

Long-term meditators self-induce high-amplitude gamma synchrony during mental practice

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Practitioners understand “meditation,” or mental training, to be a process of familiarization with one’s own mental life leading to long-lasting changes in cognition and emotion. Little is known about this process and its impact on the brain. Here we find that long-term Buddhist practitioners self-induce sustained electroencephalographic high-amplitude gamma-band oscillations and phase-synchrony during meditation. These electroencephalogram patterns differ from those of controls, in particular over lateral frontoparietal electrodes. In addition, the ratio of gamma-band activity (25–42 Hz) to slow oscillatory activity (4–13 Hz) is initially higher in the resting baseline before meditation for the practitioners than the controls over medial frontoparietal electrodes. This difference increases sharply during meditation over most of the scalp electrodes and remains higher than the initial baseline in the postmeditation baseline. These data suggest that mental training involves temporal integrative mechanisms and may induce short-term and long-term neural changes.

electroencephalogram synchrony | gamma activity | meditation

Little is known about the process of meditation and its impact on the brain (1, 2). Previous studies show the general role of neural synchrony, in particular in the gamma-band frequencies (25–70 Hz), in mental processes such as attention, working-memory, learning, or conscious perception (3–7). Such synchronizations of oscillatory neural discharges are thought to play a crucial role in the constitution of transient networks that integrate distributed neural processes into highly ordered cognitive and affective functions (8, 9) and could induce synaptic changes (10, 11). Neural synchrony thus appears as a promising mechanism for the study of brain processes underlining mental training.

Methods

The subjects were eight long-term Buddhist practitioners (mean age, 49 ± 15 years) and 10 healthy student volunteers (mean age, 21 ± 1.5 years). Buddhist practitioners underwent mental training in the same Tibetan Nyingmapa and Kagyupa traditions for 10,000 to 50,000 h over time periods ranging from 15 to 40 years. The length of their training was estimated based on their daily practice and the time they spent in meditative retreats. Eight hours of sitting meditation was counted per day of retreat. Control subjects had no previous meditative experience but had declared an interest in meditation. Controls underwent meditative training for 1 week before the collection of the data.

We first collected an initial electroencephalogram (EEG) baseline consisting of four 60-s blocks of ongoing activity with a balanced random ordering of eyes open or closed for each block. Then, subjects generated three meditative states, only one of which will be described in this report. During each meditative session, a 30-s block of resting activity and a 60-s block of meditation were collected four times sequentially. The subjects were verbally instructed to begin the meditation and meditated at least 20 s before the start of the meditation block. We focus here on the last objectless meditative practice during which both the controls and Buddhist practitioners generated a state of “unconditional loving-kindness and compassion.”

Meditative Instruction. The state of unconditional loving-kindness and compassion is described as an “unrestricted readiness and availability to help living beings.” This practice does not require concentration on particular objects, memories, or images, although in other meditations that are also part of their long-term training, practitioners focus on particular persons or groups of beings. Because “benevolence and compassion pervades the mind as a way of being,” this state is called “pure compassion” or “nonreferential compassion” (*dmigs med snying rje* in Tibetan). A week before the collection of the data, meditative instructions were given to the control subjects, who were asked to practice daily for 1 h. The quality of their training was verbally assessed before EEG collection. During the training session, the control subjects were asked to think of someone they care about, such as their parents or beloved, and to let their mind be invaded by a feeling of love or compassion (by imagining a sad situation and wishing freedom from suffering and well being for those involved) toward these persons. After some training, the subjects were asked to generate such feeling toward all sentient beings without thinking specifically about anyone in particular. During the EEG data collection period, both controls and long-term practitioners tried to generate this nonreferential state of loving-kindness and compassion. During the neutral states, all of the subjects were asked to be in a nonmeditative, relaxed state.

EEG Recordings and Protocol. EEG data were recorded at standard extended 10/20 positions with a 128-channel Geodesic Sensor Net (Electrical Geodesics, Eugene, OR), sampled at 500 Hz, and referenced to the vertex (Cz) with analog band-pass filtering between 0.1 and 200 Hz. EEG signals showing eye movements or muscular artifacts were manually excluded from the study. A digital notch filter was applied to the data at 60 Hz to remove any artifacts caused by alternating current line noise.

Bad channels were replaced by using spherical spline interpolation (12). Two-second epochs without artifact were extracted after the digital rereferencing to the average reference.

Spectral Analysis. For each electrode and for each 2-s epoch, the power spectral distribution was computed by using Welch’s method (13), which averages power values across sliding and overlapping 512-ms time windows. To compute the relative gamma activity, the power spectral distribution was computed on the z-transformed EEG by using the mean and SD of the signal in each 2-s window. This distribution was averaged through all electrodes, and the ratio between gamma and slow rhythms was computed. Intraindividual analyses were run on this measure and a group analysis was run on the average ratio across 2-s windows. The group analysis of the topography was performed by averaging the power spectral distribution for each electrode

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Abbreviations: ROI, region of interest; EEG, electroencephalogram.

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frequency oscillations (20–45 Hz) evoked by auditory stimuli (Fig. 5, which is published as supporting information on the PNAS web site). Because the evoked activity is relatively independent of muscle activity, the relationship between the prestimulation fast-frequency oscillation and the evoked activity suggests that these high-amplitude gamma rhythms are not muscle artifacts (Fig. 5 and Fig. 6, which is published as supporting information on the PNAS web site). This claim is further supported by the localization within the brain of the dipole sources of these fast-frequency-evoked oscillations (Figs. 7–9, which are published as supporting information on the PNAS web site).

Yet we still chose to cautiously interpret the raw values of these gamma oscillations because of the concomitant increase of spectral power >80 Hz during meditation. This increase could also reflect a change in muscle activity rather than high-frequency, gamma-band oscillations [70–105 Hz (19)], which are mostly low-pass filtered by the skull at >80 Hz. Thus, we chose to conservatively interpret the activity at >80 Hz as indicating muscle activity.

To remove the contribution of putative muscle activity, we quantified the increase in the average amplitude of gamma oscillation (25–42 Hz) adjusted for the effect of the very high-frequency variation (80–120 Hz) (see *Methods* and ref. 20). The adjusted average variation in gamma activity was >30-fold greater among practitioners compared with controls (Fig. 3*b*). Group analysis was run on the average adjusted gamma activity over these ROIs. Gamma activity increased for both the long-term practitioners and controls from neutral to meditation states [$F(1, 16) = 5.2, P < 0.05$; ANOVA], yet this increase was higher for the long-time practitioners than for the controls [$F(1, 16) = 4.6, P < 0.05$; interaction between the state and group factors ANOVA] (Fig. 3*b*). In summary, the generation of this meditative state was associated with gamma oscillations that were significantly higher in amplitude for the group of practitioners than for the group of control subjects.

Long-Distance Gamma Synchrony. Finally, a long-distance synchrony analysis was conducted between electrodes from the ROIs found in Fig. 3*a*. Long-distance synchrony is thought to reflect large-scale neural coordination (9) and can occur when two neural populations recorded by two distant electrodes oscillate with a precise phase relationship that remains constant during a certain number of oscillation cycles. This approach is illustrated in Fig. 1*c* for selected electrodes (F3/4, Fc5/6, and Cp5/6). For subject S4, the density of cross-hemisphere, long-distance synchrony increases by $\approx 30\%$ on average during meditation and follows a pattern similar to the oscillatory gamma activity.

For all subjects, locally referenced, long-distance synchronies were computed for each 2-s epoch during the neutral and meditative states between all electrode pairs and across eight frequencies ranging from 25 to 42 Hz. In each meditative or neutral block, we counted the number of electrode pairs (294 electrode pairs maximum) that had an average density of synchrony higher than those derived from noise surrogates (see *Methods*). We ran a group analysis on the size of the synchronous pattern and found that its size was greater for long-time practitioners than for controls [$F(1, 16) = 10.3, P < 0.01$; ANOVA] and increased from neutral to meditation states [$F(1, 16) = 8.2, P < 0.02$; ANOVA]. Fig. 3*c* shows that the group and state factors interacted on long-distance synchrony [$F(1, 16) = 6.5, P < 0.05$; ANOVA]: The size of synchrony patterns increased more for the long-time practitioners than for the controls from neutral to meditation states. These data suggest that large-scale brain coordination increases during mental practice.

Finally, we investigated whether there was a correlation between the hours of formal sitting meditation (for subjects

S1–S8, 9,855–52,925 h) and these electrophysiological measures for the long-term practitioners, in either the initial or meditative states (same values as in Figs. 2 and 3). The correlation coefficients for the relative, absolute, and phase-synchrony gamma measures were positive: $r = 0.79, 0.63,$ and $0.64,$ respectively, in the initial state, and $r = 0.66, 0.62,$ and $0.43,$ respectively, in the meditative state. A significant positive correlation was found only in the initial baseline for the relative gamma ($r = 0.79, P < 0.02$) (Fig. 3*d*). These data suggest that the degree of training can influence the spectral distribution of the ongoing baseline EEG. The age of the subject was not a confounding factor in this effect as suggested by the low correlation between the practitioner age and the relative gamma ($r = 0.23$).

Discussion

We found robust gamma-band oscillation and long-distance phase-synchrony during the generation of the nonreferential compassion meditative state. It is likely based on descriptions of various meditation practices and mental strategies that are reported by practitioners that there will be differences in brain function associated with different types of meditation. In light of our initial observations concerning robust gamma oscillations during this compassion meditation state, we focused our initial attention on this state. Future research is required to characterize the nature of the differences among types of meditation. Our resulting data differ from several studies that found an increase in slow alpha or theta rhythms during meditation (21). The comparison is limited by the fact that these studies typically did not analyze fast rhythms. More importantly, these studies mainly investigated different forms of voluntary concentrative meditation on an object (such as a meditation on a mantra or the breath). These concentration techniques can be seen as a particular form of top-down control that may exhibit an important slow oscillatory component (22). First-person descriptions of objectless meditations, however, differ radically from those of concentration meditation. Objectless meditation does not directly attend to a specific object but rather cultivates a state of being. Objectless meditation does so in such a way that, according to reports given after meditation, the intentional or object-oriented aspect of experience appears to dissipate in meditation. This dissipation of focus on a particular object is achieved by letting the very essence of the meditation that is practiced (on compassion in this case) become the sole content of the experience, without focusing on particular objects. By using similar techniques during the practice, the practitioner lets his feeling of loving-kindness and compassion permeate his mind without directing his attention toward a particular object. These phenomenological differences suggest that these various meditative states (those that involve focus on an object and those that are objectless) may be associated with different EEG oscillatory signatures.

The high-amplitude gamma activity found in some of these practitioners are, to our knowledge, the highest reported in the literature in a nonpathological context (23). Assuming that the amplitude of the gamma oscillation is related to the size of the oscillating neural population and the degree of precision with which cells oscillate, these data suggest that massive distributed neural assemblies are synchronized with a high temporal precision in the fast frequencies during this state. The gradual increase of gamma activity during meditation is in agreement with the view that neural synchronization, as a network phenomenon, requires time to develop (24), proportional to the size of the synchronized neural assembly (25). But this increase could also reflect an increase in the temporal precision of the thalamocortical and corticocortical interactions rather than a change in the size of the assemblies (8). This gradual increase also corroborates the Buddhist subjects' verbal report of the chronometry of their practice. Typically, the transition from the neutral

