NeuroImage 44 (2009) 1369–1379

Contents lists available at ScienceDirect

NeuroImage

journal homepage: www.elsevier.com/locate/ynimg

Distinct striatal regions for planning and executing novel and automated movement sequences

J. Jankowski *, L. Scheef, C. Hüppe, H. Boecker

FE Funktionelle Neurobildgebung, Experimentelle Radiologie, Radiologische Universitätsklinik, Rheinische Friedrich-Wilhelms-Universität Bonn, Sigmund-Freud-Str. 25, 53127 Bonn, Germany

ARTICLE INFO

Article history:
Received 20 June 2008
Revised 26 August 2008
Accepted 24 October 2008
Available online 14 November 2008

Keywords:
Motor control
Movement
Motor planning
Event related fMRI
Basal ganglia associative loop
Caudate
Putamen

ABSTRACT

The basal ganglia-thalamo-cortical circuits are viewed as segregated parallel feed back loops crucially involved in motor control, cognition, and emotional processing. Their role in planning novel, as compared to overlearned movement patterns is as yet not well defined. We tested for the involvement of the associative striatum (caudate/anterior putamen) in the generation of novel movement patterns, which is a critical cognitive requirement for non-routine motor behavior. Using event related functional MRI in 14 right-handed male subjects, we analyzed brain activity in the planning phase of four digit finger sequences. Subjects either executed a single overlearned four digit sequence (RECALL), or self-determined four digit sequences of varying order (GENERATE). In both conditions, RECALL and GENERATE, planning was associated with activation in mesial/lateral premotor cortices, motor cingulate cortex, superior parietal cortex, basal ganglia, insula, thalamus, and midbrain nuclei. When contrasting the planning phase of GENERATE with the planning phase of RECALL, there was significantly higher activation within this distributed network. At the level of the basal ganglia, the planning phase of GENERATE was associated with differentially higher activation located specifically within the associative striatum bilaterally. On the other hand, the execution phase during both conditions was associated with a shift of activity towards the posterior part of the putamen. Our data show the specific involvement of the associative striatum during the planning of non-routine movement patterns and illustrate the propagation of activity from rostral to dorsal basal ganglia sites during different stages of motor processing.

Introduction

Nearly every aspect of motor behavior is composed of multiple individual movement elements arranged in a sequential fashion. The order and timing of this sequential arrangement needs to be constantly adapted and modified depending on situational requirements and varying motor context. Recent neuroimaging studies using event-related functional magnetic resonance imaging (fMRI) have provided evidence that the relevant brain regions for planning sequential procedures can be dissociated from those directly involved in execution. Planning-related brain activity, preceding execution-related activity, has been demonstrated in different cortical regions, in particular superior parietal, mesial and lateral premotor, and cingulate motor areas (Cunnington et al., 2002, 2003, 2005; Weilke et al., 2001). More recently, subcortical activity attributed to motor planning phases preceding sequential tasks could be identified with event-related fMRI (Boecker et al., 2008; Elsinger et al., 2006). Using region of interest (ROI) based analyses, Elsinger et al. were able to identify enhanced anterior putamen activity when externally specified finger sequences were held in memory for delayed subsequent execution (Elsinger et al., 2006), and our recent work, comparing self-initiated with externally triggered performance of one unique automated motor sequence, further highlighted the role of the contralateral anterior putamen for determining when to initiate movements (Boecker et al., 2008). Even more anteriorly located parts of the basal ganglia (caudate/adjacent anterior putamen), corresponding to the associative striatum (Nakano et al., 2000; Postuma and Dagher, 2006), are attributed to reasoning (Melrose et al., 2007), cognitive planning required to perform set-shifts (Monchi et al., 2006), or voluntary motor selection processes (Gerardin et al., 2004). Indeed, when voluntarily selecting with which body side to execute a simple button press, movement was associated with bilateral activation of the caudate nucleus, while preparing the movement was associated with anterior putamen activity, and execution with posterior putamen activity (Gerardin et al., 2004).

In this study, the aim was to further specify the functional role of the different basal ganglia territories in planning sequential movements. Rather than interrogating activation patterns related to determining effector sides, we specifically intended to characterize basal ganglia subregional recruitments required for planning novel (none-routine), as compared to overlearned (routine) movement

* Corresponding author. Fax: +49 228 287 14457.
E-mail address: jakob.jankowski@uni-bonn.de (J. Jankowski).

1053-8119/$ – see front matter
doi:10.1016/j.neuroimage.2008.10.059

patterns, which is an important component of adaptive motor behavior. A sequence generation task allowed us to deduce brain activity during the pre-movement phases and to directly compare activity during the planning of novel sequences with activity during the recall of one overlearned sequence. For this cognitive motor planning operation, we hypothesized specific involvement of the associative striatum (caudate nucleus/adjacent anterior putamen), in contrast to more posteriorly located putamen activation during the recall of overlearned movements. We further hypothesized posterior putamen activation during the execution phase of both motor conditions. An important premise of this study on motor sequence planning was that no explicit or implicit motor learning, evidenced in decreases of response-times, execution times and/or sequencing errors would occur during the course of the sequence generation task in the scanner. Motor learning was considered as an important confound since previous imaging studies (Bapi et al., 2006; Floyer-Lea and Matthews, 2004; Hikosaka et al., 2002; Jueptner et al., 1997; Lehericy et al., 2005; Poldrack et al., 2005; Toni et al., 1998) have unambiguously shown motor learning-associated basal ganglia activation shifts along a rostro-dorsal gradient.

Methods

Subjects

17 healthy male volunteers without a history of neurological or psychiatric disorder were enrolled in the study after informed and written consent. The study was approved by the local Ethics Committee of the University Hospital, University of Bonn, and in compliance with national legislation and the Code of Ethical Principles for Medical Research Involving Human Subjects of the World Medical Association (Declaration of Helsinki). Two measurements had to be excluded due to incomplete data acquisition (scan abortion) and one due to violation of task instructions despite previous training (see below). This resulted in a total sample size of 14 (mean age 26.7±5.9 years, range 19–41 years) right-handed (mean laterality quotient=0.96, range 0.86 to 1.00) male subjects, according to the Edinburgh Handedness Inventory (Oldfield, 1971).

Task instruction and training

Before the fMRI measurements, all subjects were familiarized with the experimental procedure and instructed to perform four-digit finger sequences with their left and right hands at a fluent and comfortable pace. Besides sequences that could be freely determined by the subjects (GENERATE), one particular sequence was specified (RECALL; see below). Subsequently, both, the self generation of sequences and the execution of the specified sequence were practiced during a training session, until a consistent performance with a minimum of errors (<5%) was achieved. Errors were defined as follows: less or more than four button presses per sequence, pressing the same button more than once per sequence or wrong effector side. For the RECALL condition, in addition any sequence of button presses other than the predefined sequence was considered an error, as well as any type of button press during the rest condition. Before the experiment started, subjects additionally rehearsed the tasks in the scanner.

Paradigm

The tasks consisted of finger sequences of four button presses, which were externally triggered by a visual cue for each individual trial. All sequences had to involve the index finger, the middle finger, the ring finger, and the little finger. Two major conditions were distinguished: an overlearned recall condition (RECALL), where subjects had to press the buttons in a predefined sequential order: index finger, ring finger, middle finger, and little finger; and a non-routine generate condition (GENERATE), where subjects had to generate novel orders of button presses at the beginning of each individual trial. Subjects were instructed to vary the sequences from trial to trial. Sequences had to be performed with either the left or the right hand, as instructed, resulting in four different movement conditions: $RECALL_R$, $RECALL_L$, $GENERATE_R$ and $GENERATE_L$.

For all conditions, each experimental trial consisted of the following elements (Fig. 1A):

1) A two seconds instruction (I), defined as the time during which a text was displayed, specifying the sequence mode (RECALL, GENERATE or REST) and, the effector side (R or L) (Fig. 1C).
2) An eight seconds time frame, during which the movement had to be started after a visual cue (see below). The available time was indicated by a horizontally oriented, continuously shrinking red bar, which was displayed at the centre position (Fig. 1C).
3) A 500 milliseconds color change of the red bar to green and back, which served as cue for the subject to start the finger sequence. This color change was programmed to appear at pseudo-randomized time points during the display of the shrinking red bar (mean 4.0 s, range 0.6 to 7.6 s after onset of the red bar). To ensure,

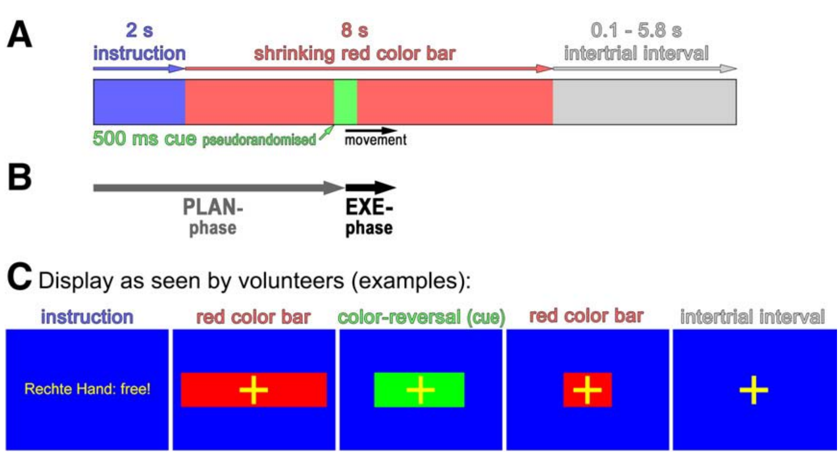

Fig. 1. Graphical display of the experimental paradigm. (A) Time scale and order of successive elements of one trial, which were identical for all conditions. The small black arrow (movement) below the bar indicates the execution of the finger sequence, with its onset delayed by the response time in respect to the onset of the cue (i.e. change of the color from red to green). (B) Arrows indicate the two phases modeled for data analysis in SPM5, a pre-movement "planning" (PLAN-) and a movement (EXE-) phase and are aligned with the trial elements shown above in A. (C) Illustration of display seen by the subject during one trial. Instructions were presented in German (background color blue, instruction and fixation cross yellow, color bar bright red and cue bright green).