A Functional Magnetic Resonance Imaging Study of Cortical Regions Associated With Motor Task Execution and Motor Ideation in Humans

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Abstract: Although motor performance may be enhanced through mental practice, the neurophysiological substrate of mental stimulation (ideation) of a motor task is not well established. We used blood oxygen level-dependent contrast echo planar imaging at 1.5 T to identify regions of increased neural activity during the performance and ideation of a motor task. Five subjects performed a sequential finger-to-thumb opposition task and also imagined themselves performing the task in the absence of actual muscle movement. In all subjects, the left primary sensorimotor cortex showed more activation with actual movement than with motor ideation, but two subjects had significant activation with motor ideation. The left premotor area showed comparable activation with both actual and imagined performance in three subjects. These findings support the involvement of the primary motor area as well as the premotor area in motor ideation.   © 1995 Wiley-Liss, Inc.*

Key words: magnetic resonance imaging, cerebral blood flow, motor cortex, brain mapping, movement control

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INTRODUCTION

Functional magnetic resonance imaging (fMRI) can be used as a noninvasive alternative to positron emission tomography (PET) or single-photon emission computed tomography (SPECT) for studying brain activity. Neuronal activity is accompanied by an increase in regional cerebral blood flow (rCBF) [Fox et al., 1986] and unchanged oxygen consumption [Fox et al., 1988]. The increase in blood flow, and hence blood volume, leads to an increase in venous diamagnetic oxyhemoglobin. This increase reduces the signal-dampening effect of paramagnetic deoxyhemoglobin, resulting in an increase in local MR signal intensity [Ogawa et al., 1993]. With sequences sensitive to the paramagnetic properties of deoxyhemoglobin, which acts as an endogenous intravenous contrast agent that

responds to fluctuations in the oxygen level of the surrounding tissue, neuronal activation can be detected by MRI with use of the blood oxygen level-dependent (BOLD) technique. The BOLD technique was applied initially to studies of the effects of photic stimulation on the visual cortex [Kwong et al., 1992; Ogawa et al., 1992]. Since then, fMRI has been used to study a wide variety of cerebral functions, including those involving the sensorimotor cortex [Bandettini et al., 1992], as well as cortical regions involved in cognitive functions, such as language processing [Rueckert et al., 1994].

The enhancement of physical activity through mental practice has been documented in the fields of rehabilitation and sports medicine [Feltz and Landers, 1983; Appel, 1992]. Many studies have been concerned with the process of motor ideation, or the mental rehearsal of executing a motor task without actual movement. None, however, have demonstrated conclusively the degree to which the neuroanatomical substrates of movement and ideation coincide. Results of early studies of rCBF changes associated with motor ideation [Ingvar and Philipson, 1977] suggested that cortical loci for motor ideation differed anatomically from those involved with actual hand movement. In a study of mental simulation of a motor task consisting of a sequence of rapid finger movements, Roland et al. [1980] detected increases in rCBF exclusively in the supplementary motor area (SMA), and not within the primary sensorimotor cortex (SM1). A recent fMRI study of two normal subjects by Rao et al. [1993] documented changes within the SMA and, to a lesser degree, the premotor cortex during motor ideation, but none within the SM1.

Functional imaging studies of mental imagery in relation to the cortical visual system have shown activation of the same visual areas in the occipital cortex in response to both actual visual stimuli and imagined recall of the stimulus [Roland and Friberg, 1985; Roland et al., 1987; Le Bihan et al., 1993]. The present study used fMRI to examine the possible overlap between functional subdivisions of the brain in processing ideation and execution of a simple motor task.

METHODS

We studied five healthy male volunteers, aged 23 to 53 years. Four subjects were right-handed and one was left-handed, according to the Edinburgh Handedness Inventory [Oldfield, 1971]. There was no history of neurological or psychiatric illness in any of the subjects. The protocol was approved by the Institutional Review Board, and all subjects gave their written informed consent for the study.

Before the experiment started, the subjects practiced the activation tasks, alternating either motor or purely mental rehearsal with rest periods. The motor task consisted of finger-to-thumb opposition, moving sequentially from the index finger to the little finger and back at a comfortable rate (approximately 2 Hz). Subjects also imagined themselves performing this same task without actual muscle movement. An initial baseline phase of rest was followed by either an ideation phase alternating with a rest phase or a movement phase alternating with a rest phase, with a total of six phases per trial. Each phase lasted 30 s. Subjects received verbal cues from the investigator on when to start and stop the ideation, movement, or rest phase. The sequence and repetition rate of the finger movement were monitored by an electrically equipped glove. Electromyographic (EMG) recording was not performed during the MRI study because of technical limitations. In a pilot study, however, another group of normal volunteers performed the ideation task without any significant change in the EMG. During the MRI sessions, an electrically equipped glove did not sense the movement of any finger during the ideation tasks.

Images were obtained by a whole-body 1.5 T MRI scanner (Signa, General Electric, Milwaukee, WI) equipped with a 27 cm diameter customized z-axis head gradient coil and using echo planar imaging (EPI) software (GE Medical Systems, Milwaukee, WI). With T2*-weighted gradient-echo EPI sequences [repetition time (TR) of 3 s; echo time (TE) of 40 ms, flip angle (FA) of 90 degrees], a 16 cm field of view (FOV) was used to acquire 60 images per trial. The digital in-plane resolution of the images was 64×64 pixels with a pixel dimension of 2.5×2.5 mm. The magnetic shim in the region of the motor cortex was optimized such that a true in-plane resolution of 2.5×2.5 mm could be realized. Head motion was minimized by the placement of tight but comfortable foam padding around the subject's head.

Three or four consecutive parasagittal slices of 5 mm slice thickness were acquired, all located between 30 and 50 mm left of the midline. The midline was determined by axial pilot scans for each subject. There were at least 6 min between trials to allow for on-line reconstruction of images.

Because the magnetization was not in a steady state for the first three images of each time-series set, these images were excluded from the analyses. Customized software using Interactive Data Language (IDL) (Research Systems Inc., Boulder, CO) was used for data

analysis. For screening purposes, the spectral density plot of a reference function was correlated with the spectral density plot of each pixel [Bandettini et al., 1993] to generate a correlation coefficient map. The reference function consisted of a piecewise exponential function with a delay constant of 5 s, considering the delayed response of blood flow change against neuronal activity [Kwong et al., 1992].

On the basis of this map, regions of interest (ROIs) were determined in each slice. ROIs ranged from 3 to 20 pixels and were composed of all contiguous pixels with a correlation coefficient > 0.9 during the subjects' movement paradigms. The ROIs obtained during the movement task were then used for the ideation task in order to compare the signal intensity within the same ROIs during the two tasks.

For subsequent anatomical reference, a high-resolution whole-brain MRI for each subject was obtained separately. A regular head coil and a conventional T1-weighted, spoiled-GRASS volume sequence with a flip angle of 30 degrees, TE of 5 ms, TR of 33 ms, and FOV of 31 cm were used. A total of 124 contiguous sagittal images was obtained. Matrix size was 512 × 512, slice thickness was 1.5 mm, and pixel size was 0.6 × 0.6 mm.

Anatomical localization of ROIs was achieved by identifying the central sulcus on the contiguous sagittal images of high-resolution MRI [Steinmetz et al., 1990] and tracing it laterally to the EPI slice locations that were used for ROI comparison. With the central sulcus used as a reference point, the rest of the regional anatomy was identified to help establish the locations of the ROIs. For each subject, one of the parasagittal slices always provided a temporal profile best conforming to the paradigm and also invariably provided the highest degree of signal enhancement with activation within the SM1 during movement. Therefore, the analysis focused on the most active slice for each subject.

The effect of ideation on the areas involved in the motor tasks was assessed using time-series data of the regions that were activated with the movement paradigm. To estimate autocorrelation, which could not be ignored because of the short sampling interval of 3 s [Friston et al., 1994], the AutoRegressive Integrated Moving Average (ARIMA) [Box et al., 1994] was used. To simplify the calculation, step functions with linear transition were chosen as the reference function (Fig. 1). Delay of response in rCBF was also considered by introducing time lag into the reference function. Reference functions with specific time lags were fitted with the observed time-series by allowing for the effect of the values of preceding time points and the effect of a
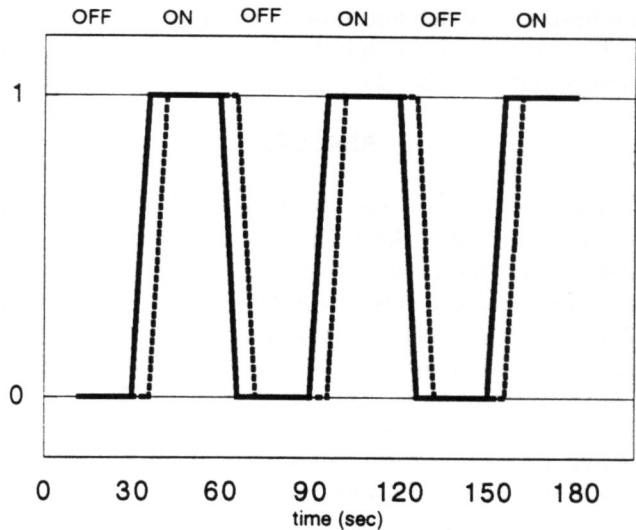

Figure 1.

Reference functions for time-series analysis. On the ordinate, level 0 is the baseline corresponding to the rest phase (off) and level 1 is the baseline corresponding to the task condition (on). Transitions between the two levels are linear over a period of 6 s. Reference functions with time lag of 0 s (solid line) and 6 s (dotted line) are shown.

linear trend. (For a detailed description of these methods, see the Appendix.) The difference in activation by movement and ideation was analyzed by using the same methods on the subtracted series (movement minus ideation).

The standardized Talairach's coordinates [Talairach and Tournoux, 1988] of each activated focus were obtained as follows. The anterior commissure (AC) and posterior commissure (PC) were identified using the midsagittal image of the high-resolution MRI of each subject. Orientation of Talairach's space is determined by three orthogonal axes: from the left margin to the right margin on the X axis, from the occipital pole to the frontal pole on the Y axis, and from the AC-PC line to the vertex on the Z axis. The centers of the activated foci detected on the sagittal images of the fMRI were identified on the sagittal images of high-resolution MRI at the same location with reference to anatomical landmarks such as the central sulcus. We relied on anatomical landmarks because the warping of the fMRI makes automated coregistration with high-resolution MRI difficult. The coordinates (in mm) of the center of the activated foci were determined with reference to the AC point. These coordinates were then linearly scaled in each axis with a different scaling factor. Scaling factors for each axis were determined using the individual brain size measured with high-resolution MRI and the standardized Talairach's

brain size, in which width (left margin to right margin) is 130 mm, length (occipital pole to frontal pole) is 174 mm, and height (AC–PC line to the vertex) is 78 mm.

RESULTS

The calculated correlation images created for each subject revealed multiple ROIs for the movement task, not all of which were located in similar anatomical regions across subjects. The SM1 (Brodmann areas 4, 3, 2, and 1), and posterior parietal cortices (Brodmann area 7) were consistently activated. The premotor cortex (Brodmann area 6) was activated in four of the five subjects. A time-series analysis confirmed that the activation in these ROIs, determined on the basis of the correlation coefficient maps, was significant during the movement task. The regions that were not consistently activated across subjects were the medial frontal gyrus (Brodmann areas 8, 9, and 10) and the inferior parietal cortex (Brodmann area 40).

During the ideation task, activation occurred in similar cortical regions (Fig. 2). The SM1 showed significant activation in two subjects, even though it was significantly smaller during ideation than during movement (Table I, Fig. 3). The time course plots for these subjects showed a strong correlation of signal intensity increase with task in the first phase of the ideation task, but reproducibility in the second and third phases was less evident (Fig. 3). The remaining three subjects did not have significant activation in SM1 during the ideation task (Table I). All five subjects showed more signal change during actual movement than during ideation.

Four of the five subjects showed activation in the premotor area during ideation. In two subjects, the signal levels rose a similar amount in both the ideation and the motor tasks (Table I). One subject had more activation in the premotor area during the ideation task than during the motor task. Another subject showed no significant activation in the premotor area during ideation (Table I).

The parietal region was significantly activated during ideation compared with rest in only one subject, for whom the signal intensity change was less than that observed with the movement task (Table I). All subjects showed significantly more signal change in this region during actual movement than during ideation.

DISCUSSION

Because fMRI is a relatively new imaging modality, there are several technical points that should be

mentioned. First, head motion is an important factor in interpretation of the data. Periodic movement of the head that is synchronized with the on-off period of the paradigm could cause false-positive results. Although our tasks (finger tapping and motor imagery) were unlikely to induce head motion, we first visually confirmed that a series of images of a particular slice was not out of plane, and also in-plane motion was not visually appreciable; hence we did not correct the motion misregistration. Correlational analysis is known to be less sensitive to motion artifact than the subtraction method [Bandettini et al., 1993]. Second, the absence of a significant response, especially for some subjects in the ideation task, may be due to a statistical technical problem. The piecewise linear response function may be appropriate for the movement task, as consistent activation was detected where it was supposed to be, but a different function might better describe the ideation response. Finally, the brain was only partially covered because of the surface coil used and the limited number of slices obtained. This limits the evaluation of the multiple brain structures functionally related to movement and ideation. Despite these technical limitations, fMRI has advantages over PET in terms of the capability of individual analysis and the higher spatial and temporal resolution.

In general, variation of activation among individuals has not been well evaluated in imaging studies. PET activation studies usually have used group analysis with anatomical normalization, which cannot evaluate an individual response. However, fMRI can evaluate activation in individuals. The individual variability noted in our study is a likely example of how different strategies of performance can affect the results.

The findings of the present study suggest an overlap of cortical regions involved with the actual and mental performance of a relatively simple motor task. The functional changes detected in the contralateral SM1 during ideation in two subjects are in contrast with the results of rCBF studies suggesting that motor ideation and actual hand movement are controlled by regionally distinct cerebral loci [Ingvar and Philipson, 1977], or of fMRI studies [Rao et al., 1993; Sanes et al., 1993] that failed to show activation in the SM1 during motor ideation. This discrepancy is probably due to differences in the techniques of motor ideation. Because motor ideation is a "pure" cognitive task, it is clearly not subject to "verification by observation," as is the motor task. Apart from the absence of visual movement of the patients' fingers, it is impossible to know exactly how the ideation task was performed. Visual imagery probably plays an important role in
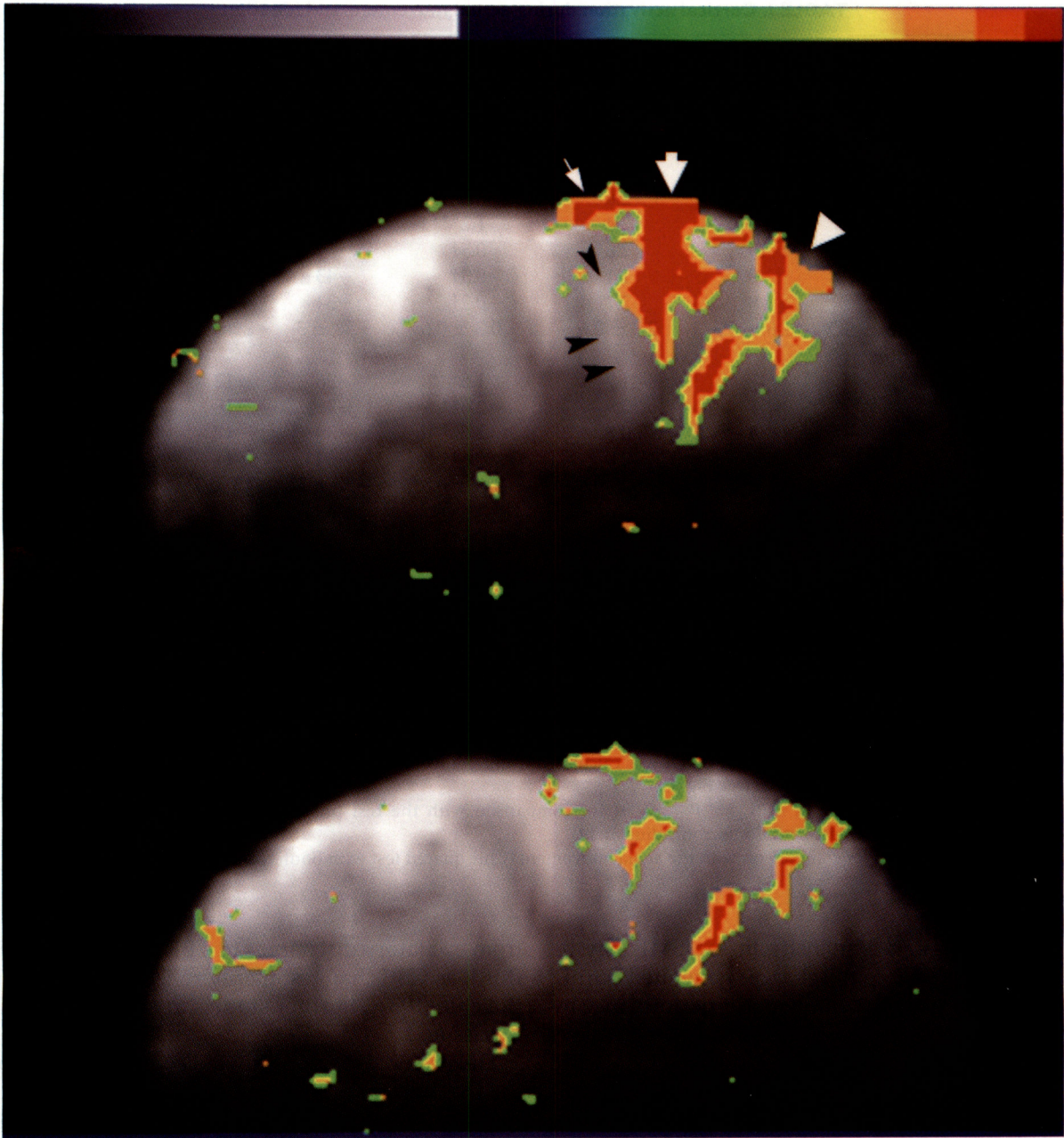
Figure 2.

Activation with movement (top) and with ideation (bottom). Calculated correlation maps were superimposed on the parasagittal image 37.5 mm left lateral to the midsagittal plane. Left is anterior and top is superior. Pixels with a correlation coefficient > 0.5 are green. Pixels with a correlation coefficient > 0.9 are red. Central sulcus (black arrowheads) was identified with reference to the high-resolution MRI of the same slice. The SM1 (thick white arrow), premotor (thin white arrow), and parietal (white arrowhead) areas were significantly activated with the movement task and less so with the ideation task.

some subjects [Jeannerod, 1994]. Motor ideation has been categorized into internal imagery (feeling oneself do) and external imagery (seeing oneself do) [Suinn, 1983; Jeannerod, 1994]. Perhaps activation in the SM1 depends on one's ability to use internal imagery. It might be possible to test these two different strategies of ideation in the same subject, covering not only the motor areas but also the visual areas to determine if different strategies might activate different sets of brain regions.

TABLE I. Cortical activation during actual movement and ideation

Cortical region and subject	ROI[a] (no. of pixels)	Percent signal change in ROI[b]		Talairach's coordinates		
		Actual movement	Ideation	x	y	z
SM1						
1	11	2.6	0.5*†	−36	−25	47
2	20	2.4	1.2***†	−38	−28	50
3	10	2.6	0.5†	−39	−32	49
4	9	1.1	−0.3†	−43	−33	43
5	8	2.7	−0.2†	−34	−29	41
Mean ± SD	11.6 ± 4.3	2.3 ± 0.6	0.3 ± 0.6	−38 ± 3	−29 ± 3	46 ± 4
Premotor						
1	7	1.7	1.8***	−36	−12	61
2	7	2.9	2.6**	−38	−18	52
3	4	0.8	2.6***†	−39	−12	61
5	5	2.0	0.6†	−34	−11	59
Mean ± SD	5.8 ± 1.3	1.9 ± 0.8	1.9 ± 0.8	−37 ± 2	−13 ± 3	58 ± 4
Parietal						
1	5	3.1	0.7†	−36	−40	38
2	7	2.2	0.9*†	−38	−39	49
3	3	3.0	1.0†	−39	−48	53
4	11	1.8	0.3†	−43	−50	47
5	4	1.7	−0.2†	−34	−53	57
Mean ± SD	6 ± 2.8	2.4 ± 0.6	0.6 ± 0.3	−38 ± 3	−46 ± 6	49 ± 7

[a] ROI was determined by a correlation coefficient map using as threshold a correlation coefficient > 0.9 (see text for details); each pixel is 2.5 × 2.5 mm.

[b] Percent signal change in the ROI was calculated using points of level 1 and level 0 defined by the fitted time-course model (see Fig. 1).

* $P < 0.05$, ** $P < 0.01$, *** $P < 0.001$ for comparison with the rest phase of the ideation task (Chi-squared test with Bonferroni adjustment).

† $P < 0.05$ for comparison with the actual movement (Chi-squared test with Bonferroni adjustment).

The increased signal intensity in the SM1 may be explained by the efferent discharges generated during ideation, which could facilitate motor performance by priming the motor pathways with descending volleys [Jeannerod, 1994]. This view was supported by a study using transcranial magnetic stimulation. Pascual-Leone et al. [in press] showed that mental practice of piano playing caused enlargement of the motor representation of both finger flexors and finger extensors in accordance with improvement in performance. However, the enlargement of the cortical map and the performance improvement were less than with physical practice. This finding indicates that mental practice modulates the cortical motor output to the muscles involved in the task and that, in turn, the primary motor cortex is involved in motor ideation.

The signal changes in the SM1 with motor ideation might also reflect inhibitory discharges to prevent muscle movement, which could not be differentiated from excitatory discharges in CBF studies with PET or fMRI, as CBF changes mainly reflect synaptic activity [Raichle, 1987]. Further studies are needed to resolve this issue.

The premotor region showed comparable activation for the two tasks in three of the five subjects. This finding is compatible with the notion that motor imagery and preparation for actual movement share common mechanisms [Jeannerod, 1994]. The premotor area is involved in the preparation or selection for movement [Fox et al., 1987; Deiber et al., 1991]. Rizzolatti et al. [1988] described a class of neurons in the rostral part of the inferior premotor cortex of the macaque monkey that fire before and during a specific sequence of actions performed by the animal. In addition, they found that the same neurons also fire while the monkey observes the experimenter performing the same action [Di Pellegrino et al., 1992]. Recently, in a human PET study, Decety et al. [1994]
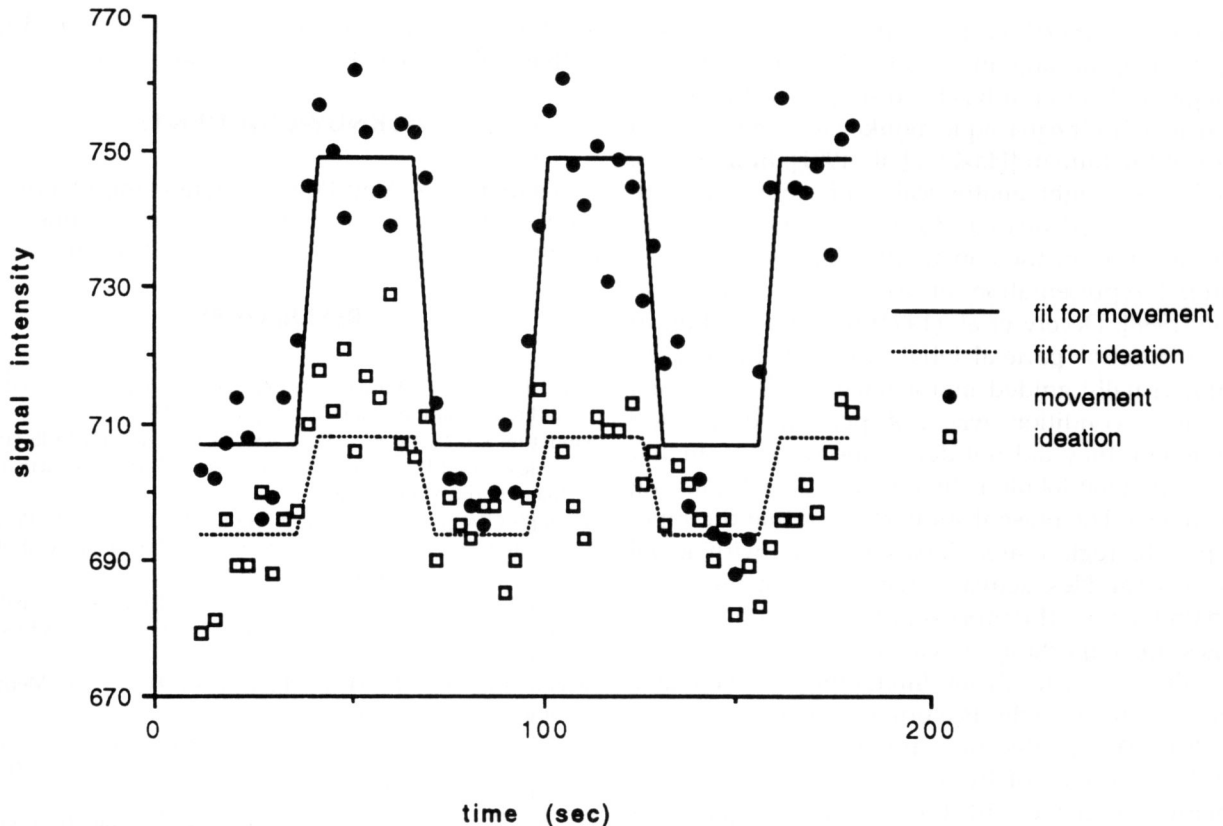
Figure 3.

Signal intensity plots of a single pixel within the SM1 during movement (closed circles) and ideation (open squares) from subject 2. Time-series plots modeled with ARIMA fitted with time-series data of movement (solid line) and ideation (dotted line) conditions were superimposed. Signal change with ideation was significantly smaller than with actual movement ($P < 0.01$, with Bonferroni adjustment for five subjects, two reference functions, and 20 voxels per ROI). In the ideation paradigm, the second and third phases of the task showed a less evident increase compared with the first phase.

reported that a motor imagery task involving simulation of visually guided movements produced activation in the inferior premotor cortex bilaterally. In comparison with these non-human primate and human studies, our study showed activation in a more dorsal region of the premotor area. This could be explained by a difference in the mental task: our task was essentially self-generated, while the others were visually guided. These findings, as mentioned by Jeannerod [1994], indicate that the neurons in the premotor cortex serve as a common substrate for motor preparation and imagery.

In comparison with actual movement, motor ideation activated the premotor area more than the SM1. This may suggest that the role of the premotor area in motor imagery is different from that of the SM1. Our subjects described the ideation experience as requiring a large degree of attention and effort. Gandevia

[1987] proposed that the discharges responsible for sensation of effort do not arise directly from the corticofugal pathway because transcranial electrical stimulation of this pathway does not produce a sensation of effort. Instead, the subject experiences a passive movement. It was also suggested that the relevant discharges for the sensation of innervation arise from structures such as the premotor cortex, which subsequently impinge upon primary motor cortex and the descending pathways [Jeannerod, 1994]. In monkeys, the premotor area provides a body-centered coordinate system for goal acquisition by arm movement [Rizzolatti, 1987]. These findings may be compatible with the idea that the premotor cortex has a greater role in higher order processing of related motor actions than the SM1 does [Sanes et al., 1993].

Actual movement caused consistent activation in the parietal cortex (area 7), whereas motor ideation

resulted in parietal cortex activation in only one subject. This finding might also be related to the strategy of ideation. It has been suggested that Brodmann area 7 of the macaque monkey is homologous to area 7 of the human [Haxby et al., 1991]. In monkeys, area 7 has a tight anatomical connection with the premotor area [Pandya and Kuypers, 1969]. It has an important role in the construction of body-centered neuronal representation of space [Wise and Desimone, 1988]. Decety et al. (1994) found activation in the left inferior parietal lobule (Brodmann area 40) during visually guided motor imagery. As an actual movement condition was not performed in their experiment, they did not determine whether the left inferior parietal lobule is involved in actual grasping movements. The present study showed that the superior parietal region (area 7) was activated with actual movement and less activated with motor imagery.

To understand the process of ideation, whole-brain images are important for viewing all cortical structures. Because of hardware limitations, we were able to obtain only a single slice orientation and relatively few slices. We selected the parasagittal slices in order to isolate the part of the motor cortex homunculus primarily associated with the hand and fingers. This permitted examination of the premotor, sensorimotor, parietal, and other regions within that slice, but necessarily precluded examination of motor association areas not in the selected plane, specifically, the SMA, which lies more medially. Using functional MRI, Tyszka et al. [1994] identified activation in the SMA during finger movement. During imagination of the same movement, there was a differential response, with rostral areas more active than caudal areas. They concluded that the SMA has multiple areas that subserve different functions in motor planning and execution.

The results of the present study agree with evidence from the fields of cognitive psychology, sports psychology, psychophysiology, and neurophysiology suggesting that mental ideation should be considered a distinct neuronal process involving specific brain structures [Decety and Ingvar, 1990]. Further fMRI studies similar to this one may help identify the neurological substrates responsible for the documented positive effects of mental simulation of movement on subsequent motor performance [Appel, 1992]. The potential importance of this finding is clear in the field of rehabilitation medicine, where the use of mental practice with more common physical modalities may help patients attain their goals. This study shows that changes associated with cognition, such as motor ideation, may be mapped noninvasively in real time with excellent spatial resolution using fMRI.

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APPENDIX

For the 57 time points observed in this experiment, the intensity Y at time i can be thought of as a random variable and modeled as a regression:

$$Y_i = \beta_0 + \beta_1 f(i) + \epsilon_i$$

for $i = 1, \ldots, 57$, where f(i) is a reference function (as in Fig. 1), β_1 is the intensity change (amplitude) associated with the task (movement or ideation), so that β_1/β_0 is the relative change, and ϵ_i is the random variable that is the error associated with this regression model at time i.

Time-series methods can be used to fit regression models that allow for correlated (rather than independent) errors over time. These correlations (where the intensity level at time i is correlated with intensities of the time or times that precede it) could be explained by physiological factors associated with hemodynamic response. Friston et al. [1994] used Fourier analysis to model the temporal correlation in fMRI.

Using y_i to denote the (nonrandom) observed time-series of intensities, then for statistical estimates b_0 and b_1 of β_0 and β_1, respectively, the residuals $e_i = y_i - b_0 - b_1 f(i)$ are modeled in the time domain using the ARIMA technique [Box et al., 1994; Diggle, 1990]. Such a time-series model, denoted ARIMA (p,d,q), depends on three integers: d refers to the dth difference series needed to achieve stationarity (no trend over time) and p and q to the orders of the autoregressive (AR) and moving average (MA) processes, respectively. Here, d = 1 is used successfully to achieve stationarity in the errors e_i by forming the first difference series $x_i = e_i - e_{i-1}$; implicit here is that the estimated regression model $b_0 + b_1 f(i)$ does not completely predict the intensity at time i. It is this difference series

that is then modeled with AR and MA processes. Diagnostic plots and the Akaike (or Bayes) information criterion are used in identification of p, d, and q [Brockwell and Davis, 1987].

In our application using an ARIMA (2,1,1) model, the parameters (two AR parameters, one MA parameter, and b1) are estimated simultaneously by iterative maximum likelihood [Kohn and Ansley, 1985] using the statistical software package S-Plus (MathSoft, Inc., Seattle, WA). The percent change $100 \, (b_1/b_0)$ is re-

ported in Table I. The statistical significance of this regression coefficient b_1 is assessed using the likelihood ratio test based on a Gaussian error model. Its approximate P value is reported in Table I; the P values are Bonferroni adjusted to compensate for the two reference functions used (lags of 3 and 6 s) as well as the five subjects and the three ROIs. All time-series have been well fit using ARIMA (2,1,1) models, although sometimes (1,1,1) models proved adequate with no change in the inference.