -10.5$ ,  $z = 51$ ) is located too posteriorly to be a FEF activation. Interestingly, very similar foci were reported by imaging studies during delayed reaching [54] ( $x = -28.4$ ,  $y = -10.5$ ,  $z = 54$ ), during reaching [56] ( $x = \pm 25.6$ ,  $y = -9.2$ ,  $z = 56.8$ ), and during directional expectation of moving objects [108] ( $x = \pm 26.3$ ,  $y = -11$ ,  $z = 53.3$ ). Together with our findings, these studies suggest a specific involvement of the dPMC region posteriorly adjacent to the FEF in reaching situations, i.e. when an object's position in space drives (or might drive) the spatial parameters of our arm movement. The dominant role of the dPMC in arm control is also suggested in monkey research. The monkey's premotor area involved in the control of arm movements based on the location of the objects in respect to the body, area F4, is located posteriorly and superiorly adjacent to area F5, which is involved in the control of more distal grasping movements based on the size of the object [32,33]. Thus, reaching movements and grasping movements seem to be represented in anatomically different, though overlapping, areas of the monkey PMC. Provided a comparison between monkey and man is possible in this context, our present results are entirely in line with the functional dissociation of reaching and grasping described in the monkey's vPMC and dPMC.

#### 4.4. Timing (T) task

Three areas were found to be most activated by the T task: the SMA proper, the FOP, and the right Caudate (BG). These findings confirm other studies that found SMA, FOP and BG to be prominent structures in timing functions [28,47,49,89,92,106,119]. Moreover, the present study shows that the same areas found to be activated by interval perception and by rhythmic tapping are also involved when temporal features of object movement are anticipated by the observer. Thus, several timing functions — or several instantiations of one and the same basic timing function — appear to share the same underlying brain network. Activations of the SMA proper, in contrast to those of the preSMA, are more closely linked to motor execution, and immediately precede motor output [26,62,65,67]. The finding that timing manipulations of motor responses modulate an EEG component ascribed to the SMA has led to the interpretation that the timing of a motor response is part of the motor program realized in the SMA [122]. A related notion comes from Rubia and co-workers [100], based on a fMRI study on temporal bridging and motor timing functions. They suggest that the SMA is engaged in movement-related processes of time management, such as the temporal anticipation of a stimulus onset in order to synchronize one's own motor response on it. According to that view we suggest that the SMA dominance in the T task implicates special demands on the adaptation of the subject's motor program prepara-

tion, i.e. prehension, to the temporal features of object movement.

In contrast to the vPMC, where mainly manual movements are represented, the FOP is known to represent both hand and articulatory movements [42]. Yet, one of the most stable findings in timing research is that the FOP is activated during timing tasks. This anatomical overlap may indicate some functional overlap between articulatory/speech functions and timing functions. A possible link might be the temporal complexity and hierarchical order inherent to uttered or perceived speech. Thus, the perceptual analysis and motor production of rapid temporal patterns is a function that appears to be a central component in speech [63,114]. From this point of view, the T task might initiate activation within areas related to the coordination of speech effectors, which are adapted to the production and imitative reflection, and therefore the perceptual analysis, of rapid temporal patterns. Or, in reverse description, the reason that timing tasks classically involves the FOP might be that rapid temporal production and perception is dominant within the language/speech domain.

#### 4.5. Non-frontal activations during O task and S task

In general, parietal areas were significantly stronger activated by both the O task and the S task, whereas no dominance was found for the T task in any parietal area. Two regions were specifically dissociated by our manipulations: area MT was only active during the S task, whereas the FG was dominant during the O task.

Area MT responds selectively to moving stimuli [74,118,124], illusory motion [117,132], and even to motion imagery [35]. Although motion was presented in all tasks in the present study, it was differently relevant for each task. Thus, the temporal features of the motion were task-relevant only in the T task, its spatial features were task-relevant only in the S task, and both temporal and spatial features of the motion should be ignored in the O task. However, only the processing of the spatial properties of the motion (S task) elicited MT activation. This finding supports the notion that not motion perception alone, but rather voluntary attention towards motion modulates activation in area MT [3,4,81]. Surprisingly, attending to the temporal aspects of motion, in contrast to attending to the spatial aspects, did not activate area MT.

In contrast, the right and the left FG was clearly dominant in the O task. As area MT, top-down processes in voluntary attention are known to modulate activations in the FG. Thus, increased FG responses were found only when attention was covertly directed towards the perceptual matching of faces, but not during unattended face perception [128]. Since the visual object features were selectively attended only during the O task, attentional modulations appear to have increased the FG activation significantly in this condition.

Finally, both O and S task elicited strong activations along the cortical banks of the pIPS. The activation foci

were located bilaterally in both conditions, but they appeared laterally to the pIPS in the O task, but mesially to the pIPS in the S task, spreading into the precuneus. Single unit data in monkey [10,12,38] as well as human imaging studies [13–15,34,80,121] give converging evidence to the assumption that the IPS area is involved in visuospatial orientation. A functional dissociation between lateral and mesial IPS regions was proposed by a PET study [17], where lateral IPS activation responded to an object memory task ( $x=\pm 34$ ,  $y=-53$ ,  $z=45$ ), whereas mesial IPS activation responded to a spatial memory task ( $x=\pm 25$ ,  $y=-61$ ,  $z=53$ ). The coordinate differences reported in their study ( $x$ -axis:  $-9$ ,  $y$ -axis:  $+8$ ,  $z$ -axis:  $+8$ ) agree perfectly with those found in ours ( $x$ -axis:  $-10.5$ ,  $y$ -axis:  $+4$ ,  $z$ -axis:  $+8$ ). Recently, it was proposed that anatomically distinct regions within the monkey pIPS area might contribute very specific to the transformation of visuospatial information into a motor plan [109]. The authors suggest that the pIPS activation focus depend on the type of movement being planned (reaches or saccades). As far as monkey and human data might be compared, this would be in line with the present finding, that object and spatial attention lead to different activations within the same parietal structures. Accordingly, *object* attention might initiate a transformation process of visual information into a *grasping* action, whereas *spatial* attention might be transformed into a *reaching* action. However, these hypotheses have to be tested in future studies.

#### 4.6. Functional dissociation of lateral premotor areas: Effector-based differentiation or degree of responsiveness?

The present study was based on the account that sensory events that guide or trigger movements are represented in the lateral PMC, even in the absence of a motor response preparation towards these events. Our findings now contribute to the increasing evidence for the notion that different stimulus dimensions are reflected by different premotor activations. But why should object, spatial, and temporal information be represented in anatomically distinct premotor areas? At least two alternative explanations are available.

First, the behavioral output functions of dPMC, vPMC, and FOP are related to different motor effectors. These differences are not clear-cut, but there seems to be a dominant role for certain effectors within each of these areas. Accordingly, the dPMC represents arm and probably, as the distance to the FEF is very small, also partly eye movement, the vPMC represents hand movement, and the FOP represents articulatory movement. Based on these effector-related premotor characteristics, we suggest that premotor activations triggered by attended events differentiate anatomically according to the effector which is most strongly involved in actions within the attended dimension. This means that spatial information corresponds to reach-

ing movements of our arms and/or to tracking movements of our eyes. Object information is related to grasping, pointing, or other manipulative movement of our hands. Timing information corresponds to fast, highly temporally structured articulatory and manual movements.

Second, an alternative or complementary explanation relates to the difference between the medial and the lateral PMC function. Provided that this difference is based on a relative functional graduation from more internally triggered (medial) to more externally triggered movement organization (lateral), rather than on a strict functional difference, the responsiveness to sensory events should be higher in the FOP than in the vPMC, and higher in the vPMC than in the dPMC. Applied to an experimental situation this means that the more a task requires a real *tuning-in*, *synchronization*, *adaptation*, or *matching to a given sensory stimulation*, the more overt motor performance is approached, the more should the premotor activation shift laterally/inferiorly, i.e. from dorsal to ventral BA 6 and finally to BA 44. When subjects are asked to imagine themselves grasping, pointing or reaching, it depends on the subject how vividly this imagination is carried out. A vivid motor imagination might already involve motor timing. When subjects are asked to imitate a movement, however, they have to tune in the movement they perceive, and this tuning certainly involves timing mechanisms. The same holds for tool use imagination, where highly skilled motor performance generates motor plan representations with timing constraints. This account appears to be supported by the findings of several imaging studies related to sensory representation in the PMC which found premotor activations, as listed in Table 3. Real imitation and pointing tends to elicit FOP activation [50,61], as well as the imagination of tool use required for action word generation or tool use naming [40,69,70]. Likewise, mental hand rotation under high time pressure also initiate FOP activation [82]. A further study reports FOP activation during preparation of manual imitation [59]. However, since in this study a classical interval timing paradigm is employed, confounding effects of timing and imitatory functions might be difficult to exclude. In contrast, grasp observation and imagination [39], tool viewing without naming or action word generation [40] does not activate the FOP, but the vPMC. Object grasping in contrast to object reaching does not activate the FOP [73], which is in line with our account since overt motor response is present in both conditions. However, the findings are much less clear for the dPMC. According to the hypothesis of functional graduation, dPMC activation would be expected in experimental conditions that do not require a close tuning-in a sensory event. Actually, activations in the dPMC and in the FOP are seldom reported within the same experimental manipulation.

Fig. 5 shows the lateral PMC activations found in the present study and the lateral PMC activations averaged over the selected imaging studies, displayed on an in-

Table 3  
Different lateral premotor activation foci reported in recent related imaging studies in comparison to the present study

Study	Task	dPMC			vPMC			FOP/Broca		
		x	y	z	x	y	z	x	y	z
[69]	Action word generation–object naming				–36	4	44	–43	18	6
[82]	Fast hand matching–rest	±28	–9	51	±43	–3	39	±58	19	14
[70]	Tool naming–animal naming				–45	0	20	–52	10	20
[61]	Delayed pointing–visual detection							–40	20	12
[61]	Immediate pointing–visual detection				–54	2	16	–46	18	12
[50]	Manual imitation–observation							–50	12	12
[40]	Tool use naming–viewing	–39	–6	51	–48	–2	29	–38	17	17
[40]	Tool naming–viewing	–39	–6	51				–38	17	17
[40]	Tool viewing–fractal viewing	–39	–6	51						
[39]	Grasp observation–object observation	22	–10	55						
[39]	Imagined grasping–observing objects	±19	–19	56	43	0	30			
[73]	Object grasping–object reaching	±32	–9	43	–44	0	11			
Mean coordinates		±28	–11	51	±44	–1	28	±47	16	14
Present study	All tasks–Control				±43	2	27			
	Spatial task–(T/O)	±23	–11	51						
	Object task–(S/T)				–40	4	35			
	Timing task–(S/O)							±44	8	8

dividual brain. As can be seen in this figure, the activations caused by the Spatial, Object, and Timing task match surprisingly well to the main foci in the dPMC, the vPMC, and the FOP. No matter if one of the two proposed explanations for this dissociation — the effector-based differentiation or the degree of responsiveness — will prove to be correct, the activations reported by several

related imaging studies and our findings concentrate distinctly on three subregions of the lateral PMC.

An important consideration remains: the FOP has been discussed as the human homologue of area F5 in monkey [72,84]. The functional purpose of area F5, in cooperation with the aIPS, was described as *mirror system*, that enables us to match observed action with own executed action in

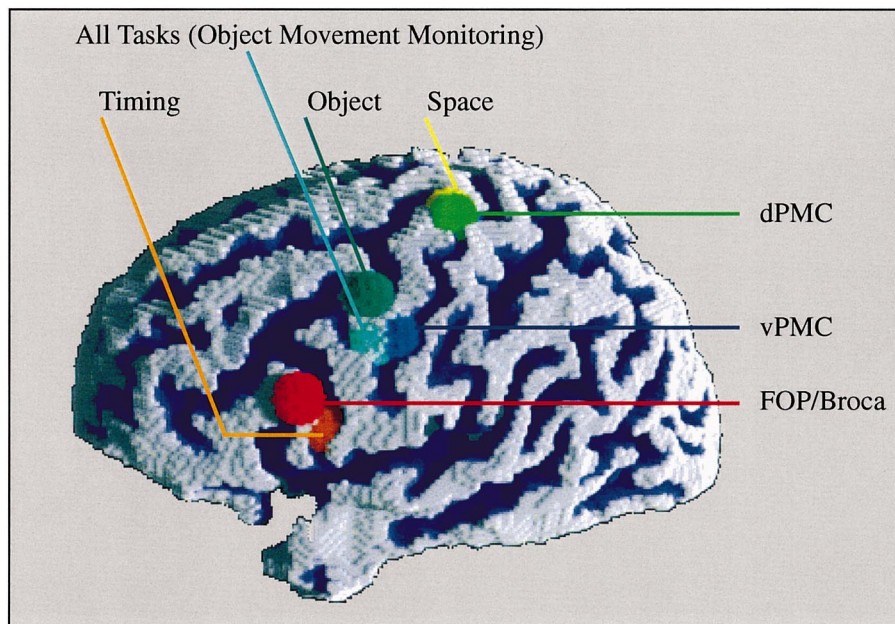


Fig. 5. Lateral PMC activation observed in the present study (labeled above the brain) and averaged across nine related imaging studies (labeled at the right side of the brain; for study references, see Table 3), shown as colored spheres on an individual brain. About 4 mm of the cortical surface are removed in order to make deeper activation foci visible. Attentively tracking moving objects elicited activation within the vPMC, independent of the attended stimulus domain (light-blue). The Object task elicited an additional, slightly more superior vPMC activation (green-blue). Both activation are close to the mean vPMC area reported by the considered imaging studies (blue). Only the Timing task activated the FOP (orange), close to the mean FOP activation of the other studies (red). In contrast, the Spatial task activated the dPMC (yellow) at coordinates nearly coincide with the averaged dPMC activation of the considered imaging studies (green).

the context of learning and communication [93]. Since in the present study, we identified a region within the vPMC to be activated by all tasks, whereas the FOP was activated only in the special manipulation of the T task, our findings seem to be in conflict with the idea of a mirror system as proposed by Rizzolatti and co-workers. Moreover, since the monkey aIPS targets specifically area F5, the fact that in the present study the activation in the aIPS co-varied with that in vPMC, but not with the FOP activation, points in the same direction.

We think, however, that our findings are not in opposition to the notion of a mirror system. We propose an extension of this concept in that the imitative co-activation described by Rizzolatti and co-workers relates to more than one specific ventral premotor region. Ontogenetic and phylogenetic developmental characteristics of these areas reviewed by Greenfield [42] indicate that the functional graduation between the inferior vPMC and the FOP is the outcome of a cortical differentiation with a gradual granularization towards FOP. Given the spatial resolution of fMRI studies, it is generally difficult to differentiate activations in this transitional area. Accordingly, imaging studies supposed to support the idea of a Broca involvement in imitative manual representations sometimes report Broca's coordinates that appear to specify foci located rather within BA 6 (vPMC) than BA 44. The label 'left inferior precentral sulcus (6/44) ventral premotor cortex' intended to describe an activation within this area [40] reflects the problematic nature of anatomical classification within this area.

Furthermore, it is crucial that the capacity to mirror or repeat sensory events by motor production is extremely well developed not only in Broca's area/FOP, but in the whole lateral PMC. Moreover, this capacity refers not only to auditory events, but also to visual events. Thus, as stated in a recent review on speech evolution, "the lateral [premotor] cortex presumably allows humans to not only say what they hear but do what they see, in general bodily terms" [68]. Thinking about the functional purpose of this outstanding *mimetic capacity* [25], it is suggested to be a core requisite in language acquisition (*vocal imitation* [60]). For example, this system allows us to repeat short speech stretches with input–output latencies often shorter than simple auditory reaction (about 140 ms) [91]. In adults, it is suggested that these sensorimotor transcoding functions are latent and are reactivated by specific task constraints [24]. However, from an evolutionary point of view it is probably a more general function, i.e. older than language [25], so that Broca's area, as the evolutionary most recent ventral premotor extension [83], realizes sensory representation ('mirror') functions just as other premotor areas. Language and timing functions revealed within this region indicate that the functional refinement present in the human FOP is especially striking in the temporal domain [63,114]. In contrast to the vPMC, which is adapted to more manual/grasp-specific sensorimotor

transcoding processes, the FOP is adapted to precisely timed mimetic functions in both manual and articulatory behaviour. In the light of recent and present findings we thus suggest that the FOP exposes the typical premotor sensory responsiveness, but in a special quality, and that this exceptional functional qualification is reflected by its mimetic capacity or mirror function.

## 5. Conclusions

1. Attentively tracking moving objects elicited activation within a frontoparietal cortical network comprising the preSMA, the vPMC, and the left aIPS. These areas are known to contribute to prehension processes. We therefore consider this 'prehension network' to be always engaged when moving objects are attentively observed, independent of the attended stimulus property and in the absence of object-directed motor preparation. A basic question that emerges from this finding is what kind of representation is reflected by this network activation. Since all stimuli used in our study had the same size and shape, the network activation might not reflect sequences of modified hand grips — the grasp preparation would be the same for all objects within a sequence — but a prevailing automatic prehension representation.
2. Except for the right vPMC, the frontoparietal 'prehension' network found to be engaged during all tasks was clearly marked in the O task, as revealed by direct task comparisons. This dominance might indicate that attending to the object appearance per se induces immediately a strong readiness for prehension, a kind of *default-use* of the 'prehension network'.
3. Additional activations within frontal and parietal areas extend the prehension network according to the attended stimulus dimension. Most importantly, the present study demonstrates the involvement of distinct lateral premotor subregions according to the attended stimulus domain. Accordingly, distinct premotor activations were observed in the left vPMC during the O task, in the dPMC bilaterally during the S task, and, finally, in the FOP bilaterally during the T task. With respect to the vPMC and FOP activations, we suggest a functional graduation within ventral premotor regions adapted differently to sensorimotor transcoding and mimetic functions. Recently, it was proposed on the basis of behavioral facilitation effects that the *premotor theory of attention* does not only hold for spatial attention, but also for orienting attention to graspable objects [19]. Our study contributed to that idea on the anatomical level, as it shows that the attentional orientation towards object-related, spatial, and temporal features of moving objects is reflected by

considerable activation modulations within distinct premotor regions.

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