

## Neural mechanisms of brain–computer interface control

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### ABSTRACT

Brain–computer interfaces (BCIs) enable people with paralysis to communicate with their environment. Motor imagery can be used to generate distinct patterns of cortical activation in the electroencephalogram (EEG) and thus control a BCI. To elucidate the cortical correlates of BCI control, users of a sensory motor rhythm (SMR)-BCI were classified according to their BCI control performance. In a second session these participants performed a motor imagery, motor observation and motor execution task in a functional magnetic resonance imaging (fMRI) scanner.

Group difference analysis between high and low aptitude BCI users revealed significantly higher activation of the supplementary motor areas (SMA) for the motor imagery and the motor observation tasks in high aptitude users. Low aptitude users showed no activation when observing movement. The number of activated voxels during motor observation was significantly correlated with accuracy in the EEG-BCI task ( $r = 0.53$ ). Furthermore, the number of activated voxels in the right middle frontal gyrus, an area responsible for processing of movement observation, correlated ( $r = 0.72$ ) with BCI-performance. This strong correlation highlights the importance of these areas for task monitoring and working memory as task goals have to be activated throughout the BCI session.

The ability to regulate behavior and the brain through learning mechanisms involving imagery such as required to control a BCI constitutes the consequence of ideo-motor co-activation of motor brain systems during observation of movements. The results demonstrate that acquisition of a sensorimotor program reflected in SMR-BCI-control is tightly related to the recall of such sensorimotor programs during observation of movements and unrelated to the actual execution of these movement sequences.

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### Introduction

Motor imagery uses the conscious effort of simulating movements without actually performing them in an overt fashion (Jeannerod, 1995; Decety, 1996). The concept of a functional equivalence between imagery of movement and the perception of performing goes back to the inception of the ideo-motor theory of thinking in the 19th century (Carpenter, 1874; Stock and Stock, 2004). Motor imagery is generally assumed to activate the same representations as the corresponding motor execution. For example, it has been shown that imagined and executed movements follow the same temporal constraints (Decety et al., 1989). Using motor imagery in a training program has even been shown to lead to measurable increases in the voluntary force production of one of the five digits (Yue and Cole, 1992). Conse-

quently mental practice of movement sequences activates similar brain areas as physical practice and also leads to improved performance when learning a sequence of foot movements (Lafleur et al., 2002; Jackson et al., 2003). There is some evidence that mental rehearsal may have rehabilitative effects in stroke and spinal cord injury (Malouin and Richards, 2010).

Brain–computer interfaces (BCIs) use voluntary control of brain activity in many applications (Kübler and Neumann, 2005). They were developed for people with neurodegenerative diseases, brain injuries or stroke that can lead to severe or complete paralysis. Various BCI paradigms have been proposed and three in particular have been evaluated with patients (mostly affected by amyotrophic lateral sclerosis (ALS), a degenerative disease of the first and second motor neurons leading to paralysis). BCIs are controlled by components of the electroencephalogram (EEG) (Berger, 1929) such as slow cortical potentials (SCPs) (Birbaumer et al., 1999), event-related potentials (ERPs, mainly the P300) (Nijboer et al., 2008b; Silvoni et al., 2009) and sensorimotor-rhythm (SMR) or  $\mu$ -rhythm (Kübler et al., 2005). Apart

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from restoring communication there is some evidence that motor imagery-based BCIs may have a rehabilitative effect in chronic stroke patients (Buch et al., 2008). It was shown that out of a sample of 8 patients, 6 were able to learn successfully to control an orthosis through a neuromagnetic BCI.

The SMR is a brain rhythm (8–15 Hz) located over sensorimotor areas and is insensitive to visual input (Kuhlman, 1978). Instead of one uniform rhythm the sensorimotor area generates a variety of rhythms that have specific functional and topographic properties. Distinct rhythms are generated by areas involving e.g. hand and foot movements over the postcentral somatosensory cortex with the strongest contributions originating from the somatosensory cortex of the hand (Hari and Salmelin, 1997; Pfurtscheller et al., 1997). Also associated with the sensorimotor system is a phase coupled second peak in the beta band (16–30 Hz) of the resting EEG over the precentral motor cortex anterior to the sources of the alpha component of the SMR (Hari and Salmelin, 1997). The alpha and the beta peak can become independent for example at the offset of a movement after which the beta band rebounds faster and with a higher amplitude than the alpha band (Pfurtscheller, 1981). Additionally, desynchronization of the beta band during motor tasks can occur in slightly different frequency bands than the subsequent synchronization (rebound) after the motor task (Müller-Putz et al., 2007). Both of these rhythms are desynchronized by overt and covert movement, planning and observation of movement and movement imagery. Specifically, the sensitivity to motor imagery renders the SMR a useful control signal for BCIs (Blankertz et al., 2008, 2010; Kübler et al., 2005; Neuper et al., 2003; Neuper et al., 2009; Nijboer et al., 2008a). Consequently SMR based BCIs are a useful tool for measuring the effectiveness of regulating the thalamocortical system responsible for SMR-modulation through motor imagery.

In the current study we aimed at elucidating differences in the cortical network between high and low aptitude users during BCI performance using motor imagery. To achieve this goal we identified 10 high and 10 low aptitude BCI users in an fMRI study. The 20 participants were recruited from the participant pool ( $n=80$ ) that participated in the study of Blankertz et al. (2010) and were assigned to the group of high or low aptitude users according to their performance in the EEG-BCI experiment (median split). Functional MRI was measured on average 2 weeks after the EEG experiment, never on the same day, and comprised a motor imagery, motor execution and motor observation task.

Motor imagery and motor observation have been extensively studied with fMRI and other brain imaging techniques such as positron emission tomography (PET) (see Lotze and Halsband (2006) for a review). The results indicate that neural networks similar to those of executed movements are activated by imagery and observation of movement (Decety et al., 1994). Differences in activations between motor imagery and motor execution tasks have been found in bilateral premotor, prefrontal, supplementary motor and left posterior parietal areas as well as the caudate nuclei (Gerardin et al., 2000). The individual capacity to imagine movements has also been studied previously with imaging techniques. Stronger activations in high aptitude than in low aptitude motor imagery performers were found in parietal and ventrolateral premotor regions and stronger activations for low as compared to high aptitude performers in the cerebellum, orbito-frontal and posterior cingulate cortices indicating that low aptitude users unsuccessfully compensate a reduced activation of motor areas with activation of cortical areas not directly related to movement execution or imagery (Guillot et al., 2008). In the previously described study motor imagery ability was assessed using questionnaires and physiological measures based on peripheral autonomic responses such as skin resistance. In a comparison of professional and amateur musicians the participant's level of expertise coincided with focused activations in the SMA, the superior PMC, more anterior areas (Larsell's lobule HVI) in the left

cerebellar hemisphere and bilateral superior parietal areas whereas amateurs showed less focused and thus more widespread activations while playing and not imaging of a well trained musical piece (Lotze et al., 2003).

Taking into account the positive correlation between the resting SMR power and later BCI performance found in Blankertz et al. (2010), we hypothesized that high aptitude BCI users would recruit and activate to a larger extent the motor network known to be involved in motor imagery, namely premotor and supplementary motor areas. We further predicted that we would find such differences to a lesser extent during the motor observation task. During observation participants were asked to image the observed movement. We assumed that this would be easier than motor imagery alone. Finally, we hypothesized that the recruitment and activation of motor areas as measured with fMRI would predict performance in the BCI controlled by electrocortical signals.

## Methods

### Participants

Twenty healthy participants (7 female and 13 male, mean age 24.5 years,  $SD \pm 3.7$ , range 19–36) took part in the study which was approved by the Internal Review Board of the Medical Faculty, University of Tübingen. Each participant was informed about the purpose of the study and signed informed consent prior to participation. Additionally, each participant signed a form informing him or her about potential risks and exclusion criteria of functional magnetic resonance imaging. Participants were compensated with 8 €/h. All participants were naive with regards to SMR-BCIs, had no history of neurological diseases and were German native speakers. Both groups participating in the experiment had equal levels of intelligence as measured using Raven's standard progressive matrices (mean 66.75, high aptitude users 71.9, low aptitude users 61.6, Wilcoxon rank test  $p=0.4$ ) (Raven et al., 2003). The datasets of three participants had to be excluded from the analysis. The dataset of VPTAB was incomplete, an incidental finding was discovered in the anatomical scan of VPTBJ (a large portion of the right hemisphere was missing making normalization impossible) and a scanner artifact made the data collected from VPTBS obsolete (frontal signal extinction possibly caused by radio frequency spike artifacts during acquisition due to a mechanical defect). A detailed overview of all participants can be found in Table 1.

### Procedure

#### EEG-BCI and neurofeedback

All 20 individuals were selected from the sample ( $n=80$ ) described by Blankertz et al. (2010). The EEG data for the SMR-BCI experiment was recorded in a single session. This session included the following tasks and provided the basis for the selection of the participants for the fMRI experiment. Details on the EEG experiments can also be found in Table 2. Firstly, ocular (eye movement, blinking) and EMG artifacts (maximum contraction of the hands) were measured followed by 10 trials of 15 s each in which the resting EEG was recorded and the participants had eyes open and closed according to auditory cues.

Secondly, EEG was recorded during observation of movement in which the participant was instructed to attend to videos of 10 s length. Videos were showing either a left or a right hand squeezing a ball or two feet moving their toes, all recorded from a first person's perspective. Twenty red movement observation trials of each type of movement were presented in random order, resulting in 60 trials per participant. The participants were instructed to mentally imitate the observed movement from a first person's perspective as opposed

**Table 1**

Description of participants that took part in the fMRI and EEG experiment. High aptitude EEG-BCI users are marked with \* in the corresponding column. Whether left hand (LH), right hand (RH) and/or feet (F) imagery was used by the participant is indicated by \* in the corresponding column. The time between the EEG experiment that determined the performance categorization and the fMRI experiment is indicated in days. Means and sums are depicted at the bottom of the table for the entire group and for the remaining participants after exclusion of 3 data sets (lowest two rows).

Participant	Male/female	Age (years)	EEG-BCI performance (%)	High apt.	LH	RH	F	Imagery performed	Time between sessions (days)	Invalid session
VPTAB	M	26	99	*	*	*		Fingers touching	7	Yes
VPTAD	M	23	100	*	*		*	Fist/Toes	5	No
VPTAE	F	22	83	*	*	*		Violin	10	No
VPTAJ	M	22	70		*	*		Wrist/Threading	21	No
VPTAK	F	23	64		*		*	Squeeze ball/Sand	11	No
VPTAL	F	22	70		*	*		Climbing grip	10	No
VPTAO	M	23	86	*	*		*	Fist/Toes	13	No
VPTAQ	F	30	94	*	*	*		Spread fingers	15	No
VPTAT	F	25	77		*		*	Fist/Toes	16	No
VPTBE	F	26	56			*	*	Flamenco/Toes	47	No
VPTBJ	M	22	91	*	*	*		Spread Fingers	2	Yes
VPTBL	M	25	51		*		*	Guitar/Toes	30	No
VPTBN	M	22	68		*		*	Climbing grip/Toes	16	No
VPTBO	F	20	81			*	*	Turn hand/Toes	23	No
VPTBP	M	22	85	*	*	*		Fist	16	No
VPTBQ	M	28	54			*	*	Fist/Toes	18	No
VPTBR	M	23	98	*	*	*		Fist	5	No
VPTBS	M	36	50		*	*		Fist	2	Yes
VPTBT	M	24	88	*		*	*	Fingers/Toes	6	No
VPTBU	M	19	97	*	*	*		Kneading	4	No
Ø (high/low):	–	23(23/23)	78 (91/64)	–	–	–	–	–	14 (8/19)	–
Σ (high/low):	13(8/5)/7(2/5)	–	–	20(10/10)	16(9/7)	14(8/6)	10(3/7)	–	–	3(2/1)
Ø (high/low):	–	22(23/21)	78 (91/66)	–	–	–	–	–	16 (9/21)	–
Σ (high/low):	10(6/4)/7(2/5)	–	–	17(8/9)	15(7/6)	11(6/5)	10(3/7)	–	–	0

to a distanced, evaluative observation of the displayed movement from a third person perspective (Zentgraf et al., 2005).

Thirdly, participants were asked to execute left hand, right hand or foot (preferred side) movement according to arrows on the screen pointing to the left, right or down. The movement execution trials lasted 8 s, and after every 15 trials a break of 15 s allowed the participants to rest. Twenty-five red movement execution trials per condition were presented.

Finally, participants were asked to imagine movement according to the cues. The participants were specifically instructed to use kinesthetic and not visual movement imagery (Neuper et al., 2005). The feeling one has when moving feet in sand was provided as an example of kinesthetic imagery to all participants. It was emphasized that the focus of the imagery should be the kinesthetic sensation. The imagined movement could be freely chosen by the participant as long as it was restricted to the three body parts (e.g. playing the piano with either the right or left hand). The length of trial and pause were the same as during movement execution. Twenty-five red movement imagery trials per condition (left hand, right hand, foot) were presented per run and altogether participants performed three runs. At the end of the three runs participants were asked what kind of imagery they performed. The data of these runs was used to calibrate the classifier needed for the feedback runs. In between runs the participants performed a computerized version of the d2-concentration-test (Brickenkamp and Zillmer, 1998).

**Table 2**

Details of EEG experiments. Each participant performed motor execution, observation, imagery used for calibration of the classifier of the BCI and finally imagery feedback with the optimal combination of two of the three classes (right hand vs. left hand, right hand vs. foot or left hand vs. foot).

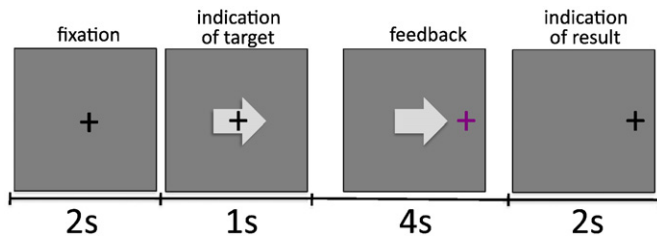
Motor task	Trial duration	Trials/class	Number of classes
Execution	8 s	25	3
Observation	10 s	20	3
Imagery calibration	8 s	75	3
Imagery feedback	9 s	150	2

In the final stage of the EEG experiment feedback was provided in three runs of 100 trials each (VPTAB, VPTAD and VPTBO only performed one feedback run due to fatigue). The two imagery classes that provided best classification results based on the data from the previous three imagery runs were used for feedback. The classes were selected based on the method described by Blankertz et al. (2010). The participants were informed about which classes were selected and instructed to use them to control the BCI. A black fixation cross on a gray background appeared in the center of the screen for two seconds. Then an arrow indicated for one second which type of imagery should be performed: the arrow pointed left for left hand and right for right hand motor imagery, and downward for foot movement imagery. Finally, the black cross turned purple, indicating the beginning of feedback, and started moving for four seconds dependent upon SMR-decrease. After a pause of two seconds, in which the cross was frozen in its last position, the cross was reset to the center of the screen (see Fig. 1). If the last position of the cross was in the direction that the arrow had pointed the trial was classified correctly. Correctly classified trials were counted, the result was presented to the participant after every 20 trials, and a break of 15 s followed. The overall percentage of correct trials was defined as correct response rate. This correct response rate was then used to split the participants into high aptitude users and low aptitude users.

Participants participated in the fMRI session depending on individual willingness and suitability. The fMRI session was conducted on average 13.9 days after the EEG experiment. During fMRI recording participants performed motor imagery, execution, and observation with the two classes used during the EEG session.

#### fMRI recording

Each participant performed a motor imagery, observation and execution experiment in the fMRI. Each experiment was repeated once, resulting in a total of six measurements (two of each task) per participant. One of the experiments consisted of seven blocks of 30 s in which participants were required to perform the motor tasks used



**Fig. 1.** Design of the EEG feedback paradigm used in this study as described by Blankertz et al. (2010). A black fixation cross on a gray background appeared on the screen for 2 s. Then an arrow indicated for 1 s which type of imagery should be performed: the arrow pointed left for left hand and right for right hand motor imagery, and downward for foot movement imagery. Finally, the black cross turned purple, indicating the beginning of the feedback, and started moving for four seconds dependent on the SMR-decrease and increase. After a pause of 2 s, in which the cross was frozen in its last position, the cross was reset to the center of the screen. Only the two imagery classes of each participant that provided best classification results during the calibration runs were used for feedback.

during feedback in the EEG experiment. Since each experiment was repeated this lead to 14 blocks per motor task. Each motor task block was followed by a 30 s resting period (block design; see Fig. 2).

Instructions on what task to perform (imagery/execution/observation of left hand/right hand/foot) were projected into the scanner using a system of mirrors positioned on the head coil. The instructions remained on the screen throughout the 30 s block. In case of motor observation the written instructions were replaced with the corresponding video.

To account for order effects, half of the participants started with a resting period instead of a movement task. Of the 17 valid datasets eight began with the resting period. Of these eight, four were high and four low aptitude users.

Finally, an anatomical T1 scan was conducted lasting about 6 min.

#### Data acquisition

##### EEG recording

During the EEG experiment the participants were seated in a comfortable chair approximately 1 m in front of a computer screen on which the cues and feedback were displayed. The EEG was recorded

with four 32 channel Brainamp DC amplifiers manufactured by Brainproducts, Munich, Germany. One hundred nineteen Ag/AgCl electrodes in a 128 channel cap manufactured by Easy Cap, Munich, Germany, were positioned according to the extended 10-20 system (Sharbrough et al., 1991), referenced to the nasion and grounded to an electrode between Fz and Fpz. The EEG was sampled at 1000 Hz with a band-pass filter of 0.05 Hz to 200 Hz and a notch filter at 50 Hz. To monitor muscular artifacts electromyography (EMG) was recorded with electrodes on both forearms and the participants preferred leg. Eye movement and blinks were recorded with electrodes placed above and below the right eye for vertical EOG (superior and inferior orbital fossa), and for horizontal EOG with electrodes placed at the outer canthi of the eyes. This data was used to exclude artifact contaminated trials.

##### fMRI recording

The fMRI experiments were performed in a Siemens Magnetom Trio Tim 3 T whole body scanner using a standard 12 channel head coil.

##### Preprocessing of fMRI data

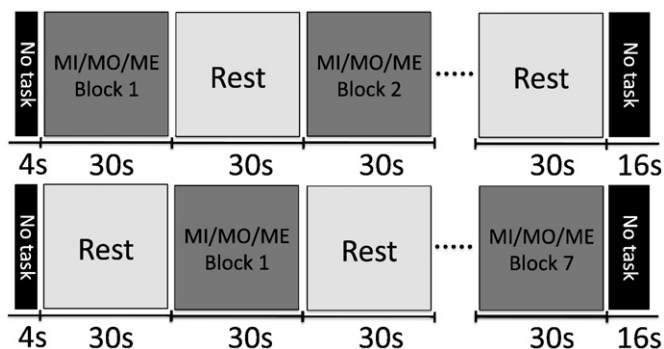
The fMRI data was analyzed using SPM 8 (Wellcome Trust Center for Neuroimaging, London, United Kingdom). After converting the raw images recorded by the scanner (DICOM) to SPM format the following preprocessing steps were performed. All functional images were spatially realigned to the first scan using a least squares approach and a 6 parameter (rigid body) spatial transformation. The chronologically first scan was chosen as reference scan. Then differences in functional image acquisition time were corrected between the slices in ascending order using the middle slice as reference. In the next step, the anatomical images were co-registered to the mean of the functional images using normalized mutual information as cost function. Additionally the anatomical images were normalized to the standard T1 template supplied with SPM 8 ( $3 \times 3 \times 3 \text{ mm}^3$ ) and regularized to a template of the International Consortium for Brain Mapping (ICBM). The functional images were subsequently normalized using the parameters of the anatomy normalization. Finally, all functional images were smoothed using a Gaussian smoothing kernel with full-width-at-half-maximum at  $8 \times 8 \times 8 \text{ mm}^3$ .

##### First level analysis of fMRI data

The first level (individual data) statistical analysis of the fMRI data was performed using general linear models (GLMs). The spatial realignment parameters from preprocessing were used as additional regressors. Additionally, a high-pass filter with a cutoff of 128 s was applied to remove slow drifts in the data. Serial correlations in the fMRI time series were accounted for using an autoregressive model (AR(1)). Each of the six runs (twice motor imagery, motor observation and motor execution) was specified as an individual session with two conditions for each combination of classes (right hand and left hand movement or right hand and foot or left hand and foot) and the resting conditions following the respective classes. The parameter estimates of each task and resting state of the two classes for each participant were used in the second level analysis.

##### Second level analysis of fMRI data

The contrast images including the parameter estimates of each voxel in the different conditions (of each subject) were entered into the second level group analysis. A  $2 \times 3 \times 3$  repeated measures ANOVA with the between subject factor group (high and low aptitude users) and the within subject factors condition (motor imagery, motor observation or motor execution) and body parts (left hand, right hand and foot) were performed using a full factorial analysis.



**Fig. 2.** During the MRI-procedure seven blocks of 30 s each were presented in which participants were required to perform a motor task, as previously performed during the EEG recording. The tasks were either motor imagery (MI), motor observation (MO) or motor execution (ME). Each motor task block was followed by a 30 s resting period (block design). Instructions on what task to perform (left hand/right hand/foot movement) were projected into the scanner and made visible for the participant by means of a system of mirrors positioned on the head coil. The instructions remained on the screen throughout the 30 s block. The tasks were presented in random order. To account for order effects, half of the participants started with a resting period instead of a movement task. Two non-task and non-rest scans were inserted at the beginning and eight at the end of each run (a total of 20 s). In total one run lasted 440 s.



### Extraction of hemodynamic response curves

The SPM toolbox Marsbar (version 0.42) was used to extract peri-stimulus time histograms for anatomically defined regions of interest (ROIs) based on finite impulse response (FIR) models (Ollinger et al., 2001). The time bins were set to the width of TR (2 s). Time points which had significantly different signal changes in percent between the two groups were marked with an 'x' in Fig. 7 (Wilcoxon rank sum test,  $n(\text{highaptitudeusers}) = 8$ ,  $n(\text{lowaptitudeusers}) = 9$ ,  $p < 0.05$ ) when plotting the peri-stimulus time histograms. Data was extracted from ROIs defined in the automated anatomic labeling (AAL) atlas (Tzourio-Mazoyer et al., 2002).

### Extraction of percentage of activated volume

Marsbar was also used to extract the volume activated during a specific task. The percentage of activated volume was defined as the number of voxels above an uncorrected significance threshold of  $p < 0.001$  divided by the total number of voxels. This value was extracted from the images of the first level analysis of the fMRI data for each participant individually and then correlated with the correct response rate achieved with the EEG-BCI (Pearson's  $r$ ,  $p < 0.05$ ). Data was extracted from ROIs as defined in the AAL atlas (Tzourio-Mazoyer et al., 2002).

### Anatomic localization

The SPM anatomy toolbox (version 1.6) was used to determine the areas of the functional differences between high aptitude and low aptitude users (Eickhoff et al., 2005, 2006, 2007).

## Results

### EEG-BCI online accuracy

Data from the EEG recording during feedback of motor imagery related brain activity was used to select participants for a group of high and low aptitude users. Ten high and 10 low aptitude users participated in the fMRI experiment. The 20 participants achieved a median performance of 82.1% in the EEG SMR-BCI feedback task. No gender effects were found in the EEG performance of all 80 participants ( $t_{(78)} = -.151$ ;  $p = .880$ ). Performance of low (64.2%) and high (91.2%) aptitude users differed significantly ( $t_{(20)} = 26.6$ ,  $p = 0.0$ ).

Participants were asked to report on the imagery strategies used during EEG feedback. Based on these reports the imagery strategies were categorized by one of the authors with respect to their complexity. According to this categorization, when the task was to perform imagery of movement of either the left or right hand, 53% of the participants performed imagery of clenching their own fist, 19% performed imagery of finger movements and 29% performed imagery of more complex movements like guitar playing or rock climbing. When the task was to perform imagery of foot movements 69% of the participants performed imagery of toe movement and 25% visualized foot movements. The imagery strategies did not lead to any significant differences in SMR feedback performance (hand:  $F_{2,77} = .254$ ;  $p = .776$ ; foot:  $t_{(73)} = -.262$ ;  $p = .794$ ). Therefore, we believe the complexity of motor imagery had no influence on BCI performance.

Participants employing right vs. left hand imagery achieved a higher performance (81.4% accuracy) than participants using one of the two hands vs. foot (70.5% accuracy;  $t_{(78)} = 2.734$ ;  $p < .01$ ).

A neurophysiological predictor based on an estimation of the SMR amplitude measured on two Laplacian filtered EEG channels recorded during 2 min of rest with eyes open was calculated for the 20 participants. Compared to the correlation of the EEG performance predictor with correct response rate with a Pearson's  $r = 0.53$  of the

whole sample described by Blankertz et al. (2010), a correlation of a Pearson's  $r = 0.73$ , was found for the subpopulation in this study (see Fig. 3); the correlations are not significantly different (z-test on the z-transformed  $r$ -values ( $p = 0.21$ )).

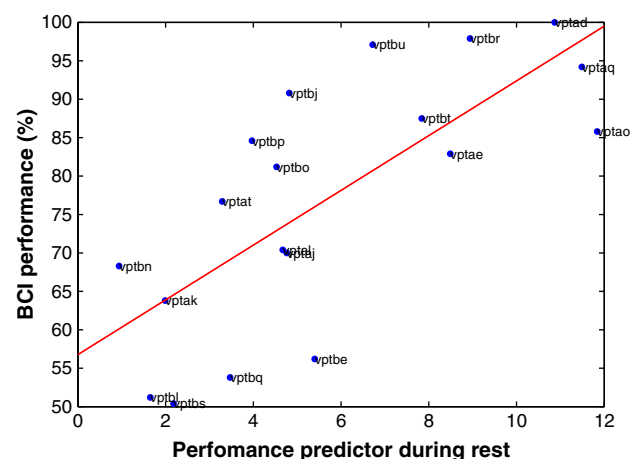
### fMRI results

Figs. 4 (motor imagery), 5 (motor observation), 6 (motor execution) show mean group activation maps separately for tasks and user groups and the group comparison contrasts between high aptitude users and low aptitude users. Low aptitude users > high aptitude users comparisons (the > indicates that comparisons showing higher values for the first group are made) for motor imagery and motor observation showed no voxels above the threshold of an uncorrected  $p$ -value smaller than 0.001 and a cluster size of at least 10 voxels (54.45 mm<sup>3</sup>), whereas for motor execution the low aptitude users > high aptitude users contrast showed active voxels.

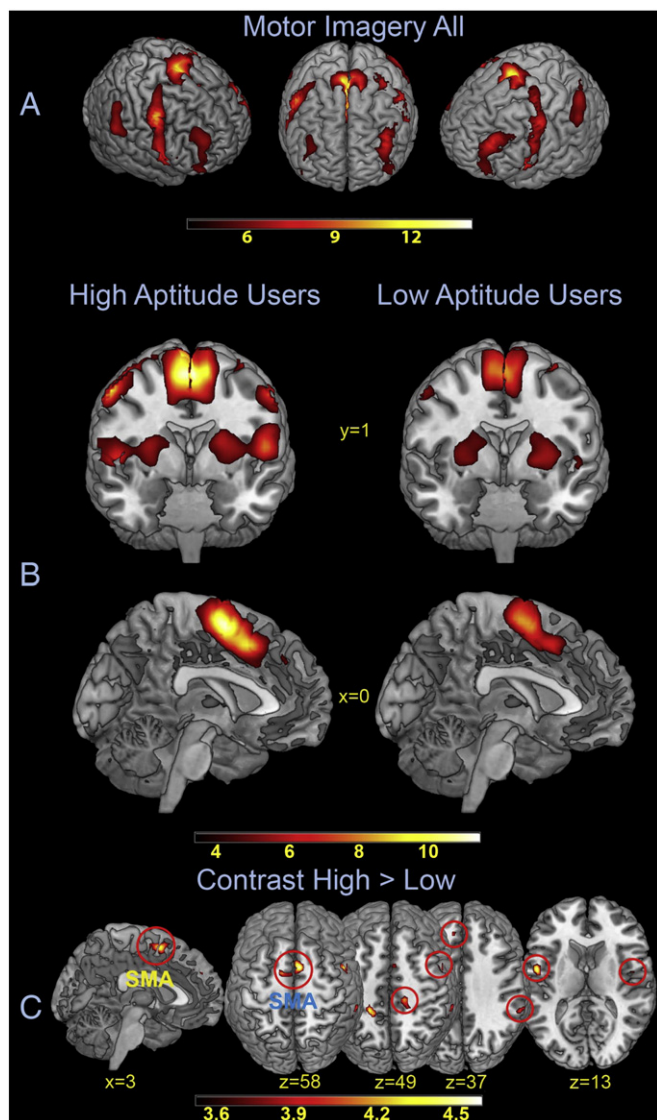
During motor imagery areas activated by both groups included SMA, right and left primary motor cortex, right and left middle frontal gyrus and right and left inferior parietal lobule. High aptitude users had stronger activations (marked with a red circle in Fig. 4) in left and right rolandic operculum, left superior medial gyrus, right supramarginal gyrus, right middle cingulate cortex, right precentral gyrus and the SMA. Not marked in Fig. 4 are activations in the left superior frontal gyrus and the right middle frontal gyrus. The inverse contrast, low aptitude users > high aptitude users showed no activated voxels above threshold (see Fig. 4).

Areas activated by both groups during motor observation included SMA, right and left primary motor cortex, right and left inferior parietal lobule and right and left inferior occipital gyrus. High aptitude users had stronger activations (marked with a red circle in Fig. 5) in left inferior temporal gyrus, right superior temporal gyrus, right medial frontal gyrus and the SMA. Not marked in Fig. 5 are activations in right precentral gyrus and right middle frontal gyrus. The inverse contrast, low aptitude users > high aptitude users showed no activated voxels above threshold (see Fig. 5).

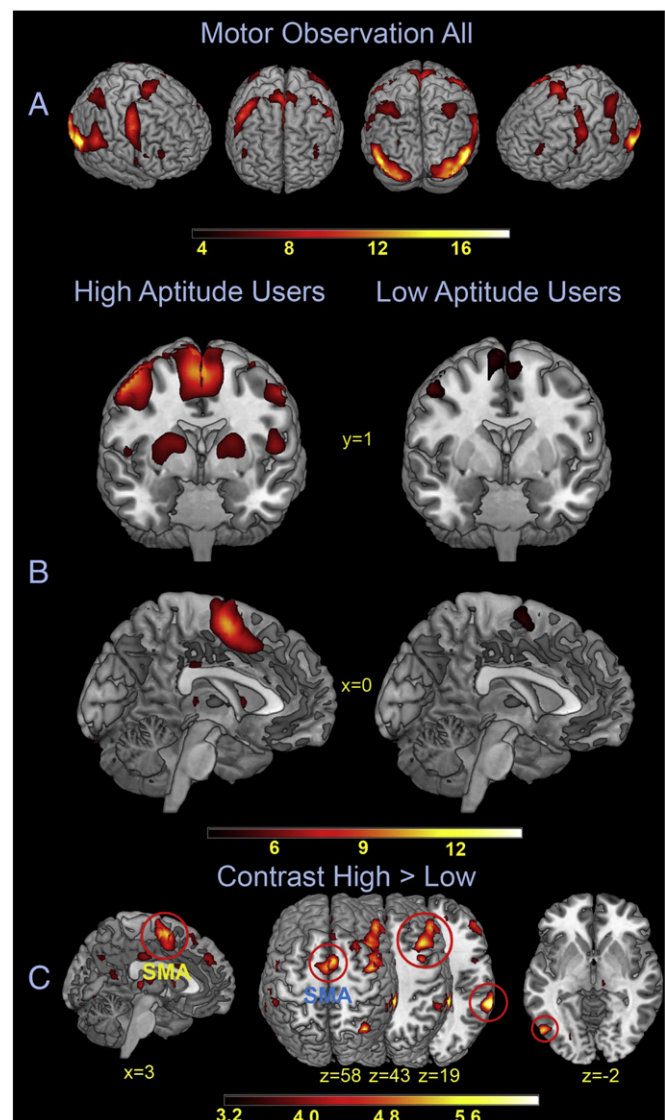
When performing the motor execution task, areas activated by both groups included SMA and right and left primary motor cortex. High aptitude users had stronger activations (marked with a red circle in Fig. 6) in the left and right hippocampus as well as the left



**Fig. 3.** BCI performance (percentage of correctly classified trials) is plotted against the performance predictor value (based on the power in the regulated alpha or beta band) for each of the 20 participants (labeled with the participant code from Table 1). The predictor is based on an estimation of the SMR amplitude measured on two Laplacian filtered EEG channels recorded during 2 min of rest with eyes open (Blankertz et al., 2010). It reaches a correlation of  $r = 0.73$  with BCI performance in this sample.



**Fig. 4.** Brain activations in motor imagery task, showing mean activation of all participants (A), high aptitude users and low aptitude users individually (B) and the contrast of high aptitude users > low aptitude users (C). Areas discussed in the main text are marked with a red circle. The color bars represent the *t*-values. All images are superimposed on a normalized canonical image (ch2better template) using the MRIcron software.



**Fig. 5.** Brain activations in motor observation task, showing mean activation of all participants (A), high aptitude users and low aptitude users individually (B) and the contrast of high aptitude users > low aptitude users (C). Areas discussed in the main text are marked with a red circle. The color bars represent the *t*-values. All images are superimposed on a normalized canonical image (ch2better template) using the MRIcron software.

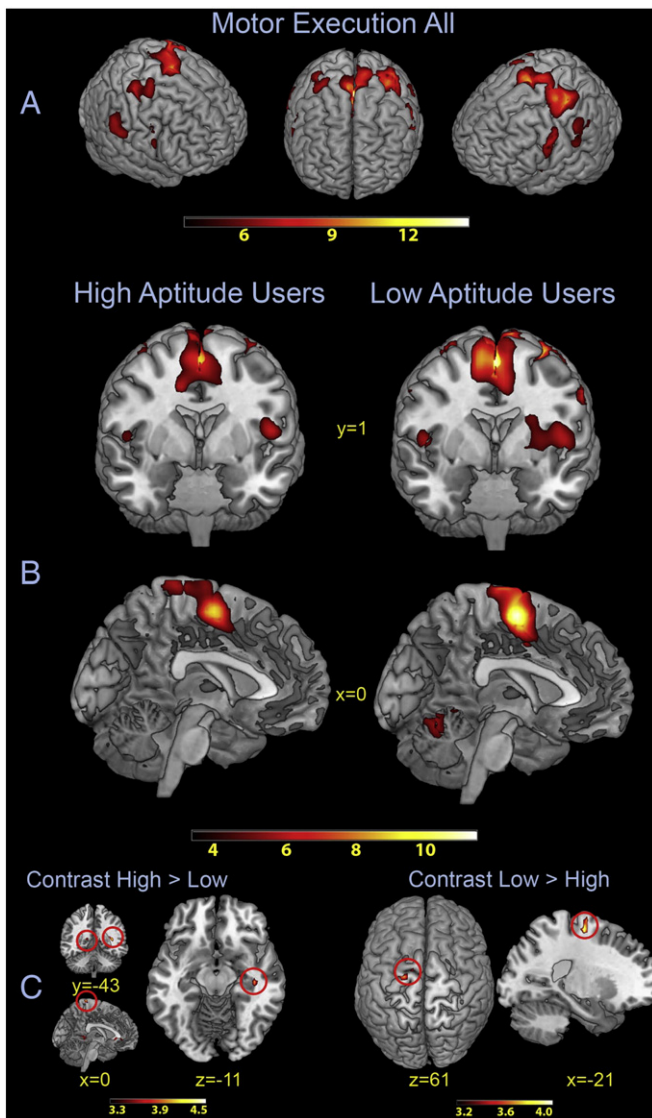
paracentral lobule (Brodmann area, BA 4a). Not marked in Fig. 6 are activations in left anterior cingulate cortex, left middle orbital gyrus, right inferior temporal gyrus and right cerebellum. The inverse contrast low aptitude users > high aptitude users revealed higher activations in BA 6 (see Fig. 6).

A full list of the activated areas during motor imagery, motor observation and motor execution is provided in the supplementary materials for high aptitude users, low aptitude users, high aptitude users > low aptitude users and low aptitude users > high aptitude users.

#### Hemodynamic response curves

Differences in activated voxels and signal change between high aptitude users and low aptitude users were strongest in the SMA for both motor observation and motor imagery. Therefore, we selected this area for a closer examination of the hemodynamic response

curves which illustrate the signal change and the temporal characteristics of the response. Values in percent signal change are shown for all voxels in the ROI corresponding to the location of the SMA in Fig. 7 ((A) motor imagery, (B) motor observation, (C) motor execution). For the motor imagery task both groups showed a similar time course but the percent signal change achieved was higher for the high aptitude users group 10–30 s after task presentation. After the task terminated at 30 s activation levels for both groups were identical. The maximum signal change was 0.4% for high aptitude users in both motor imagery and motor observation. In contrast, there was almost zero signal change for the low aptitude users group during motor observation. As a consequence the time points with significant differences (percent signal change between high aptitude users and low aptitude users, Wilcoxon rank test,  $p < 0.05$ ) extended beyond the end of the task after 30 s until the activation of the high aptitude users group returned to baseline. In the motor execution task both high and low aptitude users showed similar activation



**Fig. 6.** Brain activations in motor execution task, showing mean activation of all participants (A), high aptitude users and low aptitude users individually (B) and the contrast of high aptitude users > low aptitude users and low aptitude users > high aptitude users (C). Areas discussed in the main text are marked with a red circle. The color bars represent the  $t$ -values. All images are superimposed on a normalized canonical image (ch2better template) using the MRIcron software.

curves with only one time point being significantly different in the right SMA about 9 s after task initiation.

#### Correlation of activated volume with correct response rate

The differences in activated voxels ( $p < 0.001$  uncorrected) extracted for each participant individually are depicted in Fig. 8. The low aptitude users activated about 5% of whole volume of the brain (all measured voxels) in all three tasks. In contrast the activated volume differed substantially between the tasks for the high aptitude users, ranging from 5.21% in the motor execution task, 7.64% in the motor imagery task and 11.48% in the motor observation task. The mean difference between these values for high aptitude users and for low aptitude users was significant for the motor imagery and the motor observation task (Wilcoxon rank sum test, high aptitude users  $n = 8$ , low aptitude users  $n = 9$ ,  $p < 0.05$ ). A correlation between the activated volume with correct response rate in the EEG-BCI task was

significant for the motor observation task ( $r = 0.52$ ,  $p = 0.03$ ). A significant correlation for the motor imagery task and correct response rate was obtained if the outlier visible in the scatterplot in Fig. 8 was removed ( $r = 0.59$ ,  $p = 0.02$ ). Higher correlations were found for individual ROIs (see Fig. 9). The number of voxels activated by the motor imagery task in the right precentral gyrus significantly correlated with correct response rate ( $r = 0.65$ ,  $p = 0.01$ ). In the right middle frontal gyrus the number of voxels activated during the motor observation task correlated strongest with BCI-performance ( $r = 0.72$ ,  $p = 0.00$ ).

#### Movement during motor imagery task

The significant differences between high and low aptitude users during motor imagery and observation but not during motor execution indicate that no motor execution was performed during motor imagery and observation tasks. To validate the compliance with the instructions we extracted the BOLD response from the lobulus V in the left cerebellum and the right M1 from left hand motor imagery and execution trials. Lobulus V was chosen because it has been shown to be active during hand and arm motor execution tasks and not during imagery of the same task (Gross et al., 2001). The regions of interest from which the BOLD response was extracted were constructed using the volumes defined in the automated anatomic labeling atlas for the left lobulus V and precentral gyrus in a cross-section with the activation in this region during motor execution. The activation during motor execution was stronger and had a larger post-stimulus undershoot as compared to motor imagery and observation, again indicating, that no motor execution was performed during imagery and observation (see Fig. 10).

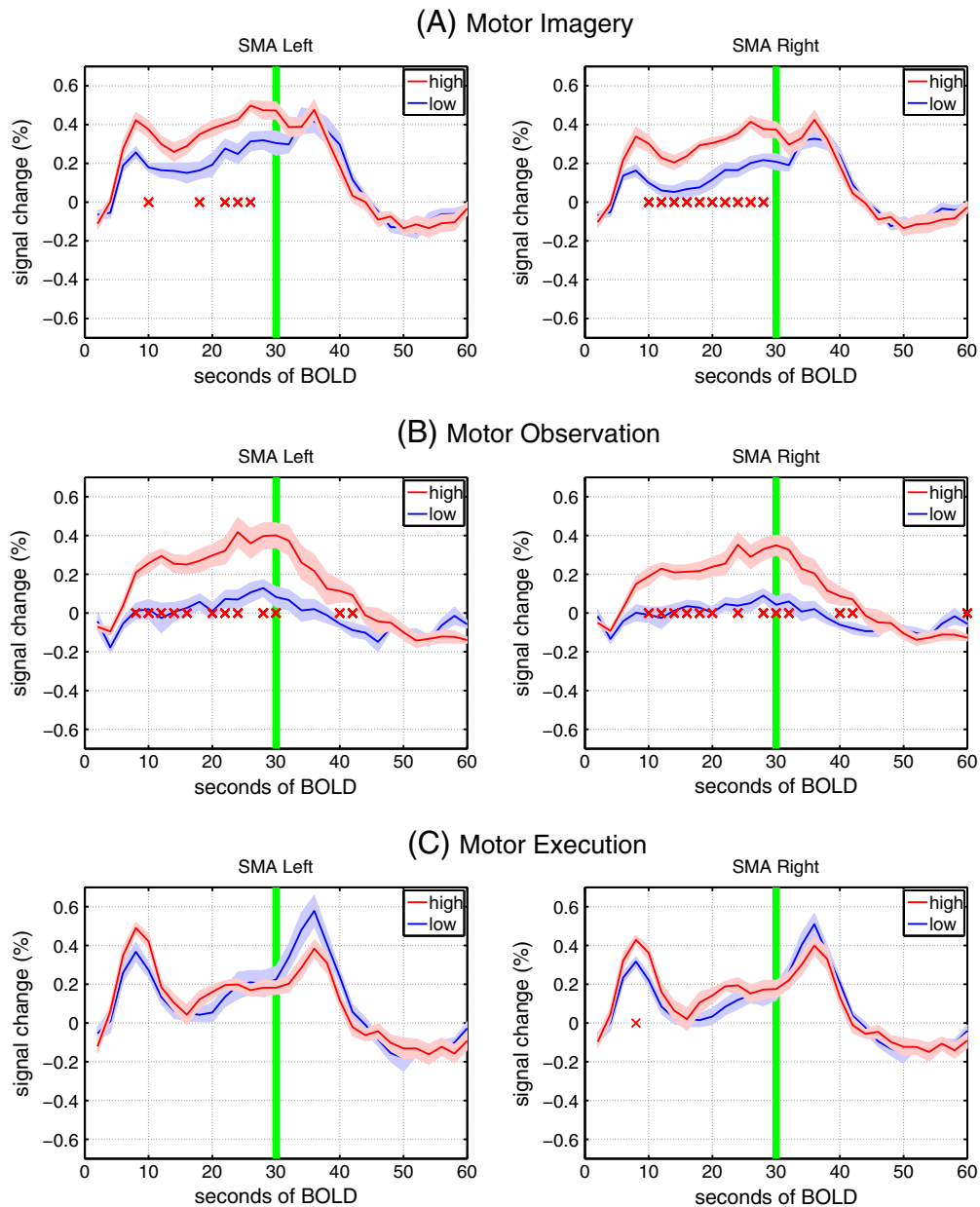
#### Time period between EEG and fMRI measurement

Unfortunately the time between the EEG and the fMRI measurement varied considerably between participants from 2 to 47 days. To ensure that this factor has no influence on our data and that the differences found between the groups are due to EEG-BCI performance and not time between measurements we compared the BOLD response of the participants with a below median time between EEG and fMRI measurement with those with an above median time. The results are shown in Fig. 11 for the SMA. During motor execution and observation there are no significant differences between the short and the long time period group, during motor imagery there are two only time points which are significantly different. This supports the assumption that the differences found in the SMA are caused by BCI performance instead of time.

#### Discussion

We succeeded to show that there were significant differences in the functional activation measured during an motor imagery and motor observation task between two groups of participants that were split according to their performance with an EEG imagery-based BCI. The activation in the right middle frontal gyrus during motor observation and precentral gyrus during motor imagery correlated significantly with task performance in a BCI session based on motor imagery which was conducted several days prior to the fMRI recording. Of all motor areas, the SMA showed the strongest differences in a group comparison of the fMRI data. The BOLD signal showed a higher amplitude in percent signal change for high aptitude users. Additionally, the extent of the volume activated during the motor imagery and the motor observation task was significantly different between the two groups while it was the same for the motor execution task. In both motor observation and motor imagery high aptitude users recruited more volume in premotor and prefrontal areas to accomplish the task.





**Fig. 7.** Time course of BOLD in SMA during motor imagery (A), motor observation (B) and motor execution (C) tasks in red for high aptitude users and in blue for low aptitude users. The green line indicates the termination of the task after 30 s. The red marks indicate significantly different means.

#### Location of the body representation

The lack of differences between high and low aptitude users during motor execution in the hemodynamic response of the SMA and also in the activated volume confirmed that the differences found in the motor imagery and the motor observation tasks were not related to the different body parts chosen by the participants to control the EEG-BCI (left hand, right hand, feet). It also serves as a general confirmation of identical measurement quality and the absence of other non-task related influences that might affect a comparison between the two groups.

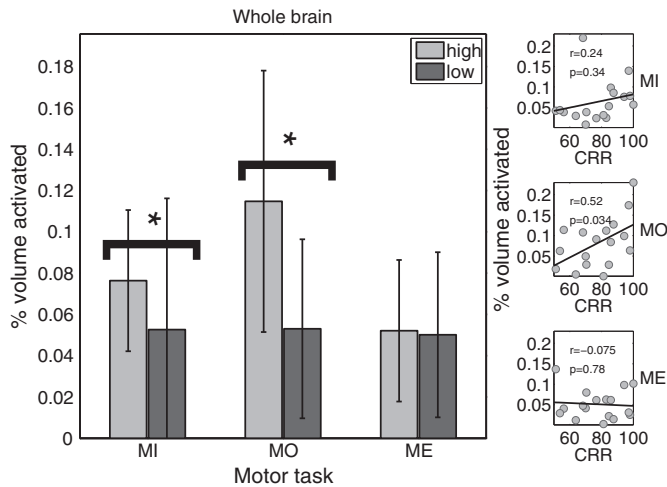
#### Implications of EEG-resting state predictor

The synchronized resting state SMR served as a strong predictor for motor imagery BCI performance (Blankertz et al., 2010). Synchronization of sensorimotor EEG occurs when the thalamocor-

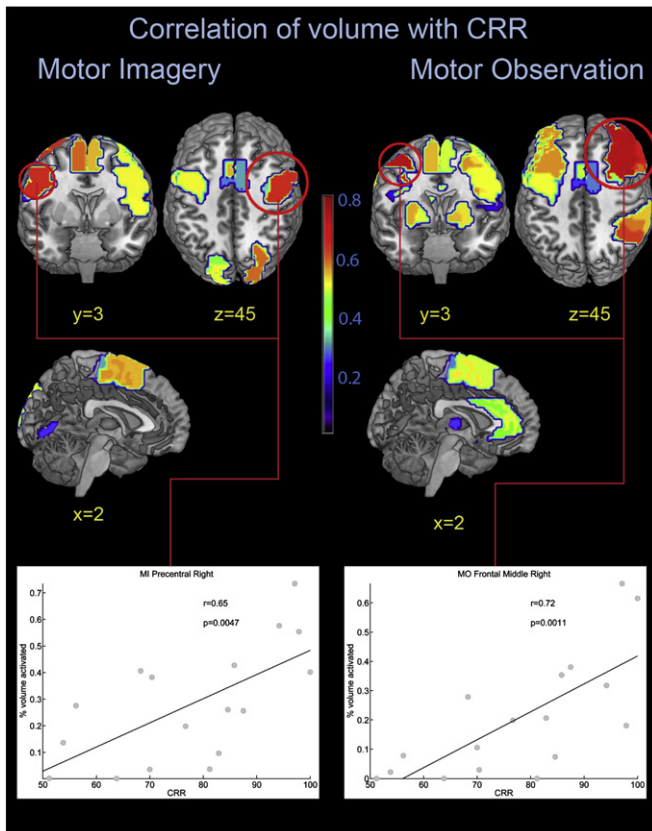
tical loop is in an idling state. It can be assumed that the higher the SMR peak during the idling state, the larger the involved cortical area as the summed activity of a synchronized population of generators increases linearly with the number of participating generators (Elul, 1972; Pfurtscheller and Lopes da Silva, 1999). The fMRI data supported this assumption. For motor imagery and the motor observation tasks, the volume significantly activated was larger in the high as compared to the low aptitude users group. We conclude that recruiting more synchronized neurons for accomplishing motor imagery and also motor observation leads to better performance in a motor imagery-based BCI.

This resting state feature as a strong predictor implicates that differences in performance were not due to the participant's cognitive strategy used to perform motor imagery or the classification procedure used in the BCI. Therefore, it can be assumed that the differences found between the groups in the fMRI are also not due to the participant's cognitive strategy but due to the "implicit" ability to





**Fig. 8.** Correlation between correct response rate (CRR) and activated volume and mean difference between high aptitude users (light gray bars) and low aptitude users (dark gray bars) of activated volume in the whole brain for all tasks. Tasks with significantly different percentages of activated volume are marked with an “\*”. If the outlier was removed in the motor imagery (scatter plot in the top right corner), the correlation increased to  $r = 0.59$ .



**Fig. 9.** Correlations of the percentage of activated voxels (during motor imagery and motor observation) in predefined ROIs with the correct response rate (CRR) achieved in the EEG-BCI task. Correlations of ROIs below a significance threshold of  $p < 0.05$  are not shown. The strength of the significant correlations is color coded in the brain images. Below the brain images scatter plots are shown for the ROIs with the highest correlations ( $r = 0.65$  for motor imagery and  $r = 0.72$  for motor observation). There were no significant correlations between the activated voxels in any ROI during motor execution and the correct response rate. The color bar represents the  $r$ -values. All images are superimposed on a normalized canonical image (ch2better template) using the MRIcron software.

recruit the relevant areas for symbolic motor tasks as required for motor imagery and motor observation.

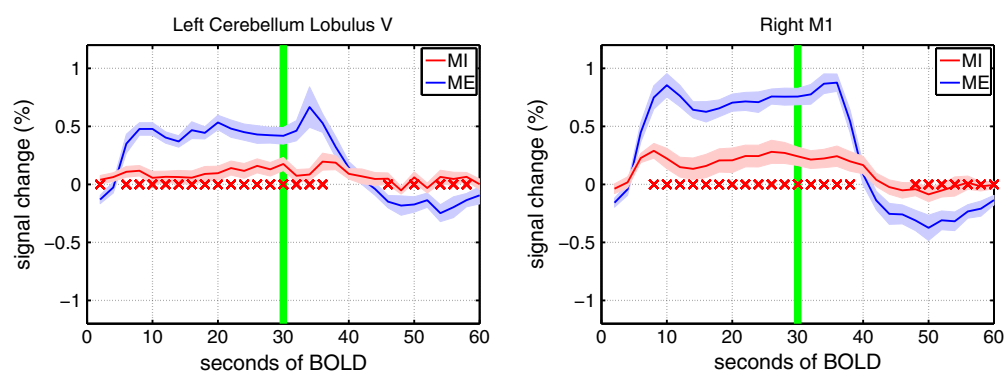
### The role of SMA

The SMA is involved in planning of complex movements (Orgogozo and Larsen, 1979). Activation of the SMA can be observed independently of other motor areas in tasks involving planning or imagery of sequences of movements. The decisive factor determining activation of the SMA appeared to be the complexity of the motor task (Roland et al., 1980; Rao et al., 1993; Shibasaki et al., 1993). Studies involving simple motor tasks did not find SMA activations, but activity focused in the primary motor cortex (Porro et al., 1996). Generally, more complex or new tasks lead to a stronger activation and recruitment of more widespread motor areas at least at initiation of training (Stippich et al., 2000). This may suggest that the differences between high and low aptitude users are caused by the novelty of the imagined movement and the corresponding activation of the SMA.

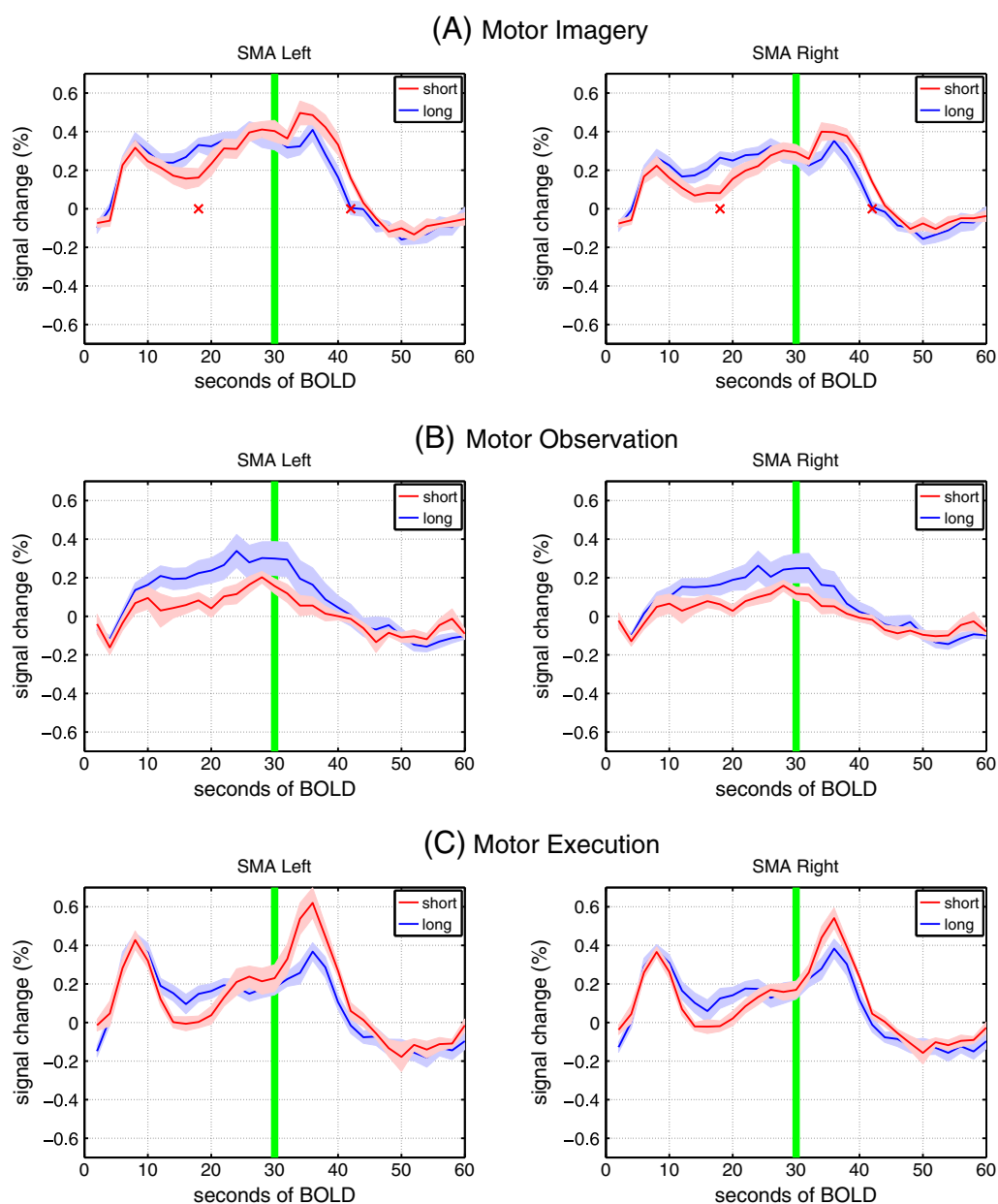
In a high temporal resolution (one image every 300 ms) fMRI study testing multiple models of the connectivity between SMA and M1, Kasess et al. (2008) concluded that the role of the SMA in motor imagery could involve the suppression of M1. As synchronization of EEG (SMR) is an indicator of an idling state, a stronger SMA activity could suggest a more complete suppression of M1 activity and subsequently a stronger idling rhythm as observed in the EEG data during rest (Pfurtscheller et al., 1996; Blankertz et al., 2010). The inhibitory influence of the SMR on motor behavior has also been shown using instrumental conditioning of SMR in cats (Wyrwicka and Serman, 1968). Thalamocortical oscillations reduce the responsiveness of neural networks (Steriade et al., 1993). An inverse relationship between the BOLD activity and the amplitude of idling rhythms has been observed (Laufs et al., 2003; Feige et al., 2005; Ritter et al., 2009). This suggests that the high resting SMR peak observed in the high aptitude users group would correspond to a low BOLD activity at baseline. During the task the relative increase of BOLD response was higher in high aptitude users than in the low aptitude users group. This increase may have been easier to achieve for the high aptitude group because of the lower BOLD baseline (“law of initial values”; Wilder (1962)).

### Differences between high and low aptitude users

The strongest difference between high and low aptitude users in the motor observation task was found in the right superior temporal gyrus (see Table in supplementary materials). This area is involved in visual exploration tasks and spatial awareness (Karnath et al., 2001; Himmelbach et al., 2006). This may indicate that the high aptitude users show more ideo-motor involvement in the video shown during the motor observation task, which is in accordance with the instruction that the participants should try to perceive the observed motion as their own and should at the same time imagine this movement (kinesthetic imagery (Neuper et al., 2005)). The activation in the left inferior temporal gyrus, more precisely in visual area V5 or MT (middle temporal) is generally associated with higher level perception of motion (Born and Bradley, 2005). Activation in this area has also been shown during imagery of motion (Goebel et al., 1998). The right DLPFC was also significantly more activated in high aptitude users than in low aptitude users during motor observation and the activation correlated strongly with performance in the EEG-BCI. The DLPFC is known for its role in executive functions, i.e. allocation of attentional resources and working memory. During motor observation and motor imagery the major function of “perceiving” the observed and imagined movement “kinesthetically” has to be maintained throughout the block of 30 s. At the same time attentional resources have to be directed to observation of the videos and imagery of the movement. Likewise, during operation of a BCI the overall goal



**Fig. 10.** Time course of BOLD in left cerebellum lobulus V (left figure) and right M1 (right figure) during left hand motor imagery (red) and motor execution (blue) tasks. The green line indicates the termination of the task after 30 s. The red crosses indicate significantly different means.



**Fig. 11.** Time course of BOLD in left and right supplementary motor area (SMA) during motor imagery (A), motor observation (B) and motor execution (C) tasks. BOLD response of participants with a below median time between EEG and fMRI measurement (short) are shown in red, that of participants with above median time between EEG and fMRI measurement (long) are shown in blue. The green line indicates the termination of the task after 30 s. The red crosses indicate significantly different means.

of maintaining and monitoring the task requirement (e.g. moving a cursor into a target) has to be activated while performing motor imagery and processing of feedback.

### Motor observation

Motor neurons that discharge in response to observed actions were found in monkeys and have been termed “mirror” neurons (di Pellegrino et al., 1992). “Mirror” neuron areas have also been observed in humans (Iacoboni et al., 1999; Rizzolatti and Craighero, 2004). Furthermore, it has been proposed that there is a link between the SMR and the “mirror” neuron system (Altschuler et al., 1998; Pineda, 2005). Consequently it has been shown that SMR suppression occurs during action observation (Muthukumaraswamy et al., 2004). One hypothesis is that there is a direct link between the “mirror” neurons localized in the premotor cortex and the cells generating the SMR in sensorimotor areas (Pineda, 2005). The observation that people (high aptitude users) with higher idle SMR, as was shown in Blankertz et al. (2010), respond stronger to motor observation (see Figs. 5 and 7 (B)) would support this hypothesis that SMR and the “mirror” neuron system are connected. Studies with individuals with autism have shown a link between the disability to imitate certain actions and the amount of SMR desynchronization caused by motor observation (Bernier et al., 2007; Oberman et al., 2005).

### Prediction of motor imagery performance

We used the percentage of the voxels above a predefined significance threshold of the first level fMRI analysis as a feature to predict performance in the motor imagery-based EEG-BCI. Correlations with correct response rate were found for the whole brain during motor observation, and for individual ROIs during motor imagery and motor observation. The strongest correlations were found in the right middle frontal gyrus. This region has been found to be active in theory of mind tasks using cartoons which involved judging the mental state of others (Gallagher et al., 2000). It has also been shown that right hemispheric stroke leads to an acquired theory of mind impairment (Happé et al., 1999). It has been repeatedly demonstrated that individuals with autism lack a theory of mind and they have also been shown to lack SMR desynchronization during motor observation (Baron-Cohen, 1989; Bernier et al., 2007; Oberman et al., 2005).

The dorsolateral prefrontal cortex (DLPFC), which includes the middle frontal gyrus, has been associated with the preparation for movement based on a previously viewed movement sequence stored in short working term memory (Pochon et al., 2001). Additionally, it has been found to be active in tasks requiring the monitoring of performance such as professional singing, where musical performance and stage acting need to be integrated (Kleber et al., 2010). Such a monitoring function appears to cause stronger activation in the right DLPFC, in accordance with our data as shown in Fig. 9 (Sharp et al., 2004). This might enable high aptitude users to perform superior in the rehearsal of a movement sequence from working memory that is needed for motor imagery and motor observation.

### Conclusions

With this study we identified a strong physiological predictor of motor imagery skill as measured in an EEG-BCI. The volume activated in the whole brain during motor observation predicted performance in the EEG-BCI with  $r=0.52$  (see Fig. 8). The activation in the right middle frontal gyrus showed correlations of  $r=0.72$  indicating the importance of prefrontal activation to guide action and monitor performance (see Fig. 9). High aptitude users had a higher resting state SMR amplitudes than low aptitude users (Blankertz et al., 2010). As the SMR rhythm coincides with a lower BOLD response in the respective brain region, desynchronization of the respective rhythm

leads to a higher contrast between rest and motor task when measured with fMRI demonstrating a high affinity of BOLD and EEG (SMR) (Laufs et al., 2003; Feige et al., 2005; Ritter et al., 2009). High aptitude users also activated a larger volume of cortical neurons which is also reflected in a higher amplitude of the SMR rhythm (Elul, 1972; Pfurtscheller and Lopes da Silva, 1999).

Taken together, low aptitude users seem to be less able than high aptitude users to recruit motor areas and specifically the SMA during motor imagery and motor observation. In low aptitude users the motor network including the loop to prefrontal areas, namely the DLPFC which is known to play a major role co-ordinating multiple tasks in working memory, seems to be less activated by symbolic motor responses such as motor imagery and observation. The reduced activation was specific for the symbolic motor observation and motor imagery as during motor execution no difference was found between high and low aptitude users indicating that the low aptitude users do not have a generally less activated motor network. We may speculate that low aptitude users have a less trained mirror neuron network which cannot be sufficiently activated by motor observation and motor imagery.

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### Appendix A. Supplementary data

Supplementary data to this article can be found online at doi:10.1016/j.neuroimage.2011.01.021.

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