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Research report

Error processing during online motor control depends on the response accuracy

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ABSTRACT

We investigated which brain areas show error-related activity during online motor control while errors occur independently from decision making. During motor tasks, error is a deviation from accuracy or correctness. The effect of the accuracy level on error-related brain activity is unclear. Using functional Magnetic Resonance Imaging (fMRI), we investigated how error-related brain activity, especially in fronto-medial wall areas, depended on motor accuracy (MA). Subjects performed a force tracking task with the thumb–index grip: to continuously follow a moving target on a monitor with a cursor which position was controlled by the force amount produced by the fingers. Task difficulty varied with changes in the cursor size (the smaller the cursor, the more difficult the task). We measured the motor accuracy (mean distance between the cursor center and the target) and the error amount (cursor out of the target). Errors were produced when motor accuracy was low and also when motor accuracy was high. For fMRI data processing, we defined a model based on both the error amount and the motor accuracy. The results showed that supplementary motor area (SMA) and dorsal anterior cingulate cortex (ACC) activation increased with error and task difficulty independent of the accuracy of motor control. Interestingly, activity in the rostral part of left ACC only increased with error when the motor accuracy was low, independently from task difficulty. These results suggest a clear functional dissociation between dorsal and rostral ACC in error processing which depends on the amount of attentional resources allocated to motor accuracy.

1. Introduction

An error refers to an act, an assertion, or a belief that unintentionally deviates from what is correct, right, or true[1]. Errors during an action elicit a specific pattern of brain activity [18] generated in the fronto-midline cortical areas [6]. Until now, most of the neuroimaging studies have focused on error-related brain activity that were based on decision making paradigms [6,10,14,29,32]. It is difficult to isolate error-related brain activity in those studies since the tasks examined induce both errors and response conflict (subjects make a choice between several possible responses among which one is correct). Furthermore in daily life, error can occur without making the wrong choice. During online motor control, perception and action are intimately coupled in a closed-loop system. In that case, errors can occur when the motor response is not adapted to environmental constraints, or when the task requirements are greater than the individual motor abilities. In this study, we have investigated which areas in the brain show error-related activity during online motor processes while errors occur independently from decision making.

The anterior cingulate cortex (ACC) shows event-related activity following not only incorrect trials [17,48,50] but also correct trials when conflict monitoring increases in both cases [31]. Therefore, ACC activity has been attributed to control processes based on the co-activation of incompatible responses [4]. More generally, cognitive control theories report a role for the ACC in evaluating the gap between the current and desired response [4,5,33], or in allocating attentional resources [19,35] when a discrepancy occurs. In order to distinguish between these alternative hypotheses, we carried out an online motor control study eliciting errors while the amount of resource allocation to the task varied. If the role of the ACC in error processes is linked to attentional resource allocation, then error-related activity will depend on the requirements of the online motor control task, the resource allocation being shared between the motor output requirements and error processing. If the role of the ACC is a generic monitor of error occurrence (i.e., when a gap

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[1] Error (n.d.). *The American Heritage® Dictionary of the English Language, fourth edition.*

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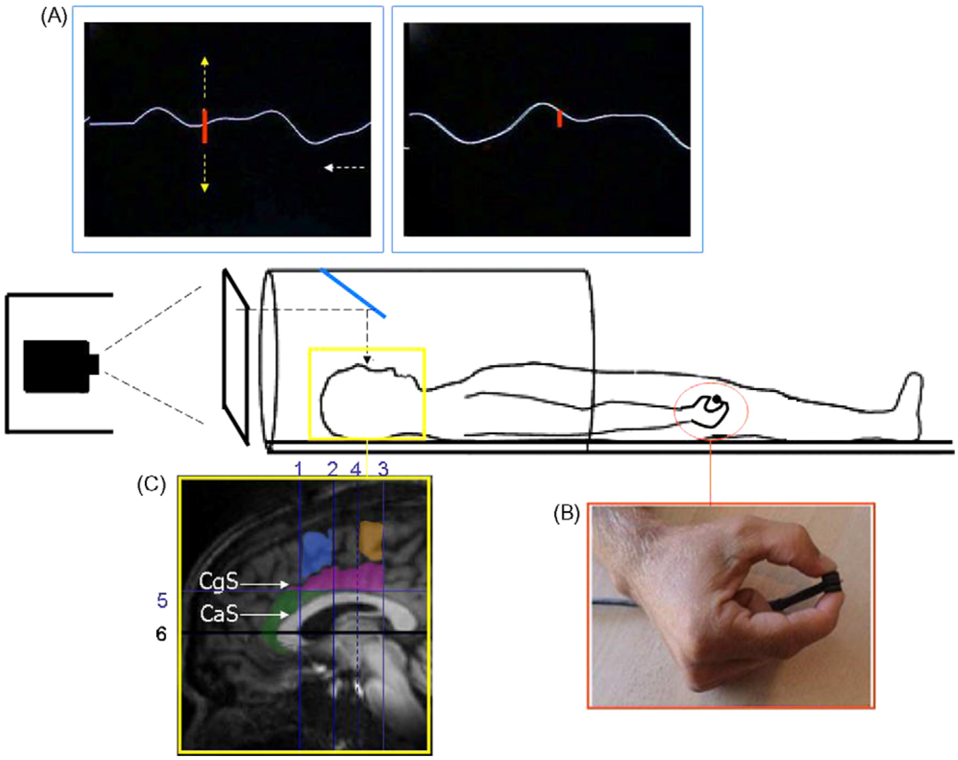

Fig. 1. Experimental setup and anatomical landmarks for the ROI analysis. (A and B) Behavioural task. The force transducer is held in a precision grip configuration between the thumb and index finger. The cursor goes up (down) when the subject increases (decreases) his precision grip forces. The curve is moving from the right to the left side of the screen (white arrow). The subject lying down in the scanner observes mirrors reflecting the task display (A), with one cursor size at a time (task display for the smallest = 0.2 N and the largest = 0.6 N cursor size). (C) ROI definition: (1) the vertical line passing through the most anterior tip of the inner surface of the genus of the corpus callosum (anterior border of the preSMA). (2) The AC line as the border between the preSMA (blue area) and the SMA proper. (3) The PC line as the posterior border of SMA proper. (4) The separation between the rostral and caudal SMA proper (orange area) located at the half distance of the AC–PC lines. 5: the perpendicular line to AC/PC plan passing through the superior border of corpus callosum is the separation between the rostral (green) and ventral ACC (pink). CgS, cingulate sulcus, CaS, callosal sulcus.

between the current and the desired response occurs), then the ACC activity will be related to error independently of the motor requirements.

Medial-frontal cortex shows error-related activity during continuous motor tasks [30]. The error-related activity could be due to the ACC activation, although the supplementary motor area (SMA) could also be involved. Online motor control requires the ability to adapt the motor output relative to feedback about the performance, processes in which SMA is involved. The SMA proper is activated relative to regulation of the motor command to fit the task aim [54], according to the direct projections that SMA proper has on primary motor cortex (M1) and interneurons/motoneurons in the spinal cord [13,20,39,40]. The preSMA is the part of SMA with more cognitive properties with connections to the prefrontal cortex, ACC, but not directly to M1 [40,51]. The preSMA is activated in response to an increase in motor planning demands and during action monitoring [17,40,54]. When errors are correctable, they can be used to adapt the motor output to the task constraints [14,19,42]. Those compensatory behaviours require increased motor planning demands and motor regulations, processes in which the preSMA and the SMA proper play a role. Thus, both of the preSMA and the SMA proper could be involved in behavioural adaptation to error during the perception/action cycle.

To identify the differential involvement of ACC and SMA sub-regions when errors occur during online motor control, we designed an fMRI (functional Magnetic Resonance Imaging) study to measure the Blood Oxygenation Level Dependent (BOLD) response related to errors during an online visuomotor control task. The task involved various difficulty and motor accuracy (MA) levels. Subjects had to track an irregular target curve (moving from the right to left on a computer screen) while controlling the vertical position of a cursor (centrally on the computer screen) using force production. Defining a contrast that cancelled the effect of task difficulty, we were able to show that ACC activity was related to error in a way that depended on the amount of resources allocated to the accuracy of the motor output. In contrast, activity in the right preSMA and left SMA proper always depended on the error amount and task difficulty, meaning that activity in these regions was related to online adaptation to fit the motor output to the perceptual constraints independent of the amount of available resources allocated to motor accuracy.

2. Material and methods

2.1. Subjects

Twelve right-handed volunteers participated in this study (5 females and 7 males; mean age of all subjects = 26.7 ± 4.8). They were screened for fMRI compatibility, gave written, informed consent, and compensated for their participation. The protocol was approved by the ethics committee of the Public Assistance of Paris Hospitals (CCPPRB RBM 01–04).

2.2. Behavioural task

Subjects were instructed to track an irregular moving curve with cursor. The position of the cursor was controlled by a hard force transducer. The force transducer was held between the thumb and the index fingers of the right hand. The mean force that subjects produced to control the cursor position for each experimental condition was 5 N. The applied forces were translated to the vertical position of the cursor, visible together with the curve on a screen (Fig. 1). Subjects were instructed to keep the cursor on the curve that moved from right to left on the screen. Task difficulty varied with 5 cursor sizes (0.2, 0.3, 0.4, 0.5 and 0.6 N), the physical cursor size corresponding to a safety margin of the force production to control the cursor relative to the target curve without error. The experiment contained 5 sessions (a