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Theta phase coupling with rhythmic motor output during visuomotor tracking

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Introduction: The entrainment of low frequency cortical brain oscillations to rhythmic stimuli was proposed to serve as a mechanism of selective attention, periodically tuning neuronal ensembles to reach maximal excitability at the optimal time [1]. In this work, we show that during visuomotor tracking, frontal theta oscillations phase-couple with rhythmic corrective sub-movements spontaneously emerging during the tracking task. An event-related potential (ERP) analysis, time-locked to these motor events revealed waveforms of theta-band spectral content, whose amplitudes were modulated by both hand kinematics and errors committed by the subjects.

Material, Methods and Results: Subjects (n=26) used a computer mouse to track a moving target along displayed trajectories while electroencephalographic (EEG) data and mouse/target positions were recorded. In a control condition, subjects performed a similar task in terms of motor output but not requiring tracking. Hand kinematics were composed of rhythmic (5 Hz) corrective sub-movements, best revealed by the hand acceleration profiles (Fig. 1A, blue). The phase-locking value (PLV) [2] was computed between those hand acceleration profiles and every electrode's theta [4-7 Hz] filtered EEG. Mean PLVs were then z-scored using the mean and standard deviation of 200 PLVs computed from surrogate signals, in order to remove the effect of non-genuine coupling.

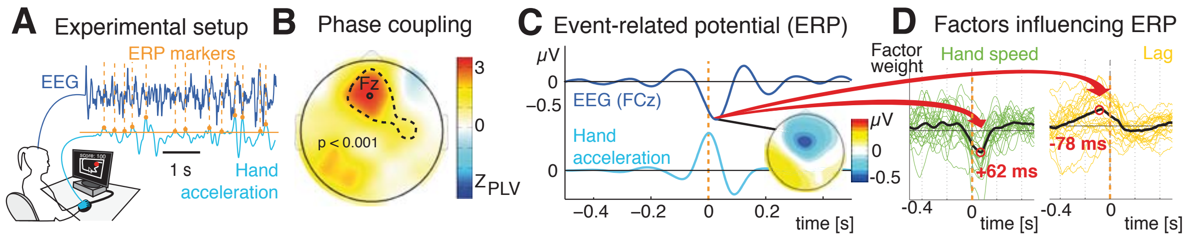

Figure 1. *A) The experimental setup with a representative example of five seconds of EEG (FCz) and rhythmic hand acceleration. The ERP markers (hand acceleration peaks) are shown in orange. B) the scalp distribution of the (z-scored) phase-locking values C) The ERP obtained by time-locking to hand acceleration peaks (blue) and the corresponding acceleration peak (cyan). D) The regression weights of the two influencial factors, for differrent time-lags and for each subject. Mean represented in black.*

Significant (p<0.001, corrected) couplings were found (Fig. 1B) at anterior midline scalp regions (peak: Fz), spreading over the hand representation of the motor cortex ipsilateral to the tracking hand. We then time-locked an ERP analysis to these sub-movements (by finding prominent hand acceleration peaks) and found a negative wave with a similar anterior scalp distribution (peak: FCz, EOG-contaminated epochs discarded), reaching a minimum ($p < 0.01$, corrected) around 40 ms after hand acceleration peaks (Fig. 1C). Finally, to find out what factors influence this negative deflection, we applied multivariate linear regression models to explain single-trial EEG amplitudes (FCz) using three behavioral factors: the speed of the hand (Fig. 1D, green), a measure of instantaneous error: how much the hand was lagging behind the target (Fig. 1D, yellow) and the speed of the target (not shown). The ERP amplitude was best explained by the speed of the hand (p<0.01, corrected) ~60 ms after the hand acceleration peak (corresponding to the sub-movement's peak speed) and by the instantaneous error ($p < 0.01$, corrected), ~80 ms before. No effect of target speed was found ($p > 0.05$). In the control condition, significantly lower theta coupling was found.

Discussion: We found a significant coupling between hand kinematics and a frontal network of theta frequency cortical oscillations during visuomotor tracking. Growing evidence supports the idea that theta cycles subserve some rhythmic selective attention process by entraining to periodic sensory input [1]. In this study, we show that even when this sensory input flows in continuously, similar couplings can exist between motor output and theta. We hypothesise that during continuous tasks requiring high attention (such as ours), the theta rhythm could be generated by the brain's performance monitoring system rhythmically sampling the instantaneous errors and producing higher amplitudes when salient errors, i.e. large and/or expeditiously corrected, are generated.

Significance: This study paves the way to a possible usage of midline frontal EEG as a proxy to probe patients' cognitive engagement in rehabilitative motor tasks, which could be used to inform assistive rehabilitation therapies.

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