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Human anterior and frontal midline theta and lower alpha reflect emotionally positive state and internalized attention: high-resolution EEG investigation of meditation

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Abstract

EEG spectral power and coherence estimates in the individually defined delta, theta, alpha-1, alpha-2, and alpha-3 bands were used to identify and characterize brain regions involved in meditative states, in which focused internalized attention gives rise to emotionally positive 'blissful' experience. Blissful state was accompanied by increased anterior frontal and midline theta synchronization as well as enhanced theta long-distant connectivity between prefrontal and posterior association cortex with distinct 'center of gravity' in the left prefrontal region (AF3 site). Subjective scores of emotional experience significantly correlated with theta, whereas scores of internalized attention with both theta and alpha lower synchronization. Our results propose selective associations of theta and alpha oscillating networks activity with states of internalized attention and positive emotional experience. © 2001 Elsevier Science Ireland Ltd. All rights reserved.

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According to recent investigations, theta and alpha oscillations defined in narrow frequency bands are regarded reflecting activity of multifunctional neuronal networks, differentially associated with orienting, attention, memory, affective, and cognitive processing (e.g. [1,2,4,5,7,12]). In this respect it is tentative to reveal how complex functions of attention and emotional processing are interwoven with these oscillations in meditation as in a model of conscious mental process, characterized by internalized attention and emerging emotionally positive experience [15].

In the model of Sahaja Yoga meditation that involves mental states of internalized attention and emotionally positive experience of 'bliss' [15] the high-resolution EEG was recorded, and spectral powers along with EEG coherence estimates were analyzed in narrow EEG frequency bands. Subjects (Ss, $n = 27$) were right-handed volunteers regularly practicing meditation. Participants were assigned to 2 experimental groups: (1) short-term meditators (STM) having lesser then 1/2 year of practice ($n = 11$, five males, six females, age: M = 35.18); long-term meditators (LTM) having 3–7 years of practice ($n = 16$, seven males, nine females; age: M = 35.00). After recording the eyes closed rest, the Ss had to go through three consecutive phases: (1) income phase; (2) deep meditation phase in which thought appearance is suppressed and yet self awareness is maintained ('thoughtless awareness'); (3) outcome phase [15]. The EEG was recorded throughout all the three phases. Ss were rated on series of unipolar (0–9) scales with the following questions: (1) Please estimate the extent of thought appearance during the meditation phase?; (2) How blissful did you feel during the meditation phase?; (3) To what extent have you felt uneasy, restless, and anxious during the meditation phase?

Scan 4.1.1 software, 128-channel ESI System (ESI-128, NeuroScan Labs.) and 64-channel QuikCap with imbedded Ag/AgCl electrodes (NeuroSoft, Inc.) were used to record EEG from 62 active scalp sites referenced to the tip of the nose along with both vertical and horizontal electrooculograms (EOGs). The EEG and EOG signals were sampled at 500 Hz and digitally filtered at 0.3–50 Hz (−6-dB gain, ≥ −12-dB/octave slope). After EOG correction (both VEOG and HEOG) [16] and visual inspection three artefact free EEG segments by 8.192 s were selected for each phase. Since fixed frequency bands blur the specific relationships

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between cognitive performance and power measurements (e.g. [8]), frequency bands were individually defined in relation to the individual alpha frequency (IAF) which was used as a cut-off point for the lower and upper alpha band. The bandwidth too, was determined individually and was calculated as a percentage (20%) of IAF [2,8]. Averaged by groups IAF was significantly lower for LTM (M = 9.42 Hz) than for STM (M = 10.04 Hz) ($P < 0.005$). The respective cut-offs for analyzed bands are reported in Fig. 1. Each EEG segment was epoched into two 4096 ms (i.e. 2048 points) epochs, fast Fourier transformed (FFT) and averaged in the frequency domain using a Parzens window. The FFTs were then grouped into individually defined bands, log-transformed, and averaged across three EEG traces. Electrodes were collapsed into 12 electrode-clusters. This procedure resulted in six regional means for each hemisphere: anterior temporal (AT); frontal (F); central (C); parietotemporal (PT); parietal (P); and occipital (O) (for details see Ref. [2]). The average power values across the respective electrode sites were calculated for these regional means. The same EEG segments were subjected to coherence analysis. Coherence was calculated between all electrode pairs.

For each frequency band, spectral power values for symmetrical cortical regions were subjected to 3-way ANOVAs (GR(2: STM, LTM) × HEM(2: left, right) × PHASE(2: eyes closed rest, meditation)) with repeated measurements on within-group factors. For midline regions 2-way ANOVAs (GR(2) × PHASE(2)) were applied for each cortical lead, belonging to AM (AFz, Fz) and PM (Pz, POz, and Oz) zones. All between-group analyses were followed by planned comparisons and separate within-group ANOVAs. Degrees of freedom were Greenhouse–Geisser corrected where appropriate. Coherence changes between eyes closed and meditation conditions were estimated using Student's *t*-test for STM and LTM.

At subjective level meditative experience of LTM vs. STM was accompanied by significantly more intense feelings of bliss (5.54 vs. 3.56, $P < 0.014$) and lower thought appearance rates (1.19 vs. 2.82, $P < 0.025$). Moreover, STM reported elevated scores of uneasiness and restlessness whereas LTM did not (3.22 vs. 0.54, $P < 0.000$) (Student's *t*-test).

ANOVAs of band power values from symmetrical regions revealed significant interaction GR × PHASE for F regions in theta ($F(1,25) = 6.48$, $P < 0.017$) and alpha-1 ($F(1,25) = 5.13$, $P < 0.033$) bands. In the alpha-2 band this interaction was significant throughout the cortical plane involving AT ($F(1,25) = 9.27$, $P < 0.005$), F ($F(1,25) = 6.76$, $P < 0.015$), PT ($F(1,25) = 6.39$, $P < 0.018$), P ($F(1,25) = 7.06$, $P < 0.014$), and O ($F(1,25) = 7.05$, $P < 0.014$) leads. Inspection of respective means of these interactions (Fig. 1) indicates that in meditation LTM increased theta and alpha-1 power over F region, alpha-2 power over AT and F regions, whereas STM were characterized by alpha-2 desynchronization over P, PT, and O leads (the lowest $P < 0.028$). Finally, alpha-3 band happened to be 'silent' during meditation in both groups.

As for the AM zone, the significant GR × PHASE interactions in the theta (AFz: ($F(1,25) = 7.47$; $P < 0.011$; Fz: $F(1,25) = 7.04$; $P < 0.014$), alpha-1 (AFz: $F(1,25) = 5.57$; $P < 0.026$; Fz: $F(1,25) = 6.79$; $P < 0.015$), and alpha-2 (AFz: $F(1,25) = 6.15$;) bands show that during meditation phase LTM yielded power increases in these bands whereas STM revealed no power changes (Fig. 1). By contrast, in the PM region, significant GR × PHASE interactions were obtained only for alpha-2 band (Pz: $F(1,25) = 5.40$, $P < 0.029$; POz: $F(1,25) = 6.64$, $P < 0.016$; Oz: $F(1,25) = 5.57$, $P < 0.026$), stemming from desynchronized activity in STM during the meditation phase (Fig. 1).

According to statistical analyses, only theta coherence revealed sensitivity to meditation experience (Fig. 2). LTM were characterized by increased theta synchronization between prefrontal and posterior association cortex with distinct 'center of gravity' in the left prefrontal region (i.e. AF3 site) along with less pronounced intra- and interhemispheric coherence decreases over posterior brain regions.

Correlational analyses revealed that intensity of blissful experience positively correlates with theta power (range from $r = +0.44$ to $r = +0.55$) in anterior frontal and frontal midline leads. In turn, thought appearance rates negatively correlated with theta power (range from $r = -0.43$ to

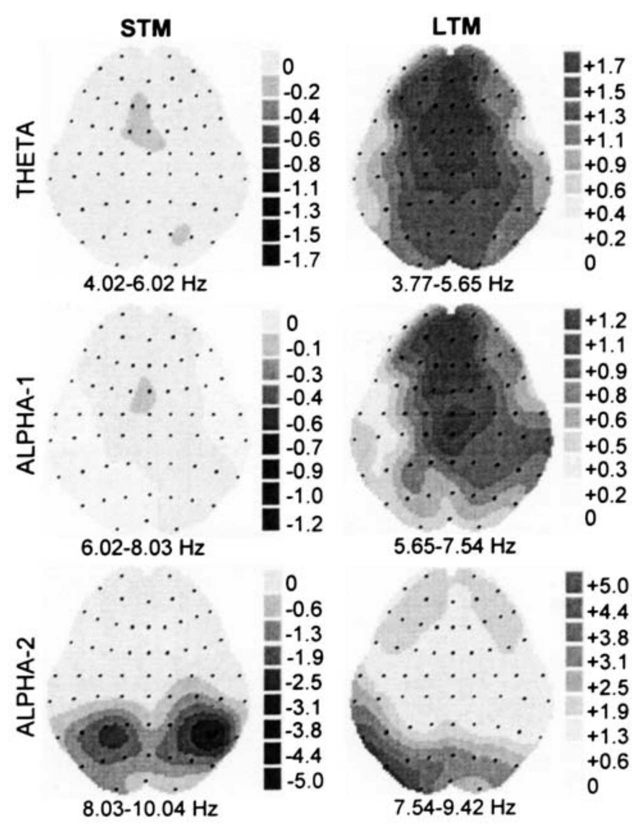

Fig. 1. Spectral power changes between eyes closed and meditation conditions in the short-term (STM) and long-term (LTM) meditators in the theta, alpha-1, and alpha-2 bands.

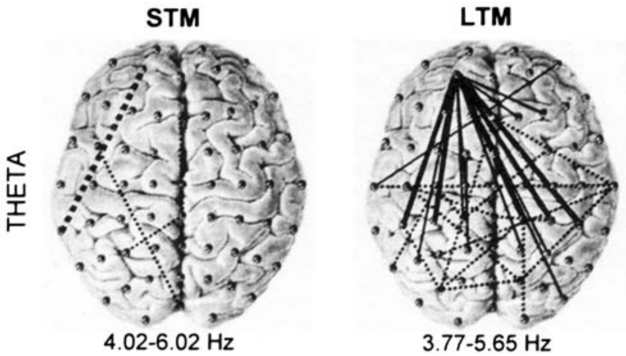

Fig. 2. Coherence changes between eyes closed and meditation conditions in the STM and LTM in the theta band. Solid lines indicate coherence increase whereas dashed lines point to coherence decrease (the thicker lines relate to error probability of $P < 0.001$, the thinner lines relate to $P < 0.01$, Student's *t*-test).

$r = -0.60$) in anterior frontal, frontal midline, central frontal, and right central regions and alpha-1 power (range from $r = -0.41$ to $r = -0.50$) in midcentral (FCz, Cz, and CPz) and adjacent leads (Fig. 3). There were no significant correlations with alpha-2 and alpha-3 power.

Summarizing, the most reliable effects of meditative emotionally positive state and internalized attention were differentially reflected by local theta and lower alpha power as well as theta coherence changes.

In the human EEG as well as in animals, theta band power increases with increasing task demands and is related to orienting [7], attention [5,7], memory [10,12], and affective processing mechanisms [1,2]. In contrast to theta activity during certain sleep stages, this task-related increase occurs within a small frequency window only [4,12]. Along with

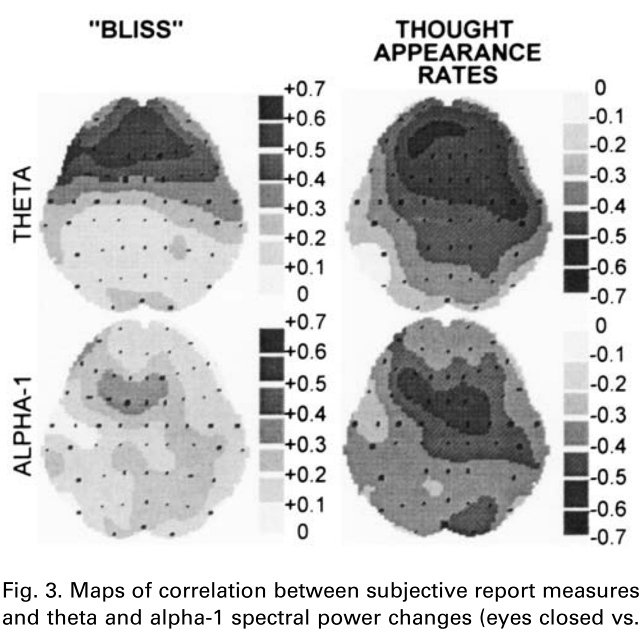

Fig. 3. Maps of correlation between subjective report measures and theta and alpha-1 spectral power changes (eyes closed vs. meditation); on the scale both positive and negative significant correlations go up from the +0.40 and down from the −0.40 scale grades.

general theta activity, a distinction is made for the frontal midline theta rhythm (FM theta). It appears during concentrated performance of mental tasks or meditative concentration in normal subjects, reflects focused attentional processing and correlates with autonomous activity (e.g. [9,13]). Recent findings from high resolution EEG and MEG investigations suggest that attentional networks of anterior frontal lobes including anterior cingulate cortex (ACC) are involved in the generation of this activity and that Fm theta during consecutive mental tasks reflects alternating activities of the medial prefrontal cortex and ACC [3]. The revealed theta power increase in LTM over anterior midline electrodes falls into categories of both general theta and FM theta processes. It may reflect recruitment of theta oscillating networks in memory, focused attention, and positive emotional experience mechanisms, associated with meditative process. The absence of midline theta synchronization in STM may be explained by excessive alertness and anxious/frustrative feelings at subjective level, due to inability to reach and reliably retain the desired meditative state. These findings are in line with earlier observation according to which the Fm theta correlates negatively with anxious experience [9].

A possible interpretation of alpha power changes during meditation may be ascribed to both functional heterogenity of different alpha frequency bands and peculiarities of meditative state. As it was shown in a variety of experimental paradigms, desynchronization in the lower and medium alpha bands is associated with processes of external attention such as alertness/vigilance (lowest alpha) and expectancy (medium alpha) whereas desynchronized upper alpha reflects enhanced cognitive processing (e.g. [11,12]). One may assume that successful meditative experience of LTM is mediated by switching off mechanisms of external attention as indexed by alpha-1 and alpha-2 synchronization over anterior cortical regions. In turn, unsuccessful attempts of STM in reaching target state may prompt enhanced expectancy processes, reflected by posterior alpha-2 desynchronization. It is also indicative that during period of suppressed cognitive activity alpha-3 band [12] turned out to be insensitive to meditative experience for both groups.

There is general agreement that coherence changes can be considered as an indicator of information flow along local and/or distant cortico-cortical projections (interconnecting pathways) [14]. Increased long-distant theta connectivity between prefrontal and posterior association cortical regions in LTM group may be regarded, on the one hand, as a more general phenomenon occurring when task demand increases and more efficient information processing is required (e.g. [14,17]). On the other, a prevailing activation of long-distant fibers, i.e. connecting of farther distant prefrontal and posterior association cortex regions seems to be required for positive emotional experience. Few investigations on EEG coherence also suggest enhanced long-distant connectivity during experience of positive vs. negative emotions [1]. As for the 'center of gravity ' of coherence increases (e.g. [14]), lateralized to the left prefrontal region, it may be related to emotionally positive experience [6]. This suggestion may be partly supported by recent findings from our laboratory indexing that emotionally positive stimuli favor larger left than right anterior prefrontal theta synchronization [2].

The revealed differential associations of theta and alpha activity in narrow EEG frequency bands with states of internalized attention and positive emotional experience land additional support to general theories on multiple functions of these oscillations.

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