Original article

The ideation of movement is supported by fronto-temporal cortical regions involved in the retrieval of semantic knowledge

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Abstract. *Background and aim of the work:* The neurofunctional correlates of movement ideation, which should be distinguished from motor imagery, have not been fully investigated. This functional Magnetic Resonance Imaging (fMRI) experiment revealed the brain activation patterns associated with different motor processes, including ideation. *Methods:* Fifteen healthy participants underwent fMRI and performed three tasks using the right index finger: 1. execution of a simple prespecified movement; 2. execution of a simple voluntary movement; 3. ideation of a simple voluntary movement without execution. A number of t-test comparisons across conditions were carried out. *Results:* The execution of a simple prespecified finger movement activated the right inferior parietal cortex and substantia nigra, the left middle frontal gyrus ,and thalamus, and bilaterally the post-central gyri, the superior parietal lobule and the cerebellum. Execution of a simple voluntary movement activated the left anterior cingulate cortex. The ideation of a voluntary simple movement activated the left inferior, middle and superior temporal gyri and the inferior frontal gyri bilaterally. *Conclusions:* The execution of a prespecified action involves structures within the somatosensory cortex, such as the post-central gyrus. The execution of a voluntary action is achieved with the support of the anterior cingulate cortex, a structure active when resolution of conflict is required. The ideation of a voluntary action requires the contribution of associative areas of the left frontal and temporal lobes, which support the retrieval of semantic knowledge necessary in the planning of a voluntary act.(www.actabiomedica.it)

Key words: Movement, ideation, fMRI, motor behaviour, voluntary action

Introduction

The execution of a simple movement is a process that involves several independent components, mostly supported by different neuronal structures (1, 2). Ideation, choice and execution are the most important processes involved in the production of a simple voluntary act. The organization of brain structures responsible for movement has been defined as hierarchical (3). The primary motor cortex is the area where actions of the superior cortical levels converge, and from where the descendent motor commands, which require cortical processing, start, directed to the sub-cortical areas and to the spinal cord. The premotor cortical regions are connected with the prefrontal and posterior parietal cortices through associative fibres. A fundamental role in the actioning of movement is carried out by the premotor cortex and the supplementary motor area (SMA), which receives afferences from the posterior parietal areas and sub-cortical regions, and projects to the motor cortex. The SMA receives information mainly from the lateral ventral nucleus of the thalamus, and is also influenced by efferent projections from the globus pallidus. The involvement of SMA in this cortico-thalamic circuit determines that it plays a primary role in the planning of motor sequences. The premotor cortex also receives cerebellar efferent projections via the ventro-lateral thalamic nucleus. Via its connections with the posterior parietal lobe, the premotor cortex contributes to processing of sensory signals, and does have a role in the generation, selection and memory of voluntary movements of the limbs (1, 4). Because the SMA receives several projections from the prefrontal cortex and the basal ganglia, this structure is deamed essential in the execution of movements based on an inner decision.

To interpret motor behaviour, some models have been proposed. It was suggested that after the ideation of a given movement, information about that movement might be processed by the associative cortex, which then would send signals to the basal ganglia, involved in the elaboration of the required sequence of actions, and then to the SMA that would select a specific movement. The SMA would communicate with the premotor cortex which then selects the movement in relation to the external relevant stimulus, and transmits this information to the lateral cerebellum that prepares the appropriate motor programme. The lateral cerebellum would communicate with the motor cortex which controls the activation of the necessary muscles and enables the movement, and gives information to the intermediate cerebellum that corrects and implements the motor programmes necessary for a given selected action. The somatosensory cortices would also be connected with the motor cortex and the intermediate cerebellum and provide functional support to these latter structures. Finally, the somatosensorial cortex would feed back information to the associative cortex (5). Although in this model the neural correlates of selection and execution of actions were clearly defined, the neural regions involved in the initial movement ideation process were hypothetically linked with the associative cortex without any experimental evidence pointing to a specific brain area. The present study aims to clarify whether this particular aspect of motor ideation is achieved with the support of specific structures within the associative cortex.

A voluntary movement requires the subjective experience of decision and intention to act, as well as the neural control of its execution (5). The schema of an action is the product of several processes, such as the definition of the objective, the strategy of behaviour, the selection of the more efficient response, the planning and initiation of a movement. A voluntary action becomes an active behaviour when the brain is able to match the consequences of that motor action with the original intention. The brain would use internal motor representations or internal models to predict the result of a certain action. The parietal cortex is said to have a role in the activation and maintenance of these internal models and the cerebellum would predict the future effect of the movements (6).

Some neuroimaging studies have shown that segregated brain regions sustain the preparation and execution of voluntary and involuntary actions. A Positron Emission Tomography (PET) study showed that the preparation of a copied hand movement induced a regional cerebral blood flow increment in the supramarginal gyrus and in the frontal regions (BA 44), whereas its execution resulted in blood flow increase in the right cerebellum and in the basal ganglia (7). The dorso-lateral prefrontal cortex, the SMA and the cingulate gyrus seem to be particularly involved in the preparation of voluntary movements (8). Indeed, the planning of a prespecified movement activated a neural circuit which includes the prefrontal cortex, the anterior cingulate, the premotor and intra-parietal cortices (4).

The cortical representation of a movement was, however, different depending on the characteristics of the motor actions required: more finalised ones, e.g. those directed to a specific target, were more localized, whereas more complex actions had a more flexible representation (5). Roland et al. (9) found an increase in cerebral blood flow in the contralateral sensorimotor cortex during the execution of a simple motor task, whereas an increase in blood flow was found in the SMA, in the bilateral premotor cortex (BA 6) and in the contralateral sensorimotor regions during a complex motor task.

A movement can be defined as voluntary, when freely generated by an agent, or prespecified, when dependent on predefined external constraints. The neural substrates of these two types of motor behaviour are different. Voluntary actions activate areas involved in motor and executive functions, such as bilateral prefrontal cortex and the rostral portion of the SMA (10). A functional Magnetic Resonance Imaging (fMRI) study showed that freely generated finger movements determined a higher level of activation in the prefrontal cortex (BA 46) and in the anterior cingulate (BA 32), than prespecified ones (11). Similarly an increase in blood flow in the premotor cortex, in the prefrontal cortex (BA 46/9 and BA 10 and BA 32), in the SMA and in the superior parietal associative cortex was observed in a PET study during the execution of voluntary movements (12). In particular, internally generated movements produced the highest blood flow increase in the SMA (8).

Other neuroimaging studies have investigated the neural substrates of mental imagery for motor behaviour. Imagery of the execution of a prespecified complex movement activated the SMA, and to a lesser extent the premotor cortex (13). Subsequently it was also shown that imagining a movement would involve other structures in addition to the SMA, including the inferior parietal region (BA 40) bilaterally, the anterior cingulate (BA 24 and 32), premotor areas (BA 9 and 46), the caudate nucleus bilaterally and the left cerebellum (14). This study also evidenced a dissociation between the areas involved in the imagery of a movement, such as the SMA and the cingulate gyrus, and those supporting the execution of a movement, such as the dorsal parts of the medial and lateral premotor cortex, adjacent cingulate areas, and rostral parts of the left superior parietal cortex. There is a functional distinction between the rostral and caudal parts of the SMA: the rostral part plays a role in the imagery of movement, whereas the caudoventral part supports the actual execution of a movement. Further studies have observed activation in the primary motor cortex during the imagery of movement (15). A further study looked at cerebral activation during imagery of a complex prespecified motor task, its execution and the imagery of a natural landscape. Imagery of a complex prespecified movement activated the left premotor cortex, independently of the hand used, the posterior part of the precentral gyrus (which includes the primary motor cortex) and the bilaterally SMA. The execution of movement activated the precentral gyrus and the SMA as well, suggesting that these regions are a common neural substrate involved both in the imagery and execution of movement (16).

In summary, several studies have shown that a large neuronal network including the primary motor cortex, the primary somatosensory cortex, the premotor areas (SMA), the superior parietal lobe is implicated both in movement execution and imagery (17, 18), while the imagery of movement would activate, in addition to these areas, the medial superior frontal gyrus, anterior cingulate, precentral sulcus, supramarginal gyrus, fusiform gyrus (19).

Although a large number of imaging studies have focused on detailing the neural substrates implicated in several aspects of movement, to our knowledge, no study has investigated the neural substrate associated with the ideation of a voluntary movement, distinguished from motor imagery. Studies to date have investigated the neural substrate of executing voluntary actions, or those supporting the imagery of a prespecified action, but so far none has looked at the ideation of voluntary movements.

The aim of this study, therefore, was to investigate which brain regions support the ideation of a simple voluntary action, i.e. moving the right index finger up or down with functional Magnetic Resonance Imaging (fMRI).

Materials and Methods

Participants

Fifteen healthy participants (10 females and 5 males, all right handed; mean age=37.5, standard deviation=13.3, age range=23-58 years; mean education=16.4, standard deviation=1.7) took part in this study. Each participant underwent a detailed clinical interview to exclude the presence of left-handedness or manual ambivalence, neurological and psychiatric pathologies and drug abuse. Each participant gave written consent to take part in the study. This study was approved by the joint University and regional NHS ethics committee.

Procedure

Each participant was administered an experimental paradigm lasting thirty-five minutes, during which three experimental conditions were presented: 1. A baseline condition which required the execution of a simple prespecified movement of the right index finger up or down as indicated by a written cue which appeared on screen ('UP', 'DOWN'); 2. An active condition which required the execution of a simple voluntary up or down movement of the right index finger, at the choice of the participant when indicated by a written cue which appeared on screen ('NOW'); 3. An active condition in which participants were instructed to think about the execution of a simple voluntary movement of the right index finger, up or down at their choice when indicated by a written cue which appeared on screen ('NOW'), but not to actually execute any movement.

Participants were provided with oral and written instructions about the tasks they were required to do in the scanner. All baseline and active conditions involved the right index finger only. The instructions were 'please move your right index finger as indicated', 'please move your right index finger up or down when indicated' and 'please think about moving your right index finger up or down when indicated' for the baseline and active conditions respectively. Three five minute runs were carried out. Each run contained four repetitions of each condition. There were ten trials in each condition, and in each run there were four repetitions of each condition for a total of 40 trials per condition per run. Instructions were displayed for 2500 ms, followed by a written cue which remained on screen for 1500 ms and by an interval of 1000 ms during which the screen stayed blank. Instructions were written in black ink on a white screen positioned in front of the participant and visible from a mirror located on the head coil. The right hand of the participants was strapped onto a polystyrene cast which had an opening below the index finger so that only an up/down movement was possible. Movements in other directions or dimensions were not possible. Participants were invited to execute the tasks as soon as cued and return to the initial position after each movement. To ensure that participants were complying with task instructions, an experimenter stayed in the scanner room to record the participants' movements.

fMRI method and data analysis

Echo planar imaging was carried out on a GE 1.5T Signa NVi system (TR=2500ms, TE=33ms, flip angle=90°, voxel size=1.88x1.88x5 mm). One hundred and twenty sets of 24 contiguous axial images were acquired. A PC drove stimulus presentation with a purpose-devised program written using the software Presentation for Windows. Stimuli were projected via an Epson LCD projector onto a screen viewable with a mirror attached to a standard head coil. A block fMRI design was used. Total imaging time, including localisation and structural 3D T1 weighted image acquisition, was approximately thirty minutes.

Imaging data were analysed using Statistical Parametric Mapping (SPM) image analysis software (Wellcome Department of Imaging Neuroscience, London). Images were re-aligned using the first volume as reference, spatially normalised to the standard EPI template available in SPM and normalised images were then spatially smoothed with an 8 mm full width at half maximum isotropic Gaussian kernel to compensate for any residual variability after spatial normalization. A synthetic haemodynamic response function (HRF) was used as the reference waveform. Proportional scaling was applied to remove any within subject difference in blood flow. Image data were high-pass filtered with a set of discrete cosine basis functions with a cut-off period of 128 s. Head motion was not included as a regressor in the first level analyses since the individual movement was less than 2 mm. The signal changes for each voxel were analysed with predefined contrasts using a one sample t-test. Contrast images obtained from each participant individual data sets were then entered into a random effect group analysis. Height threshold was set at $p < 0.001$ corrected. Anatomical regions were identified using the Talairach Daemon Client (http://ric.uthscsa.edu/projects/tdc/), following appropriate conversion of the Montreal Neurological Institute coordinates extracted from the SPM analysis into Tailarach coordinates.

Results

Prespecified movement execution versus voluntary movement ideation

Cluster of significantly higher activation were found in the left middle frontal gyrus (BA 6) and thalamus, in the right inferior parietal lobule (BA 40) and substantia nigra, and bilaterally in the post-central gyrus (BA 2), superior parietal lobule (BA 7) and cerebellum (Table 1a and Figure 1).

Voluntary versus prespecified movement execution

A cluster of significantly increased activation was found in the left cingulate gyrus (BA 32), (Table 1b and Figure 2).

Voluntary movement ideation versus voluntary movement execution

Clusters of significantly higher activation were present in the left inferior (BA 20), middle (BA 21 and 22) and superior (BA 22) temporal gyri and bilaterally in the inferior frontal gyrus (BA 47) (Table 1c and Figure 3).

Discussion

The present fMRI study investigated the neural substrate which is associated with ideation and execution of a simple voluntary finger movement of the right hand. The findings indicate that different struc-

Table 1. Areas of significant activation during a) prespecified movement execution; b) voluntary movement execution; c) ideation of voluntary movement

Brain area - Brodmann area (BA)	L/R	BA	T	Talairach coordinates		
				x	y	z
a) Prespecified movement execution						
Post-central gyrus	L	2	12.48	-48	-30	56
	R	2	6.78	48	-28	40
Superior parietal lobule	L	7	11.99	-26	-50	64
	R	7	6.20	34	-46	58
Middle frontal gyrus	L	6	11.62	-6	-8	62
Cerebellum	L		5.62	-34	-52	-28
	L		4.49	-26	-60	-30
	R		9.11	26	-58	-30
			8.09	16	-52	-20
			7.60	16	-68	-26
Substantia nigra	R		4.31	-8	-22	-10
Inferior parietal lobule	R	40	5.50	32	-40	52
Thalamus	L		7.51	-12	-28	2
b) Voluntary movement execution						
Cingulate gyrus	L	32	5.01	-6	23	30
			4.95	-8	20	43
c) Voluntary movement ideation						
Inferior frontal gyrus	L	47	8.62	-53	21	-1
				-30	21	-16
				-40	23	-11
	R	47	5.24	44	25	-6
Inferior temporal gyrus	L	20	7.23	-50	-1	-29
Middle temporal gyrus	L	22	6.66	-63	-33	2
		21	6.59	-59	-51	-4
Superior temporal gyrus	L	22	4.94	-59	-50	12

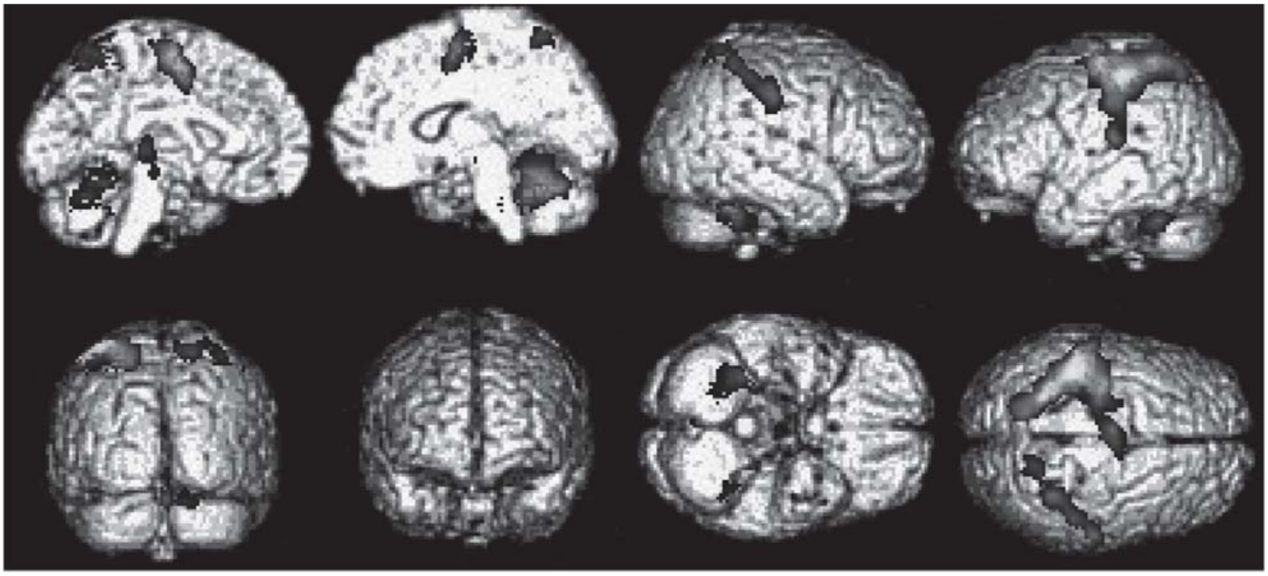

Figure 1. Areas of significant activation during the execution of a simple prespecified movement of the right index finger

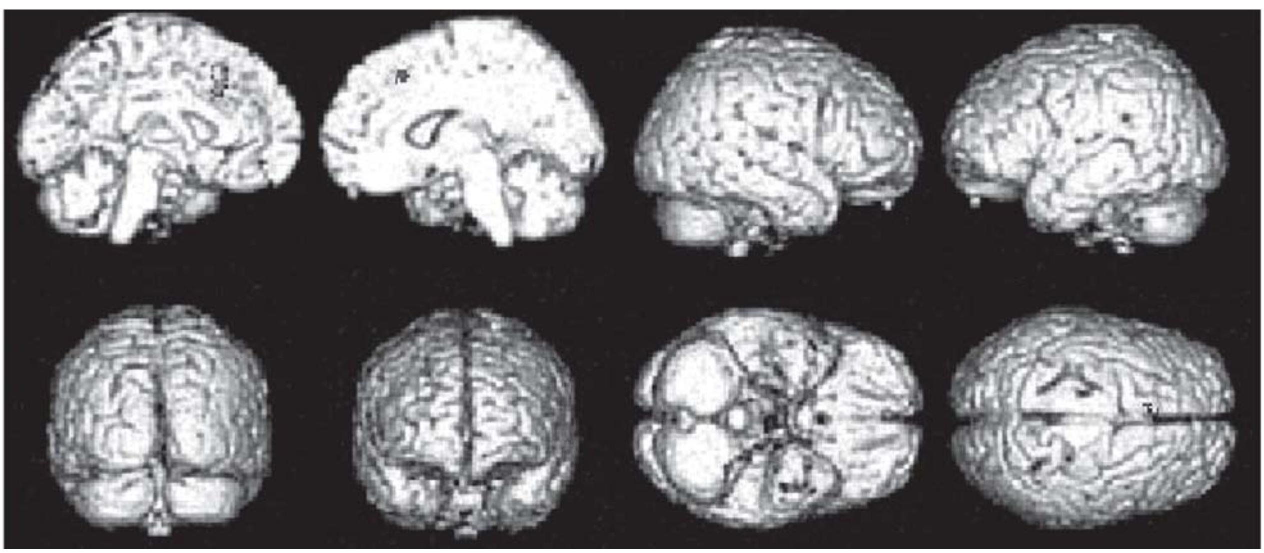

Figure 2. Area of significant activation in the left anterior cingulate cortex during the execution of a simple voluntary movement of the right index finger

tures are implicated in these tasks. The execution of a simple prespecified finger movement activated the left premotor cortex (BA 6), the bilateral primary somatosensory cortex (BA 2), the right associative temporo-parieto-occipital cortex (BA 40) and the superior parietal lobule bilaterally (BA 7). This latter is a structure which has a major role in visuo-motor coordination. Areas of significant increase in activation were also found in the cerebellum bilaterally, in the left thalamus and in the right substantia nigra. In line with the present findings, previous studies of this kind with human participants have shown activation of a large network of neural structures, all strongly connected with each other, including the supplementary

Figure 3. Areas of significant activation during the ideation of a simple voluntary movement of the right index finger

motor area (SMA), the somatosensory cortex, the cerebellum and the thalamus, during the execution of prespecified movements (1, 2, 7, 20).

Making a choice between two possible alternative simple movements of the right finger resulted in selective activation in the anterior cingulate cortex (BA 32). This neural structure has been shown to have a role in the control of attention, in monitoring and resolution of conflicts, as in one of the active conditions in this study that required a choice between two equivalent alternatives. There is additional evidence that significantly increased activation in the anterior cingulate has been detected in motor behaviour and interference tasks which involved high level of cognitive conflict (21, 22).

Ideation of a simple voluntary finger movement was associated with increased activation in orbito-frontal areas bilaterally (BA 47) and in the left inferior, middle and superior temporal gyri (BA 20, 21 and 22). The orbito-frontal region of the left hemisphere is strongly associated with the processing of verbal and written linguistic material. A few imaging studies have suggested that this area of the brain plays an important role in the processing of high-structured stimuli, which evolve over time, independently from their linguistic nature (23) and that is also the repository of more general semantic conceptual representations (24). Similarly, left temporal structures have also been shown to have a major involvement in semantic processing, including visual semantic representations (24-26). Activation of these inferior-frontal and temporal structures specifically in this condition suggests that the process of ideation of a simple voluntary movement needs support from a semantically based neural network.

Previous neuroimaging studies of movement ideation have always asked participants to imagine the execution of a prespecified simple movement, but none has asked people to ideate how to execute a movement of their choice without visualising the action, as it was the case in the present research. Those studies found that several structures associated with sensory-motor control, such as the SMA, the anterior cingulate, the premotor cortex, Broca's area, its homolog in the right hemisphere, and the posterior parietal cortex were involved during imagery of a prespecified movement (13, 14, 24). This network of structures is strongly implicated also during the preparatory phase of an action (7). Furthermore, a strong overlap between the neural areas involved in movement imagery and its execution was found (16). Activation of this set of neural structures did not appear in the condition of ideation of a simple voluntary movement. There was a substantial difference in the requirements of the condition used in this study and those of previous research in which participants were asked to imagine a prespecified movement as if they were actually doing it. It has been suggested that mental imagery of a specific movement requires the retrieval of its mental representation, which is considered by some authors as functionally equivalent to the preparation of its execution and characterized by activation of a high-order motor control neural circuit (25).

The process of ideation of a simple voluntary act, however, appears to be related to a different neuro-functional substrate. The finding of a prevalent involvement of structures which are primarily associated with the semantic representational system during voluntary movement ideation suggests the existence of an important link between the generation of a specific thought involving a movement and the activation of its related semantic concept. Indeed, ideation of a voluntary motor action would not be possible in the absence of its semantic knowledge.

In conclusion, the present findings showed that different brain regions were activated during the three experimental conditions of this study. Execution of a pre-specified movement activated higher level motor areas, in line with previous results. The anterior cingulate, a structure which has repeatedly been seen active when situations require resolution of conflict, showed increased activation in the condition requiring the execution of a simple voluntary action, a task that required the participants to make a choice between two possible alternatives. Voluntary movement ideation, in contrast, showed significant activation in a set of structures which were not seen by other studies, and these involved frontal and temporal associative areas, mainly in the left hemisphere, most likely because of their fundamental role in the planning and retrieval of semantic knowledge related to a voluntary act.

In summary, these data suggest that the process of ideation of a voluntary action is achieved by using a neural route independent from the brain areas responsible for motor behaviour *per se*, and mainly relies on semantic and conceptual processes. These findings provide some empirical support for the model of motor behaviour proposed by Gazzaniga et al. (5). They also suggest that the neuroanatomical circuit involved in movement ideation is located in fronto-temporal associative regions.

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