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Original Research

The Posterior Parietal Cortex (PPC) Mediates Anticipatory Motor Control

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ABSTRACT

Background: Flexible and precisely timed motor control is based on functional interaction within a cortico-subcortical network. The left posterior parietal cortex (PPC) is supposed to be crucial for anticipatory motor control by sensorimotor feedback matching.
Objective: Intention of the present study was to disentangle the specific relevance of the left PPC for anticipatory motor control using transcranial direct current stimulation (tDCS) since a causal link remains to be established.
Methods: Anodal vs. cathodal tDCS was applied for 10 min over the left PPC in 16 right-handed subjects in separate sessions. Left primary motor cortex (M1) tDCS served as control condition and was applied in additional 15 subjects. Prior to and immediately after tDCS, subjects performed three tasks demanding temporal motor precision with respect to an auditory stimulus: sensorimotor synchronization as measure of anticipatory motor control, interval reproduction and simple reaction.
Results: Left PPC tDCS affected right hand synchronization but not simple reaction times. Motor anticipation was deteriorated by anodal tDCS, while cathodal tDCS yielded the reverse effect. The variability of interval reproduction was increased by anodal left M1 tDCS, whereas it was reduced by cathodal tDCS. No significant effects on simple reaction times were found.
Conclusion: The present data support the hypothesis that left PPC is causally involved in right hand anticipatory motor control exceeding pure motor implementation as processed by M1 and possibly indicating subjective timing. Since M1 tDCS particularly affects motor implementation, the observed PPC effects are not likely to be explained by alterations of motor-cortical excitability.

Introduction

Flexibility of motor control relies on anticipation of subsequent events as well as concurrent and quick adaptation to spatio-temporal changes. A well-established experimental paradigm to investigate anticipatory motor timing is the synchronization task requiring subjects to synchronize their finger tap as precisely as possible with an isochronous auditory pacing signal. Despite the subjective impression of exact synchrony between the pacing signal and the finger tap, subjects anticipate the pacer by tapping several tens of milliseconds prior to its actual appearance – the anticipation error or so-called *negative asynchrony* [1,2]. Anticipatory motor control is associated with functional interactions within a cortico-subcortical network comprising primary motor (M1), posterior parietal (PPC), premotor cortex (PMC) and supplementary motor area (SMA) as well as cerebellar and subcortical structures [3–5]. While SMA and PMC are assumed to be responsible for motor preparation and M1 to be primarily dedicated to movement initiation, a cerebellar-thalamo-PPC-subnetwork has been related to anticipatory motor control [3]. The cerebellum may predict sensory events via an internal model and the PPC may maintain this prediction for subsequent motor adjustment depending on actual sensorimotor feedback [3,6]. Although the PPC has been pointed out as key structure for anticipation and sensorimotor feedback matching [5–7], the causal involvement of PPC in anticipatory motor control remains to be established.

Motor anticipation has previously been differentially modulated by non-invasive brain stimulation of distinct network components with low-frequency 1 Hz repetitive transcranial magnetic stimulation (rTMS) [7–9]. 1 Hz rTMS yields a transient reduction of neuronal excitability within the targeted brain region in most instances – although associated with interindividual variability

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[10,11]. Reduction of left PMC excitability yielded an increased negative asynchrony [9], while reduced left M1 [8] and left PPC excitability [7] led to a smaller negative asynchrony suggesting superior motor anticipation. Krause et al. (2012) assumed a significance of PPC for matching between anticipated and actual sensorimotor feedback. They attributed the reduced negative asynchrony to impaired feedback matching possibly associated with a transient interruption of the PPC-cerebellum-interaction. However, they could not rule out that suppression of left PPC activity might have affected the functional PPC-M1-interaction leading to M1 inhibition and, thus, general motor slowing.

In the present study, we applied transcranial direct current stimulation (tDCS) to non-invasively modulate PPC excitability. As compared to rTMS, tDCS is superior for double-blind experimental designs and for the polarity-dependent modulation of brain excitability [12]. Anodal tDCS increases the likelihood of spontaneous neuronal activity by subthreshold depolarization, while cathodal tDCS most likely inhibits spontaneous neuronal activity by subthreshold hyperpolarization [12–14]. tDCS for at least 9 min has been shown to yield after-effects on cortical excitability for at least 30 min [12].

Intention of the present study was to further disentangle the functional relevance of PPC for anticipatory motor control. Anodal vs. cathodal tDCS of the left M1 served as control condition. *Anticipation* was measured by mean negative asynchronies during auditorily paced synchronization performance. We, furthermore, investigated *interval reproduction* with a continuation task. Subjects were required to continue tapping at the same pace once the pacing signal vanished measuring the intertap interval between two subsequent taps. An auditory reaction task served as measure for *simple motor control*. We hypothesized that tDCS of PPC yields a stronger effect on synchronization than reaction, if the left PPC is superordinate for anticipatory motor control. Since PPC has been related to the matching between anticipated and actual feedback, a smaller effect on interval reproduction is also expected. Because evidence for a left-hemispheric lateralization of motor control [15–17] exists, we further hypothesized that left PPC stimulation may modulate synchronization performance of both hands. If tDCS of left M1 does not affect motor performance, the expected PPC tDCS effects are most likely not mediated via PPC-M1-interaction.

Methods and materials

Subjects

31 healthy, right-handed subjects participated in the present double-blind study and were assigned to either anodal vs. cathodal PPC stimulation or anodal vs. cathodal M1 stimulation. Subjects were naïve with respect to the exact hypotheses of the study. General exclusion criteria were history or family history of epileptic seizures, history of migraine, unexplained loss of consciousness, or brain related injury, history of other neurological or psychiatric disorders, pregnancy, intake of central nervous system-effective medication, cardiac or brain pacemaker. Written informed consent was given prior to study participation. The study was accomplished with the approval of the local ethics committee and is in accordance with the Declaration of Helsinki. All subjects were classified as right-handed by means of the Edinburgh Handedness Inventory (EHI) [18] requiring a minimum score of 40 for right-handedness. Handedness score was 85.0 ± 4.26 (mean ± standard error of mean (SEM)). 16 subjects (6 male, 10 female) with a mean age of 23.69 (±1.03) years were assigned to PPC stimulation. 15 subjects (8 male, 7 female) with a mean age of 25.40 (±1.32) years were assigned to M1 stimulation. Handedness scores did not differ between subjects receiving PPC vs. M1 tDCS ($t(29) = 1.23$, $P = .23$). All subjects received anodal vs. cathodal tDCS in two sessions separated by at least one week in order to avoid carry-over effects. The order of sessions was counterbalanced across subjects.

Localization of left M1 and left PPC

The left M1 was localized by the optimal cortical representation of the right first dorsal interosseus (FDI) muscle by eliciting motor-evoked potentials (MEPs) by single TMS pulses with a standard figure of eight coil (MC-B70, MagPro Stimulator, Mag Venture, Hückelhoven, Germany). The coil was placed tangentially to the scalp with the handle pointing backwards and laterally at about 45° away from the midline. By moving the coil in .5 cm steps anterior, posterior, medial and lateral to this area, the exact localization of the spot which evoked the maximal motor response of the FDI muscle in 3 out of 5 consecutive trials was determined as motor hot spot. The left PPC was localized using neuronavigation (LOCALITE, Sankt Augustin, Germany) based on subjects' individual anatomical high resolution T1-weighted magnetic resonance imaging (MRI) scans. MRI scans had been acquired in a previous session (3-Tesla MRI scanner, Siemens Magnetom, Erlangen, Germany). In each scan, the left PPC had been determined a priori as stimulation hot spot. Mean Talairach coordinates (*X*, *Y*, *Z*) were −24.69 (±1.41), −59.19 (±1.57), 54.75 (±1.47) corresponding to Brodmann area (BA) 7. BA 7 involves the superior parietal lobe defined by the anatomical landmarks of the postcentral sulcus, intraparietal sulcus and parieto-occipital sulcus (Fig. 1A). PPC was localized 5.06 cm (±.34) posterior to the individual M1 hot spot rendering overlapping M1 stimulation during PPC stimulation unlikely. In each subject, the same Talairach coordinates were used for both sessions.

Transcranial direct current stimulation (tDCS)

tDCS was applied via two saline-soaked sponge electrodes (3×3 cm^2) placed on the skin surface (DC-Stimulator Plus, Eldith, NeuroConn, Ilmenau, Germany). Prior to stimulation, the skin surface was degreased and slightly abraded in order to reduce skin resistance. For PPC stimulation, the electrodes were attached above left PPC and right orbita with the anode above PPC during anodal tDCS and the cathode above PPC during cathodal tDCS. For M1 stimulation, the electrodes were placed above left M1 and right orbita with the anode above M1 during anodal tDCS and the cathode above M1 during cathodal tDCS. tDCS was applied with an intensity of .25 mA (peak-to-peak-amplitude; .0278 mA/cm^2 current density under the electrode) for 10 min at rest. Additional fade-in and fade-out time was 5 s, respectively. Noteworthy, stimulation was carried out using 3×3 cm^2 electrodes in the standard montage. We did not control for possible co-stimulation of right prefrontal cortex as restrictive point. Experimental evidence suggests that the likelihood of prefrontal co-stimulation can be reduced by the combination of small, focal stimulation electrodes with larger, less efficient orbitofrontal electrodes [19]. Impedance was kept below 10 kOhm. Stimulation was carried out in accordance with current safety guidelines for electrical current stimulation [13,20]. Subjects and investigator were naïve with respect to stimulation (anodal vs. cathodal). In order to ensure that blinding was successful, subjects were asked at the end of each session to rate which type of stimulation they received and to evaluate the confidence of their decision using a numerical rating scale ranging from 1 (totally uncertain) to 10 (totally certain). Subjects correctly identified anodal stimulation in 48% of anodal sessions with a mean subjective confidence of 2.73 (±1.94). Cathodal stimulation was correctly identified in 39% of cathodal sessions with a mean confidence