Supplementary Information

Differential Effects of Meditation States on Neural Pain Processing in Novice and Long-Term Meditators

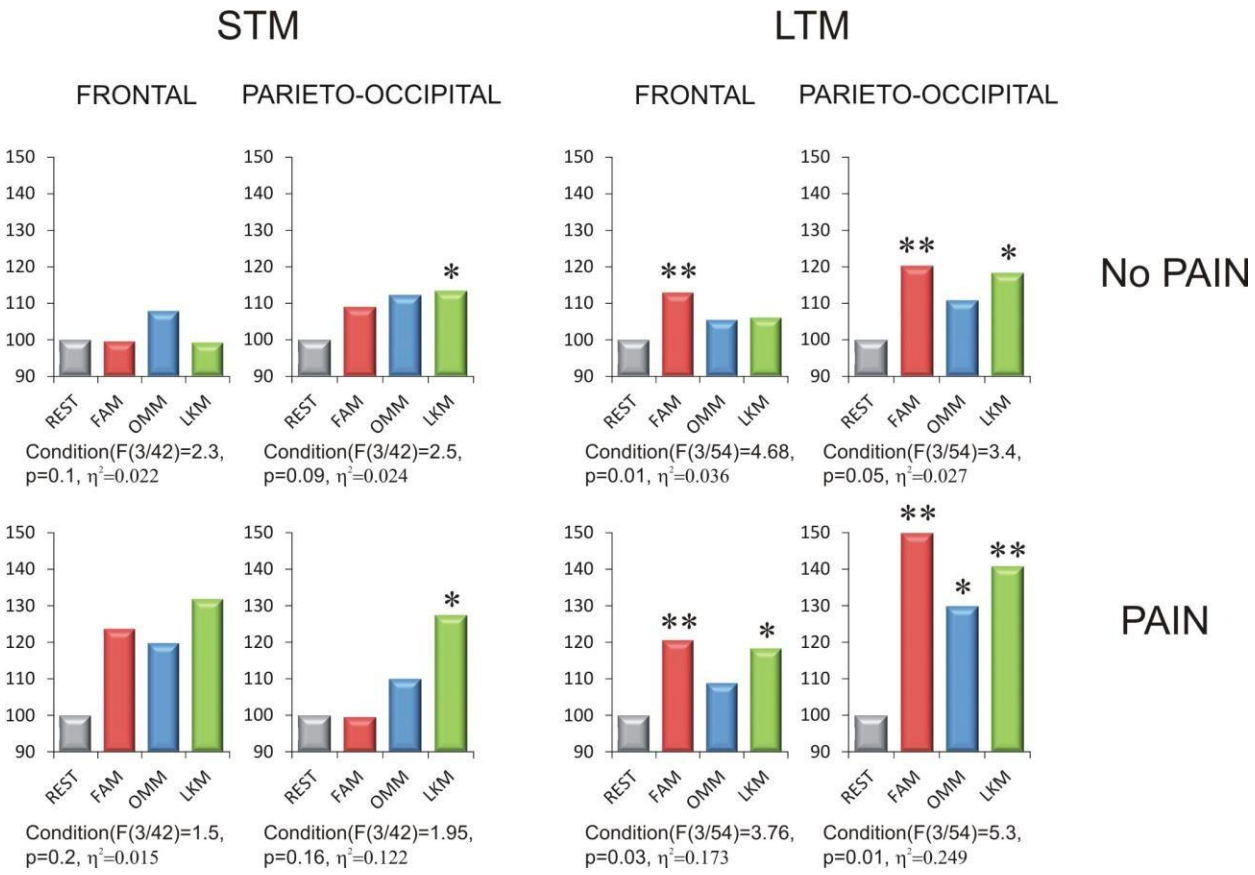
Supplementary Information 1

Pain Conditions: EEG was recorded during in pain conditions REST, FAM, OMM, and LKM as described in the main text. Pre-stimulus activity was measured by computing the mean value of TOTP for theta-alpha frequency band (f_0 = 7.5 Hz) layer within -450/-50 ms. Measures at frontal electrodes (F5, F3, Fz, F4, F6, FC5, FC3, FCz, FC4, FC6) and parieto-occipital electrodes (P7, P5, P3, Pz, P4, P6, P8, PO7, PO3, POz, PO4, PO8, O1, Oz, O2) were used for analysis.

No Pain Condition: EEG was recorded with eyes closed for 5-6 minutes in no pain conditions REST, FAM, OMM, and LKM using the same recording setup and pre-processing as in the pain conditions. Recording was performed for the same groups of STM and LTM participants. The experiment was conducted in a quiet, dimly lit room suitable for meditation and recording EEG. Using independent component analysis (ICA) and current source density (CSD) EEG was pre-processed as described in the main text. All analyses were carried out with CSD-transformed data from 50 electrodes. EEG recordings were segmented in equal-sized epochs of 4.096-s duration with 1.024-s overlap. The average number of epochs for each participant was 70 (±20). After the Hanning window with a duration of 20% from the total epoch length applied to all epochs, fast Fourier transform (FFT) was computed, yielding the representation of complex values with a frequency resolution of 0.244 Hz (1/4.096 s). The same frontal and parieto-occipital electrodes were used for analysis.

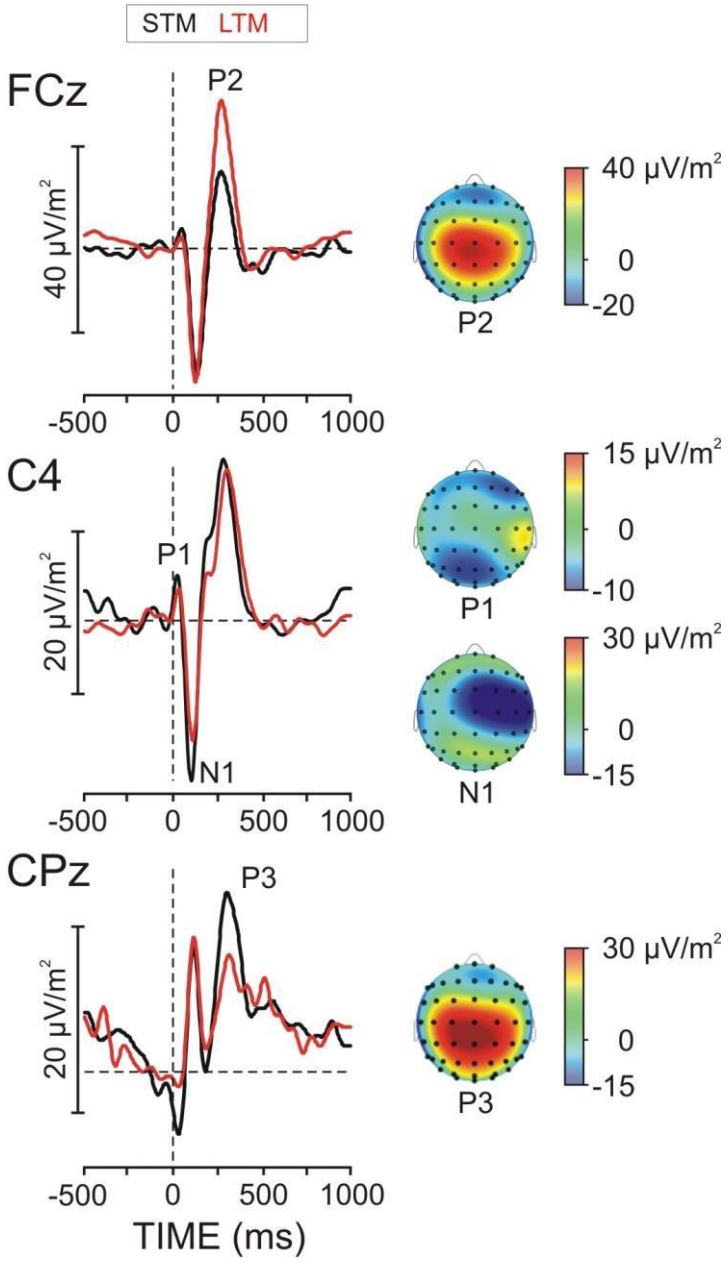
Statistical analysis: Measures of theta-alpha power were subjected to a repeated-measures ANOVA with 2 within factors (Condition, REST vs. FAM vs. OMM vs. LKM) and Electrode. Analyses were performed separately for each group (STM and LTM) and each ROI (frontal and parieto-occipital). Comparisons between REST and meditative states (FAM, OMM, LKM) were carried out using post-hoc F contrasts. Analyses reporting main Condition effects and between-state contrasts (depicted in the figure) were performed using log-transformed power values. Because there was a substantial difference in theta-alpha power between STM and LTM, to improve visualization of results and emphasize the changes in meditative states according to REST, normalized theta-alpha power values are depicted in Supplementary Figure 1. Values were normalized by computing rate of change in percent in meditative states according to REST in each group.

These analyses showed that at both the frontal and parieto-occipital electrodes theta alpha power in LTM increased in meditative states relative to REST in both no-pain and pain conditions. Although similar increases were visible in STM, they were not statistically significant with exception of the LKM. It is not unexpected that STM participants might not be able to modulate efficiently their theta-alpha activity. The relevant implication is that the modulations observed in each group in meditative states relative to REST were similar in no-pain and pain conditions implying that the participants were able to engage in meditation-induced processes during pain stimulation, irrespective of task-related events during the pain experiment.

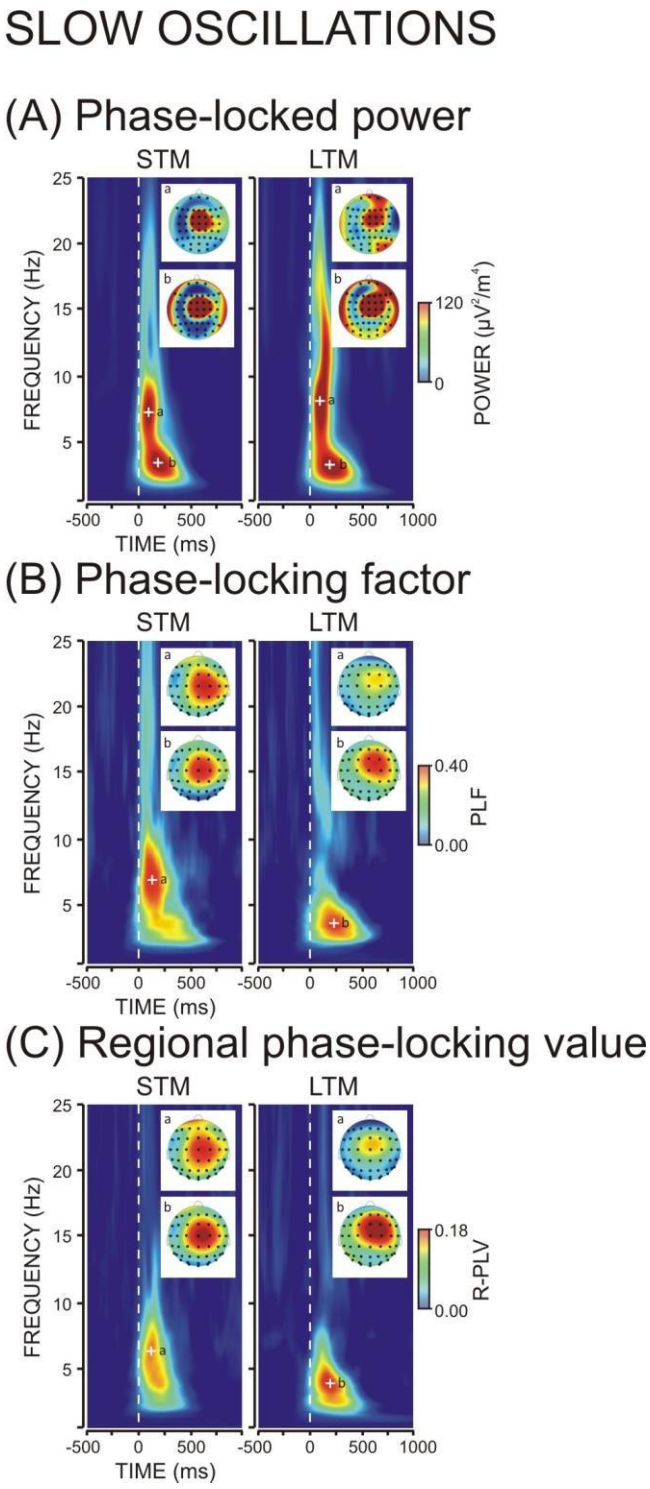


Supplementary Figure 1. Group mean normalized power values of short-term meditator (STM) and long-term-meditators (LTM) at FRONTAL and PARIETO-OCCIPITAL regions (averaged across electrodes in each ROI) in No PAIN and PAIN conditions – REST, FAM, OMM, and LKM. Significant differences, where available, between REST and meditation states FAM, OMM, LKM are designated with stars: *, $p<0.05$; **, $p<0.01$.

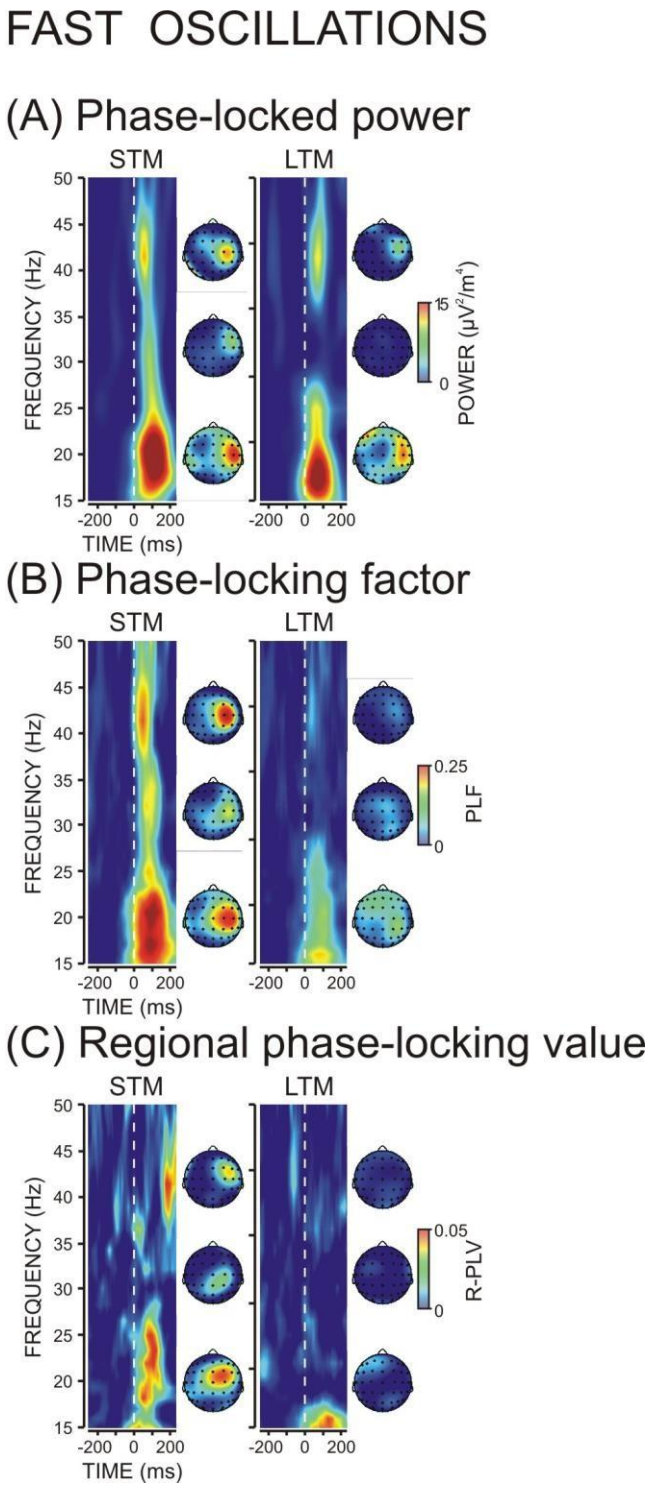
Supplementary Information 2



Supplementary Figure 2. Grand averaged pain-related potentials (PRP) in short-term meditators (STM) and long-term meditators (LTM) at relevant electrodes. Time-domain PRP components P1, N1, P2 and P3 are demonstrated at relevant electrodes. Topography maps (right panel) demonstrate topographic distribution at anterior midline area, right-hemisphere sensorimotor regions contra-lateral to the side of pain stimulation, and centro-parietal regions for P3 component.



Supplementary Figure 3. Grand averaged time-frequency (TF) plots and topography distribution maps for slow-frequency pain-related oscillations (1-25 Hz) of short-term (STM) and long-term (LTM) meditators during resting state. The TF plots are presented for FCz electrode. In the maps, 'a' refers to theta-alpha mainly expressed in STM and 'b' refers to delta TF component mainly expressed in LTM. Stimulus occurrence at 0 ms. (A) Phase-locked power (PLP); (B) Phase-locking factor (PLF); (C) Regional phase-locking value (R-PLV).



Supplementary Figure 4. Grand averaged time-frequency (TF) plots and topography distribution maps for fast-frequency pain-related oscillations (15-50 Hz) of short-term (STM) and long-term (LTM) meditators during resting state. The TF plots are presented for C4 electrode. Pain-related fast-frequency components from beta, gamma-1, and gamma-2 frequency ranges are illustrated. Stimulus occurrence at 0 ms. (A) Phase-locked power (PLP); (B) Phase-locking factor (PLF); (C) Regional phase-locking value (R-PLV).

Supplementary Figures 3 and 4 in STM demonstrate that in the slow frequency band, two main components were temporally synchronized by pain stimulus – theta-alpha (5-10 Hz) and delta (1.5-4 Hz). In the fast frequency bands, three distinct TF components were evident – beta (16-25 Hz), slow gamma (gamma-1, 30-35 Hz), and fast gamma (gamma-2, 38-42 Hz). Inspection of TF plots in LTM demonstrates that these TF components of pain potentials were strongly reduced in LTM. It is shown that the maximal expression of frequency-specific PROs occurred with different timing after pain stimulation: within 500 ms time window for delta (group mean across all electrodes 200±80 ms), within 250 ms for theta-alpha (group mean 128±20 ms), within 200 ms for beta (group mean 110±15 ms), and within 150 ms for gamma-1 (group mean 80±10 ms) and gamma-2 (group mean 50±10 ms).

Supplementary Figures 3 and 4 also demonstrate the different topographic distributions of frequency-specific components. Specifically, an anterior midline dominance is observed for delta and theta-alpha, whereas a focused localization at central/postcentral centro-lateral (right-hemisphere) electrodes is demonstrated for beta, gamma-1, and gamma-2 TF components. The same TF components, topography maps and STM vs. LTM differences were revealed for each meditation state (FAM, OMM, and LKM).