Unlocking deep relaxation: the power of rhythmic breathing on brain rhythms

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The pandemic has exacerbated mental health issues across the world. The limited availability of mental health professionals is preventing many from seeking help, which highlights the need for easily available mental health care routines like yoga, breathing, and meditation. A breath-based meditation technique known as Sudarshan Kriya Yoga (SKY) harnesses the power of breath to induce deep relaxation and makes meditation easier for beginners and has proven beneficial across multiple conditions, including depression, anxiety, and hypertension. The exact EEG dynamics happening during the practice are not well understood. We collected EEG data from 43 subjects undergoing SKY and analyzed their brain rhythms before, after, and during various stages of the technique, and found that rhythmic breathing accentuates theta rhythms ($d = 0.63$) which allows for an easier transition to a relaxed meditative state predominant with delta-theta rhythms, reduced alpha power ($d = 1.70$) and aperiodic signals ($d = 2.04$).

The current global mental health crisis presents an alarming challenge as individuals worldwide grapple with rising levels of stress, anxiety, and depression. This escalating situation is further compounded by the limited availability of mental health resources, making it increasingly difficult for many to access the support they need. In the face of these constraints, the significance of easily accessible, self-managed practices like yoga, breathing exercises, and meditation cannot be overstated. These practices offer a practical and cost-effective means to manage mental well-being, making them vital tools in addressing this widespread issue.

Multiple studies have observed the benefits of meditation to boost mental and physical health[1]. Meditators show better emotional processing[2,3], empathy[4,5], and executive functioning of the brain[6]. Even short-term interventions of meditation bring about a reduction in fatigue, improved mood, and lowered anxiety and depression[7–9]. Meditators and yoga practitioners exhibit widespread brain changes in self-referential, attention, and executive networks[10]. Mindfulness training strengthens hippocampal circuits which allow for better fear extinction[3,11]. Meditators also exhibited connectivity changes between the Default Mode Network and Dorsal Attention Network[12–15] along with modifications in caudate and insular functional connectivity[16,17]. The striatum, anterior cingulate cortex, and amygdala also express decreased activations in meditators[1].

The Yoga Sutras of Patanjali, the de facto guide to the philosophy of yoga, considers postures (*asanas*), along with breathing practices (*pranayama*) and meditation, to be parts of the eight limbs to help achieve the state of the union (yoga) between the mind, body, and spirit. Breathing plays a crucial role in modulating brain activity. Studies have demonstrated the effect of breathing on mental states and electrical activity in the brain[18]. The sympathetic nervous system is triggered during stress responses and causes a change in breathing rhythms, and in contrast deep and controlled breathing induces the parasympathetic nervous system bringing about a relaxation response which can mitigate the stress response[19,20], help lower anxiety[21], reduce symptoms of PTSD[22], and alleviate depression[23]. Rapid breathing induces higher frequency oscillations whereas slow and deep breathing induces delta and theta oscillations[19,20]. Breathing practices allow an easier transition to deeper meditation states[24].

Though long-term practice of breathwork and meditation brings about changes across multiple networks in the brain, how are various brain dynamics affected during these practices? Research in Sahaja Yoga meditation has suggested that theta and alpha power in the midline and frontal regions increase during meditation[25]. Sahaj Samadhi meditation exhibited enhanced theta band activity in the frontal areas during deep meditation[26]. Transcendental meditation shows higher alpha coherence in anterior-posterior and frontal regions[27]. Brahmari *pranayama* is accompanied by an increase in paroxysmal gamma waves[28]. Studies have suggested that meditation styles vary across traditions, could be classified into multiple kinds, and have varied effects on the meditator along with different spatiotemporal dynamics[29].

Sudarshan Kriya Yoga (SKY) is a breathing-based meditation technique composed of specific postures (*asanas*), *pranayamas*, and cyclical breathing (*kriya*) which invokes a deep state of meditation and relaxation[21,30]

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using the breath as a way to control the modulations of the mind[24]. It is based on Yoga Sutras of Patanjali (PYS 2.49-2.51[31]) and has been extensively documented to be beneficial for the treatment of depression[23], stress-related medical illnesses, anxiety, post-traumatic stress disorder, substance abuse, and rehabilitation of criminal offenders[32]. It also potentiates natural host immune defenses with an increase in antioxidants and NK cells[33], and a decrease in cortisol and blood lactate levels[34].

Previous studies have attempted to determine the effects of SKY on the brain waves as detected using EEG[35,36]. SKY induces a state of wakeful alertness, and enhances theta band activity and coherence[37], stress regulation with enhanced workload tolerance capacity[38], and inter-hemispheric synchronization of the brain rhythms[39]. The analysis of these studies was limited to differences in the oscillatory activity before and after the SKY practice. The present paper is intended to observe the change in oscillatory dynamics for slow brain oscillations more linked to relaxation (alpha, theta, and delta waves)[19,20] and non-oscillatory signals during the different stages of SKY meditation practice by comparing it with baseline resting state EEG data collected prior to the start of the technique and analyse the brain rhythms of the deep relaxation state accompanied by the technique.

Methods

Participants

We recruited 43 subjects (23 M, mean age = 25.45, S.D = 5.75) without cardiovascular disease, diabetes, any psychological disorder, or with a history of epilepsy. Subjects were selected randomly from the Art of Living Foundation's Centre in Bengaluru, Karnataka, India. The research was advertised by the Human Resources Department and interested volunteers were selected. The participants had learned the SKY meditation prior to our research study and were regular practitioners. The experience with the SKY practice ranged from 1-18 years (mean=7 years). 15 subjects had more than 6 years of experience. Informed consent and permission were obtained from all subjects before the start of the study. The Ethical Committee of Ved Vignana Maha Vidya Peeth provided the ethical clearance for the research. The study was done following the human subjects research guidelines as stated in the Declaration of Helsinki.

We ran the experiment on control group subjects ($n = 10$, 4 males, mean age = 32.4, S.D = 11.71) who instead of going through the SKY protocol, listened to relaxing music during the entire duration.

Procedure for Sudarshan Kriya Yoga

Sudarshan Kriya Yoga, as practiced in a regular setting, consists of following phases: three stages of pranayama, bhastrika pranayama, om chanting, cyclical rhythmic kriya breathing and yoga-nidra meditation, all done with eyes closed. As part of the three-stage pranayama, the subject sits in the diamond posture (sitting on one's heels and hands resting on the thighs). For the first stage, the hands are placed on the hip bones (parallel to the ground). For the second stage, the hands are tucked deep into the arm pits. For the third stage, the hands are placed on the shoulder blades. The three stages are formed by 6-8 Ujjayi breaths (a slightly forceful breath with gentle throat contraction) with a cadence of breath in–hold–breath out–hold and takes about 10 minutes to complete. Afterward, the subject performs Bhastrika pranayama, in which forceful breaths are taken in and out along with up-and-down hand movements. It is done in three cycles consisting of 15–20 breaths and takes about 4–5 min. With the spine erect, the subject now sits comfortably and chants om three times. Kriya rhythmic breathing follows, where the subject is guided to breathe in and out, and it involves normal breathing in three different cycles (deep and slow 8–20 breaths; shallow and medium 40–50 breaths; short and fast 60–80 breaths). These three cycles are repeated without any break for about 25 min. Following this, a yoga-nidra session in the supine position is followed by eight minutes of silent relaxation, followed by a single gentle bell sound and a set of meditation instructions for twelve minutes on becoming aware of different parts of the body, starting at the feet and gradually progressing to the head. After that, the subject sits up with the spine erect, keeping their eyes closed, and continues relaxing. The procedure concludes with them opening their eyes when they are ready.

For the study, we asked the subjects to sit relaxed with their spine erect on a chair and not change positions during the different stages. The yoga-nidra was also done while sitting to avoid any displacement of the electrodes or motion artifacts. Following the session, participants were qualitatively assessed regarding their experience and were asked whether the practice resembled their daily routine and if they felt relaxed, to which all participants responded affirmatively.

Protocol

Figure 1 describes our experimental protocol. We recorded the EEG in sitting position with eyes closed for five minutes before the SKY practice, during the SKY practice, and for five minutes after the SKY practice for a total of around 1 hr 15 mins. Audio guided instructions allowed consistency in the frequency of breathing for all participants.

Electroencephalography (EEG)

A 24-channel EEG system, Superspec 24 (Recorders and Medicare Systems, Chandigarh, India) was used for data acquisition. We placed the electrodes according to the international 10-20 system. EEG was acquired from the frontal (FP1, FP2, F3, F4, F7, and F8), centro-temporal (T3, T4, C3, C4, FZ, CZ, PZ, T5, and T6), parietal (P3 and P4), and occipital (O1 and O2) regions. The ground at the forehead and earlobe reference was used for all electrodes. The system had a sampling frequency of 256 Hz and the bandpass filter of 0.1–75 Hz was applied. Impedance levels were kept under 5k. A temperature of 25°C was maintained throughout the experiment and the lights were kept dim to provide a comfortable space for meditation.

Analysis

The raw EEG data were sampled at 256 Hz. It was bandpassed between 0.1–75 Hz with a notch filter at the line frequency of 50 Hz. We analyzed the EEG data by dividing the paradigm into five phases: pre-resting (5 min), three-stage pranayama (10 min), kriya period (25 min), yoga-nidra period


Fig. 1 | Protocol and analysis. a Protocol for breath-based meditation. EEG was recorded in a 10/20 arrangement from participants undergoing the various steps in the Sudarshan Kriya Yoga (SKY) meditation which involved pranayama based breathing exercise for 15 min (the first 9 min analyzed in the paper) followed by the rhythmic breathing (kriya) followed by rest in the sitting position. Pre and post the meditation data recording represents resting state activity. **b** Analysis method: After data cleaning and preprocessing, spectral properties including the delta, theta, and alpha peak frequency, amplitude, and bandwidth were extracted along with aperiodic signal characteristics using the FOOOF toolbox. The diagram illustrates relevant features extracted from the frequency spectrum.
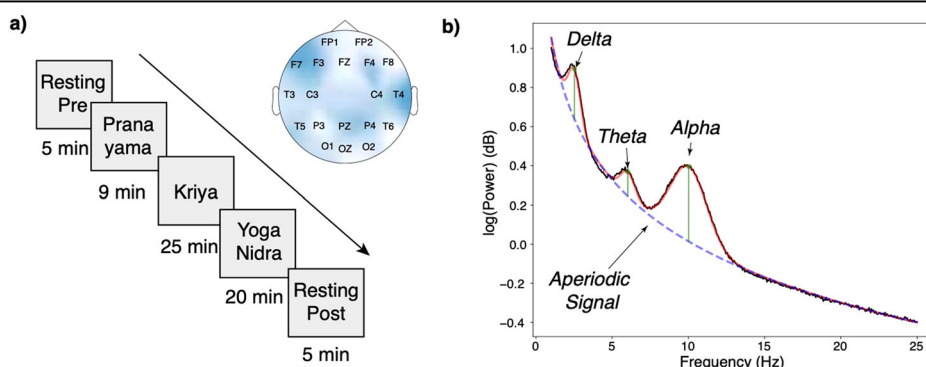
(20 min), and post-resting period (5 min). We did not analyze the bhastrika pranayama period which had large motion artifacts due to hand movements. We screened the data visually to remove mechanical and motion artifacts. F7 and O2 channels were removed due to excess noise across multiple (31) subjects during the paradigm. Overall, 7% of the data were removed due to noise. We utilized the mono-polar montage of channels, followed by referencing it with Cz. We used the Multitaper Spectral Analysis toolbox[40] (https://github.com/preraulab/multitaper_toolbox) to compute the spectrogram. Multitaper spectral analysis allows for a better estimation of the spectrogram of continuous time series data by incorporating multiple taper functions around our time window, which reduces variance by lowering power around the edges. In the toolbox, the parameters that control the algorithm include time window size (which we set to two seconds), and time-half bandwidth product of 2 which relates the frequency resolution (1 Hz) to the time window size. We set the number of tapers for the multitaper spectral estimation to three and the frequency range between 0.1 and 45 Hz. We used a moving window of 2 seconds with a step size of 1 s which resulted in a frequency spectrum at each second of the entire SKY technique. We then used the Fitting Oscillations and One Over F(FOOOF) toolbox[41] to extract spectral parameters from the spectrum at each time point (2 s window size, 1 s shift) resulting in model fit for each second of SKY practice. The FOOOF toolbox extracts the aperiodic signal for the entire spectrogram (0.1-45 Hz) and then computes the peaks apriori from the spectrogram. The default FOOOF model was run with the parameters (minimum peak height of 0.05 and max number of peaks at 5) and the model fit was highly accurate across the channels with

an averaged R-squared value greater than 0.75 across all subjects and channels. We then characterized the peaks as delta with frequency between 1–4 Hz, theta between 4–7 Hz, and alpha between 7–13 Hz. The aperiodic signal had an exponent and offset component. We extracted the peak frequency, amplitude, and band-width for the three rhythms and the aperiodic exponent value at each spectrum. We averaged the peak frequency, amplitude, and band-width components across these separately across the five phases.

To compare the peak frequency, amplitude, and band-width across the different phases, we performed a one-way repeated measures ANOVA where the independent variable was phase of the practice and the dependent variable was one among amplitude, peak frequency or band-width. We computed the ANOVA separately for each channel followed by Tukey's pairwise post hoc analysis across various phases using the statsmodels package in Python 3.7[42]. We tested for normality using the Schapiro Wilks test using the Scipy package in Python[43]. We repeated it across the seventeen channels and Bonferroni corrected it to reduce multiple comparisons error. We utilized Bonferroni correction to control for the potential inflation of Type I error rates, as our analysis involved multiple comparisons across 18 EEG channels and different rhythmic parameters. We highlighted all the relevant channels with significance after Bonferroni correction in Figs. 2–5b and selected one of the significant channels for across subjects and time analyses in panels a and c of Figs. 2–5. ChatGPT4 was used to refactor some of the text in the manuscript with the query "Kindly suggest alternative ways of rephrasing 'X'. The authors take full responsibility for the accuracy of the text in the manuscript.
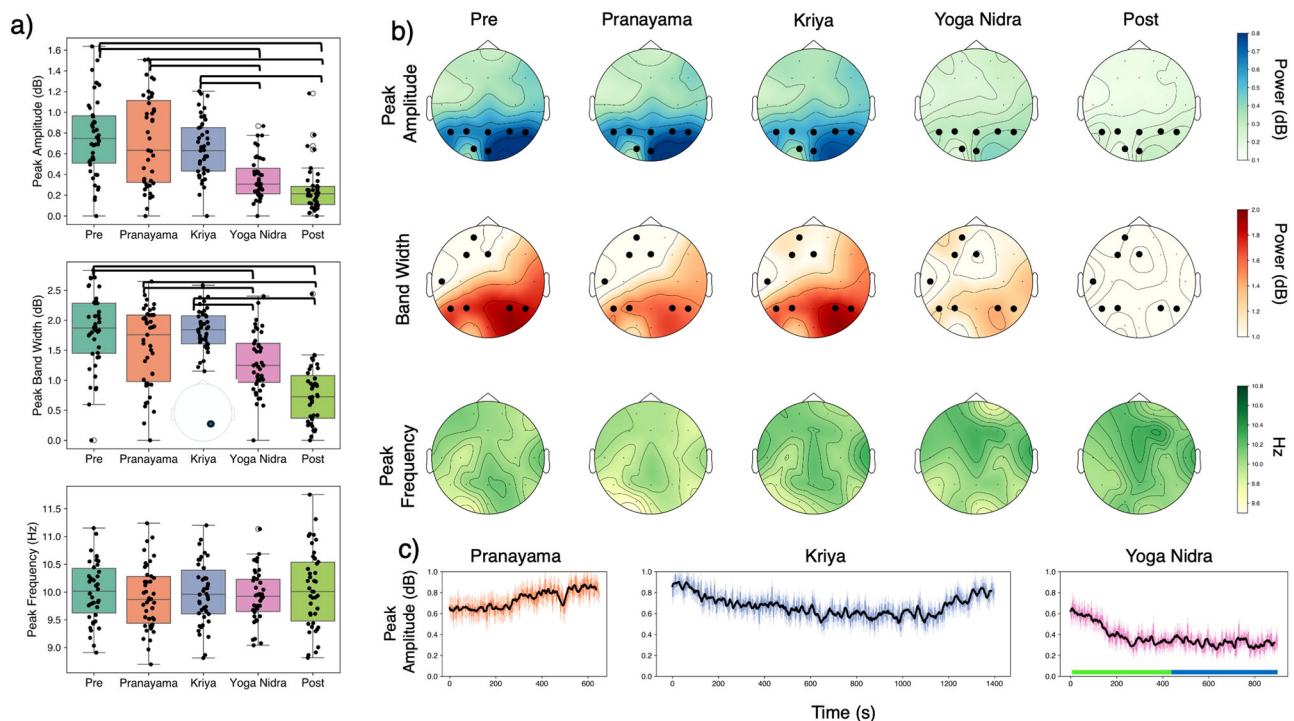
Fig. 2 | Effect on alpha wave dynamics. a Bar plots show the peak amplitude, band-width, and frequency for the alpha band computed using the FOOOF toolbox for the P4 channel. The middle panel highlights the selected channel on the topomap. Pairwise comparisons are shown using brackets with significance $p < 0.0001$. We saw significant reductions in peak alpha amplitude between breathing (pranayama, kriya) and yoga nidra phases coupled with the decrease of band width during yoga nidra period. **b** Topomap plots for the peak amplitude, band-width and peak frequency for the alpha waves across the various parts of the SKY meditation - pre-resting state, pranayama breathing, kriya breathing, yoga-nidra, post-resting state. Dots on the channels signify statistical significance at $p < 0.00001$ from a repeated measures ANOVA ran across the five phases of SKY per channel individually. The

most significant changes in activity were observed in the parietal and occipital areas for the peak alpha amplitude and the fronto-parietal areas for the alpha band width. **c** Change of peak alpha amplitude (dB) of the P4 channel across time during pranayama, kriya, and yoga-nidra phases. The colored line denotes the peak alpha value at each time point, the light color bar is the standard deviation across subjects and the black line denotes the moving average of the mean signal with a window of 4 s. The yoga-nidra phase was divided into the silent (green) and guided instructions (blue) parts as highlighted in the third panel. The first 100 s each phase were not plotted. We see a slow decrease in the alpha amplitude during the kriya phase which sharply drops during the yoga-nidra phase highlighting the transition to a relaxed state with reduced feedback signals denoted by the reduction in alpha amplitude.

Results

We collected EEG data (in 10/20 arrangement) across 43 subjects when they went through the SKY technique composed of various breathing exercises (*pranayama*) and cyclical breathing (*kriya*) followed by yoga-nidra meditation. We collected eyes-closed resting state data before and after the SKY technique. Subjects were asked to sit on a chair comfortably and follow the instructions of the researcher.

To analyze the data across the different parts of the SKY meditation, we divided the duration into five phases: resting-pre, pranayama, kriya, yoga-nidra, and resting-post (Fig. 1a). We extracted the peak frequency, amplitude, and band-width component (described in the methods section) for each period (as illustrated by the graphical description of our method in Fig. 1b). The power spectral densities during various events can be observed in Fig. S1. The components in the alpha (7–13 Hz), theta (4–7 Hz), delta (1–4 Hz) bands, and aperiodic signals were compared across the five phases. Aperiodic signals are non-periodic signals which do not repeat over time unlike other bands like alpha, theta etc. These signals can represent non-repeating signals which occur spontaneously and can represent one off cognitive process or random disturbances. They are estimated using the slope of the power spectral density curve, the 1/f exponent using a Python-based toolbox called FOOOF[41](further details in the methods section). Figure S2 highlights the ability of the FOOOF model to fit across delta, theta, alpha rhythms and detect the aperiodic slope with high precision.

Impact on alpha rhythm

Figure 2 illustrates the alpha band-width, peak frequency, and amplitude across the five phases. The repeated measures ANOVA was applied for the five phases across the subjects for each channel's band-width, frequency, and amplitude separately. We corrected for multiple comparisons across channels using Bonferroni correction. A statistically significant decrease of alpha peak amplitude in the parieto-temporal and occipital regions (P4, P3, PZ, T5, T6, O1, and OZ channels) was observed as the SKY meditation progressed (P4 channel: $F(4,164) = 49.44$, $p < 0.00001$). Yoga-nidra ($M = 0.36$, $SD = 0.15$) and post-resting period ($M = 0.23$, $SD = 0.19$) had lower alpha amplitude as compared to the earlier phases of the pre-resting state ($M = 0.72$, $SD = 0.36$), pranayama ($M = 0.68$, $SD = 0.42$) and kriya ($M = 0.64$, $SD = 0.27$). No other pairs had significant differences. We observed a gradual decrease in the peak amplitude during the yoga-nidra period as can be seen from the last panel in Fig. 2c. The peak frequency did not change across the phases (P4: $F(4164) = 1.00$, $p = 0.411$). The band-width decreased significantly in parietal-temporal and frontal regions (FP1, F3, FZ, T3, T5, T6, and P3) with $F(4164) = 45.38$, $p < 0.00001$ (P4 channel). Yoga-nidra ($M = 1.40$, $SD = 0.49$) period had lesser band-width as compared to Pre resting state ($M = 1.88$, $SD = 0.57$) and pranayama period ($M = 1.62$, $SD = 0.69$). No other pairs had significant differences using Tukey's post hoc analysis. All statistics reported here are for P4 channel. Supplementary Table 1 lists the mean and standard deviation value along with pre and post-differences (Cohen's d) for each of the alpha rhythm parameter across subjects.
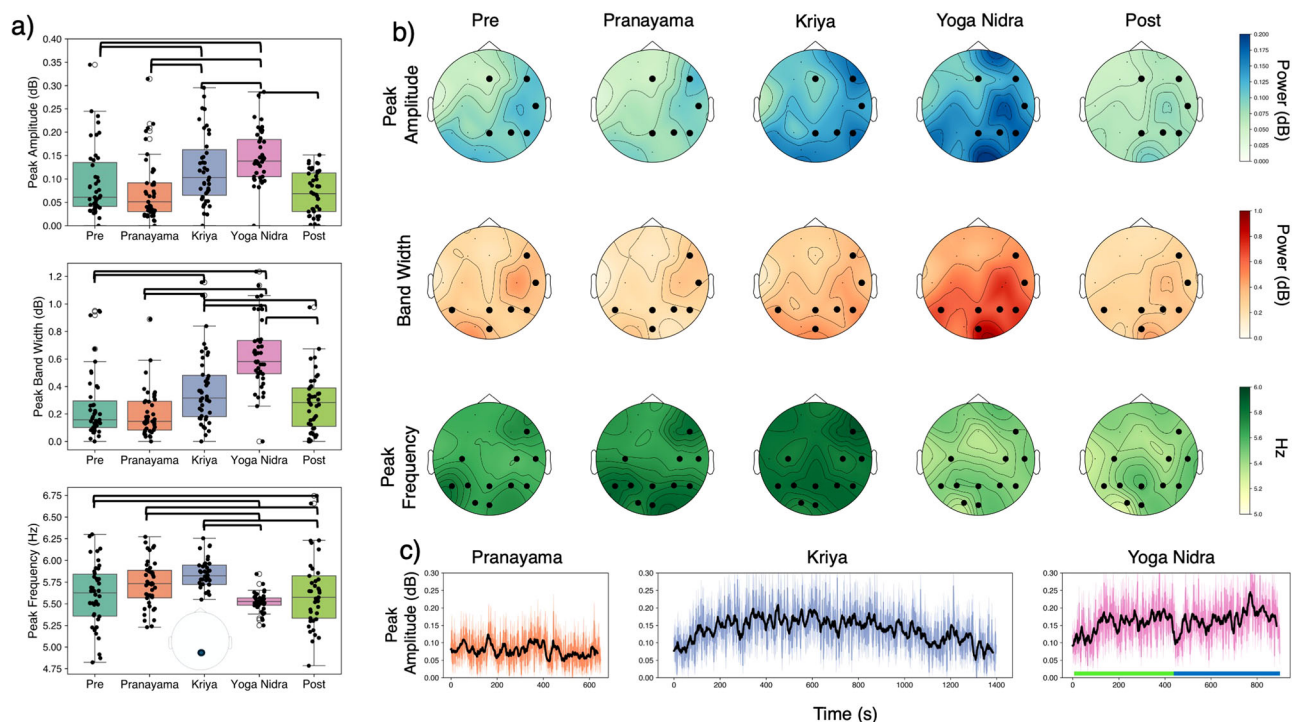
Fig. 3 | Effect on theta wave dynamics. a Bar plots show the peak amplitude, band-width, and frequency for the theta band computed using the FOOOF toolbox for the PZ channel. The bottom panel highlights the selected channel on the topomap. Pairwise comparisons are shown using brackets with significance $p < 0.0001$. We saw significant changes in peak amplitude which was maximum during the kriya phase and sustained afterwards. The theta bandwidth increased during the yoga nidra period accompanied by a shift to a lower peak theta frequency value. **b** Topomap plots for the peak amplitude, band-width, and peak frequency for the theta waves across the various parts of the SKY meditation -pre-resting state, pranayama breathing, kriya breathing, yoga-nidra, post-resting state. Dots on the channels signify statistical significance at $p < 0.00001$ from a repeated measures ANOVA ran across the five phases of SKY per channel individually. We saw the most significant changes in the peak amplitude in frontal, temporal and parietal channels. Band-width and peak frequency changes were significant along the temporal, parietal-central, and occipital channels. **c** Change of peak theta amplitude (dB) of the PZ channel across time during pranayama, kriya, and yoga-nidra phases. The colored line denotes the peak theta value at each time point, the light color bar is the standard deviation across subjects and the black line denotes the moving average of the mean signal with a window of 4 s. The yoga-nidra phase was divided into the silent (green) and guided instructions (blue) parts as highlighted in the third panel. The first 100 s in each phase were not plotted. We observe sharp increases in theta power during the kriya and yoga-nidra phases. The dip during the yoga-nidra period denotes the transition to audio-guided meditation instructions after the end of silence period. We found that the theta rhythms increased during the kriya phase and were sustained during the yoga nidra period as well.
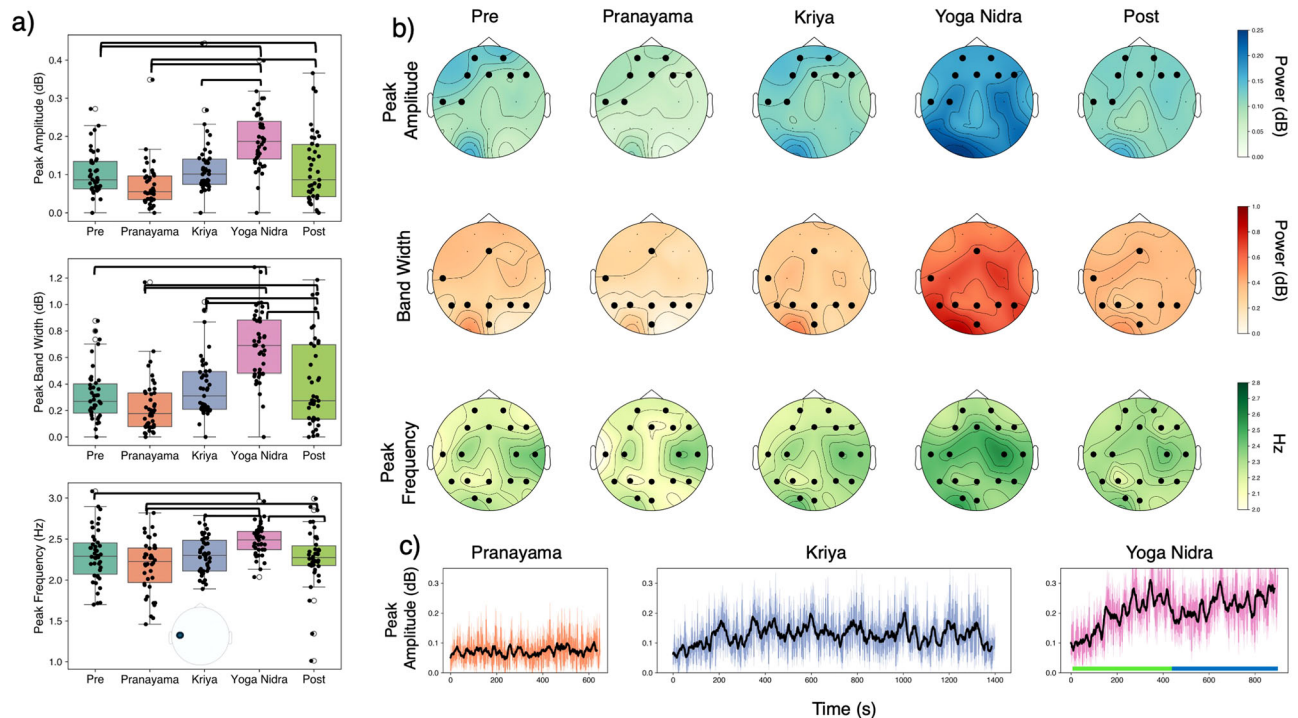
Fig. 4 | Effect on delta wave dynamics. a Bar plots show the peak amplitude, bandwidth, and frequency for the delta band computed using the FOOOF toolbox for the T5 channel. The bottom panel highlights the selected channel. Pairwise comparisons are shown using brackets with significance $p < 0.0001$. We saw significant changes in peak amplitude increased during the kriya phase and further enhanced during yoga nidra period. The delta bandwidth increased during the yoga nidra period accompanied by a shift to a higher peak delta frequency value.
b Topomap plots for the peak amplitude, bandwidth, and peak frequency for the delta waves across the various parts of the SKY meditation - pre-resting state, pranayama breathing, kriya breathing, yoga-nidra, post-resting state. Dots on the channels signify statistical significance at $p < 0.00001$ from a repeated measures ANOVA ran across the five phases of SKY per channel individually. We saw the most significant changes in the peak amplitude in frontal and temporal channels. Bandwidth changed mostly along parieto-occipital channels whereas peak frequency

changes were significant across the whole brain. **c** Change of peak delta amplitude (dB) of the T5 channel across time during pranayama, kriya, and yoga-nidra phases. The colored line denotes the peak delta value at each time point, the light color bar is the standard deviation across subjects and the black line denotes the moving average of the mean signal with a window of 4 s. The yoga-nidra phase was divided into the silent (green) and guided instructions (blue) parts as highlighted in the third panel. The first 100 s in each phase were not plotted. Delta amplitude further increases during the yoga-nidra period suggesting a state of deep relaxation and meditation. The dip during the yoga-nidra period denotes the start of guided instructions for meditation, suggesting a temporary awareness followed by progressive relaxation. We found that the delta rhythms increased during the kriya phase and were sustained during the yoga nidra period as well with sharp transition during the start of guided instructions eventually coming back to the higher delta state during the relaxation period.

Impact on theta rhythm

We then analyzed the theta band-width, peak frequency, and amplitude across the five phases (as illustrated in Fig. 3) and observed that the theta peak amplitude increases significantly (PZ channel: $F_{(4164)} = 13.24$, $p < 0.00001$) during the kriya period and stays high afterward in the frontal, temporal and parietal regions (FZ, F8, P4, PZ, T4, T6). Statistical differences were observed between kriya ($M = 0.13$, $SD = 0.11$) period and pre-resting state ($M = 0.09$, $SD = 0.07$); yoga-nidra period ($M = 0.15$, $SD = 0.06$) and pranayama ($M = 0.08$, $SD = 0.07$) period. We found that theta band-width during the yoga-nidra period in the temporal-parietal regions (T4, T5, T6, P4, PZ, F8, OZ) and sustained during the post-resting phase (PZ: $F_{(4164)} = 35.98$, $p < 0.00001$). Tukey's post hoc differences were observed between the yoga-nidra period ($M = 0.63$, $SD = 0.25$) and the three earlier phases: pre ($M = 0.25$, $SD = 0.24$), pranayama ($M = 0.20$, $SD = 0.17$) and kriya ($M = 0.38$, $SD = 0.25$). Pairwise differences between post ($M = 0.28$, $SD = 0.21$) and pranayama and kriya were also significant. The theta peak frequency stayed consistent across right frontotemporal and parieto-occipital regions (T4, T5, T6, P3, P4, PZ, O1, OZ) till the kriya period and then decreased during the post resting phase (PZ Channel: $F_{(4164)} = 6.96$, $p < 0.00001$) We found Tukey's post hoc differences between post ($M = 5.63$, $SD = 0.40$) and earlier phases: pre ($M = 5.59$, $SD = 0.36$), pranayama ($M = 5.79$, $SD = 0.30$) and kriya ($M = 5.83$, $SD = 0.19$) and between yoga-nidra period ($M = 5.53$, $SD = 0.10$) and kriya. The variances across the parameters during the yoga-nidra period were very low suggesting a high

degree of similarity in the state across subjects. Figure 3c illustrates the sustained increase in theta peak amplitude during the kriya and the yoga-nidra period. All statistics reported here are for the PZ channel. Supplementary Table 2 lists statistics for all channels related to theta parameter changes.

Impact on delta rhythm

Looking at the delta band components (Fig. 4), we find that delta rhythm amplitude increased across the whole brain during the yoga-nidra period (T5 Channel: $F_{(4,164)} = 37.19$, $p < 0.000001$). Statistical differences using Tukey's post hoc analysis indicated that delta amplitude was higher for yoga-nidra ($M = 0.22$, $SD = 0.09$) period as compared to other phases: pre ($M = 0.08$, $SD = 0.05$), pranayama ($M = 0.05$, $SD = 0.04$), kriya ($M = 0.12$, $SD = 0.08$), post($M = 0.11$, $SD = 0.10$). We also detected a pairwise difference between post-resting state delta amplitude and pranayama. We found similar statistics for other channels listed in the supplementary Table 3. Delta band-width increased significantly in the parietal-temporal and occipital regions (T3, P3, PZ, P4, T6, OZ, FZ) during the yoga-nidra and post resting state phase (T5 channel: $F_{(4,164)} = 49.03$, $p < 0.00001$, Pre ($M = 0.23$, $SD = 0.18$), pranayama ($M = 0.13$, $SD = 0.12$), kriya ($M = 0.33$, $SD = 0.20$) phases had less band-width than yoga-nidra ($M = 0.74$, $SD = 0.29$); difference was also observed between pranayama and post ($M = 0.38$, $SD = 0.36$) resting phases. Peak delta frequency first increased slightly during yoga nidra period ($M = 2.40$, $SD = 0.16$) as compared to pre
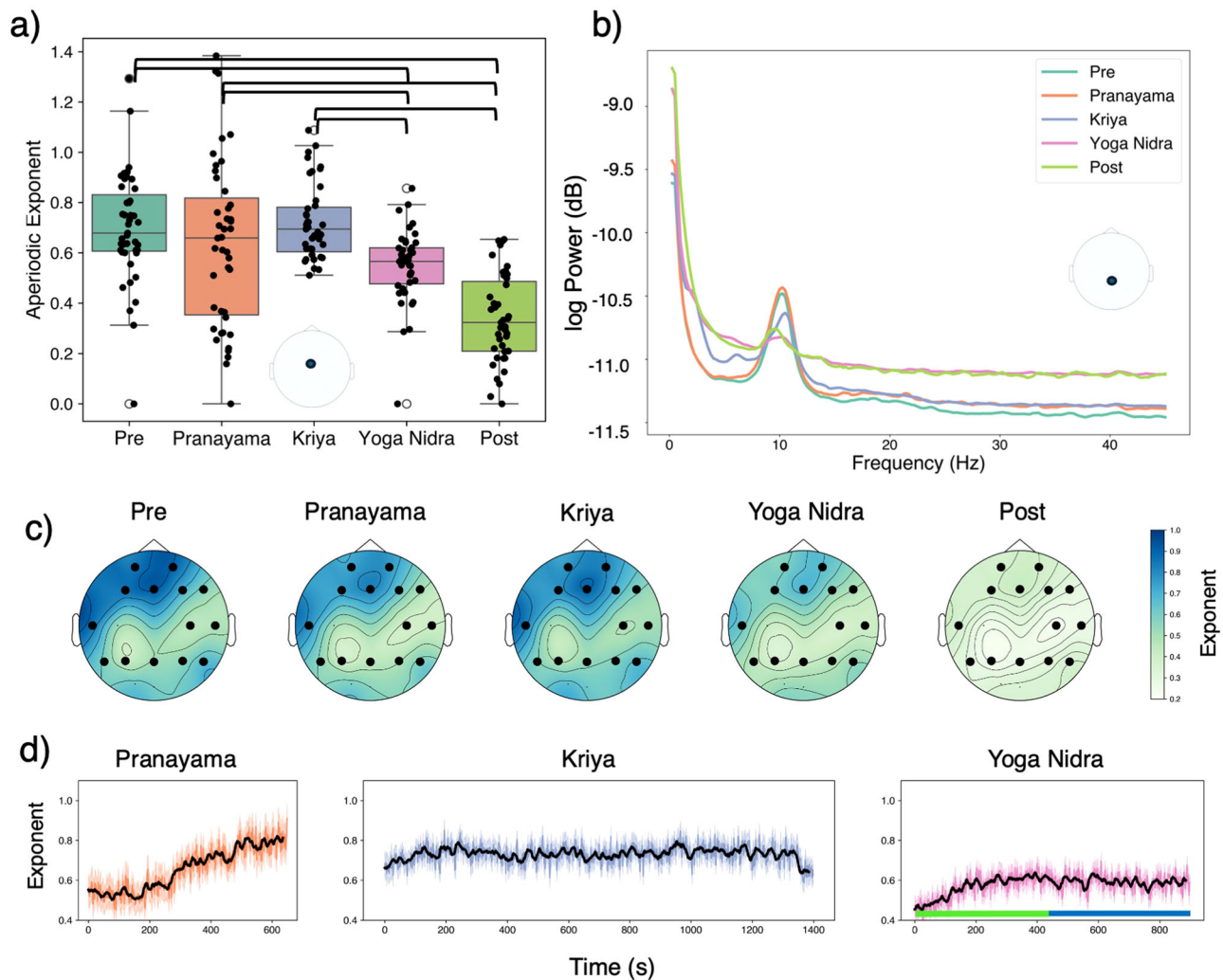
Fig. 5 | Effect on aperiodic signal exponent (1/f slope). a Bar plots show the aperiodic exponent computed using the FOOOF toolbox for the F4 channel across the five phases in the SKY technique. The panel highlights the selected channel on the topomap. Pairwise comparisons are shown using brackets with significance $p < 0.0001$. The aperiodic exponent dropped significantly during the yoga nidra phase. **b** Spectrum plot (Power v/s frequency) for each of the phases averaged across subjects for channel PZ. The plot becomes flatter as the SKY technique progresses, highlighting the change in the 1/f aperiodic characteristics of the spectrum. **c** Topomap plots for the aperiodic exponent across the various parts of the SKY meditation - pre-resting state, pranayama breathing, kriya breathing, yoga-nidra, post-resting state. Dots on the channels signify statistical significance at $p < 0.00001$ from a repeated measures ANOVA ran across the five phases of SKY per channel individually. The most significant changes were observed across frontal, parietal, and right temporal regions. **d** Change of aperiodic exponent of the FZ channel across time during pranayama, kriya, and yoga-nidra phases. The colored line denotes the aperiodic exponent at each time point, the light color bar is the standard deviation across subjects and the black line denotes the moving average of the mean signal with a window of 4 s. The yoga-nidra phase was divided into the silent (green) and guided instructions (blue) parts as highlighted in the third panel. The first 100 s in each phase were not plotted. We saw an increase in aperiodic signals during pranayama followed by sustained activity during kriya period followed by a sharp decrease across the channel during the yoga-nidra phase.

($M = 2.17$, SD = 0.41), pranayama ($M = 2.15$, SD = 0.30), kriya ($M = 2.24$, SD = 0.25) and then decreased afterwards ($M = 2.32$, SD = 0.34) (T3 channel: $F(4,164) = 27.79$, $p < 0.00001$). We find a similar trend across frontal and left temporal regions (FP1, FP2, F3, FZ, F4, F8, C3). Just like theta rhythms, we also found low variances across the parameters with delta rhythm highlighting that the delta-theta dominant meditative state is very robust and similar across subjects. Within period differences also occur where Fig. 4c depicts a sharp rise in delta amplitude during the yoga-nidra period suggesting a transition to a deep meditative state unencumbered by external stimuli highlighted by the decreased alpha amplitude. Such a relaxed and internal oriented state has been classified as the state of samadhi in Yogic texts[24]. All statistics reported here are for the T5 channel. Supplementary Table 3 lists statistics for all channels related to delta parameter changes.

Impact on aperiodic signals

Recent literature on aperiodic signals[41,44,45] has discovered the association of the exponent of the aperiodic signals with age-related decline, states of consciousness[46], attention and working memory[47], and even meditation[48]. As illustrated in Fig. 5a, we observe a sharp decrease in the aperiodic exponent across the whole brain during the yoga-nidra and post-resting period (FZ Channel: $F(4,164) = 55.71$, $p < 0.00001$, Tukey's post hoc differences between yoga-nidra ($M = 0.68$, SD = 0.17) and first three phases: pre ($M = 0.91$, SD = 0.29), pranayama ($M = 0.81$, SD = 0.40), kriya ($M = 0.88$, SD = 0.23), similar differences were observed between post-resting state ($M = 0.41$, SD = 0.19) and first three phases). Figure 5b depicts the change in the spectral power across the five phases. The spectral plot during the yoga-nidra and post-resting state becomes flatter with the exponent (slope of 1/f) becoming smaller. A similar trend can be observed in the time series of the exponent change represented in Fig. 5d.

Supplementary Table 4 lists statistics for all channels related to aperiodic parameter changes.

Behavioral correlations and control participants

We also correlated the EEG indices with the number of days of meditation practice and found no significant correlations (effect sizes in range 0.15–0.25, all $p > 0.05$). We compared the dynamics during SKY practice with control subject ($n = 10$) (supplementary material, Figure S3) who listened to music during the matched time period. They did not show differences across various spectral bands suggesting that the changes in brain dynamics during SKY practice are technique dependent.

Discussion

Our research fills a critical gap in understanding the EEG spatiotemporal dynamics during different phases of SKY breath-based meditation. We found that the kriya period of SKY meditation is marked by an increase in theta power, while the yoga-nidra period shows a decrease in alpha power, a sustained increase in theta and delta power, and a reduction in the 1/f aperiodic signal exponent. This pattern suggests a transition to deeper meditation states, like *samadhi*[24] which is a meditative state where the mind and intellect are in equanimity (*sama* means equanimous and *dhi* mean intellect). It could also be interpreted as a state of being where the meditator is not engaged in any action and is just being with no top-down executive signals (thus reduced beta and alpha) accompanied with reduced signals from the thalamus to the cerebral cortex[49–52].

The impact of breathing on neuronal oscillations is significant, as seen in both surface and intracranial recordings in animal models and humans, showing that altered breathing patterns correlate with changes in theta rhythms, which is consistent with our findings[53–57]. Breathing not only affects neuronal activity in specific brain areas but also induces synchronized oscillations across the brain, suggesting it acts as a fundamental rhythm organizing various cognitive processes[58,59]. The SKY technique, through pranayama and cyclical breathing, seems to entrain the brain into a relaxed state dominated by theta and delta rhythms. This is consistent with existing literature demonstrating the efficacy of breath-based interventions in alleviating mental health issues like anxiety, depression, and PTSD[32,60].

During SKY meditation, we observed a decrease in alpha amplitude in the parietal-temporal and occipital regions, particularly during the yoga-nidra period. Alpha rhythms, typically associated with sensory inhibition and information processing[61–65], seem to play a role in attention and alertness[49,66–69]. Recent studies have shown that it is associated with arousal following sleep[52] and closely linked with thalamocortical activity that follows arousal. Another study[49] investigated the propagation of alpha rhythm and found that it is a feedback signal from higher order to lower order brain areas. Alpha propagates from the anterosuperior parietal areas to the occipital cortex which is predominantly seen during eyes closed condition. Alpha reduction during SKY meditation may suggest a decrease in sensory feedback[69] and a more relaxed mental state. Variations in meditation styles likely contribute to differing impacts on alpha rhythms, as seen in focused attention or open monitoring meditations where there is a top down signal as compared to more non-action techniques like Sahaja Yoga meditation[25,70–72]. We also find a decrease in the alpha bandwidth in frontal midline regions follows the decrease in the alpha amplitude highlighting the reduction in alpha due to SKY.

Theta rhythms (4–7 Hz), known for their role in a range of cognitive tasks[73–78], possibly originate in the frontal midline regions including the prefrontal cortex and anterior cingulate cortex[79,80]. Theta activity has been associated with attentional engagement[81] and the autonomic system[82], and shows an increase during various meditation practices like focused attention, open monitoring, loving-kindness, and transcendental meditation[37,83–85]. Our findings reveal an increase in peak theta frequency and amplitude in the frontocentral regions during the kriya breathing period, shifting to a low theta peak frequency with increased bandwidth during yoga-nidra, likely reflecting changes in the autonomic nervous system balance related to rhythmic breathing.

Our study also highlights changes in delta oscillations, particularly an increase in peak delta amplitudes and frequency in the frontocentral regions during the kriya period. The pranayama breathing phases, however, did not show significant changes in delta wave parameters. The observed increase in delta activity during the yoga-nidra period suggests a transition to a more relaxed state, aligning with previous findings on meditation and delta activity[86–88]. However, we should note that some prior research on different meditation styles shows a reduction in delta frequency[83], whereas delta waves are stronger during the early stages of sleep. The combination of delta-theta activity can serve as an important biomarker for the state of deep relaxation and allow for easy tracking of meditation progress given the easy availability of commercial EEG measuring devices.

SKY technique through the use of breath brings people to a relaxed meditative state which is characterized here by decreased alpha power and increased theta/delta power. The observations align with what was observed in studies on Transcendental meditation[27] where the practice results in an increase of fronto-parietal theta and delta waves. Similar results are also found for Sahaj Samadhi meditation[37] which results in an effortless relaxed concentrative state. These results are different from what we observe from meditation paradigms like focussed attention (Anapanasati), loving kindness, or other forms of meditation that requires attention to a certain object either mental or physical where we see an increase in alpha power[29]. Different kinds of meditation have varied goals, and thus involvement of different mental processes. Whereas SKY is utilized to bring about a deep relaxation in the practitioner which can then enable to access deep meditative states like Samadhi[24], other meditation styles are intended towards developing compassion (Loving Kindness), friendship (metta) and develop focus in the mind (focussed attention). Since the objectives of these meditation styles are inherently different, we do not see any contradiction in our results with those from other meditation styles.

An interesting observation is the nudge we observe during the yoga-nidra phase around the eight-minute mark where the silent meditation ends and gentle meditative instructions follow. We see a slight decrease in the theta and delta amplitudes which gradually increase back suggesting a temporary sway from the deep relaxation state. The transition from a quite state to incoming sensory data would have triggered the salience network which could have pushed the thalamus to start the relay of the sensory signals which is highlighted by the increase in alpha rhythm and decrease in theta and delta[49,51,52]. And as the meditator follows those instructions starts to go back into the absorptive delta and theta state. Further investigation would be required to determine if these sensory signals impact the absorptive samadhi state and track brain signals associated with the shift and reorienting.

The 1/f aperiodic signal dynamics observed during meditation are intriguing, reflecting changes in states of consciousness and cognitive tasks[89,90]. Our study noted a decrease in the 1/f aperiodic signal during meditation, hinting at an increased excitation-inhibition (E:I) balance in the brain. This contrasts with other states like drug-induced unconsciousness, where the spectral exponents show different patterns[46,91]. Prior findings on meditation have also shown an increase in the aperiodic exponent[48,92] in contrast with the present study. One reason could be that both studies investigated the focused attention meditation paradigm which requires holding attention on an external or internal object (point in front, breath etc.). It involves a top down attention process which would be different from the samadhi like state reached after the SKY technique. This finding underscores the distinct nature of meditation-induced brain states and highlights the need for further research using more detailed methodologies, such as intracranial recordings, to understand these changes in detail. Also, aperiodic signal estimation is still a work in progress[93] and small errors in exponent estimation can cause significant errors in the determination of periodic oscillation parameters.

The focus of the current study was to analyze the brain dynamics during the different phases of the SKY technique across experienced meditators. This observation aligns with other research showing altered baseline physiology and brain wave patterns in long-term meditators[94–97]. Future research

should extend to include novice practitioners and simultaneous imaging modalities like EEG/fMRI to understand detailed brain dynamics during the SKY technique and how experience influences various brain states.

The research has some limitations like we did not collect additional data like EOG that could have allowed us to regress out eye motion signals and confounds for our estimation of various rhythm parameters. We also did not collect quantitative data about how relaxed the participants felt, we qualitatively assessed their relaxation as compared to their daily practice. Future research should employ use of state estimation questionnaires to determine how relaxed the participant felt in the laboratory setting. Future studies should also look at how beta and sensorimotor rhythm (SMR) dynamics change with breathwork-based meditation protocols.

In conclusion, our findings underscore the significant role of SKY breath-based meditation in altering brain rhythms, particularly in theta and delta frequencies, associated with deep relaxation and mental well-being. This study not only contributes to the understanding of the neurophysiological effects of SKY meditation but also highlights the broader importance of exploring such techniques for mental health improvement. Given the global mental health crisis and the limitations in mental health resources, the accessibility and utility of meditation and similar practices offer a promising avenue for supporting individual mental health. The observed EEG changes during SKY meditation suggest its potential to foster a relaxed mental state, an aspect crucial in the context of rising stress and anxiety levels worldwide. These signatures can help track a relaxed state and could be helpful in designing a meditation-based neurofeedback tool for people with anxiety who have trouble relaxing. Further research in this area is essential to fully unravel the therapeutic potential of meditation and similar practices in mental health care.

Data availability

The dataset is publicly available in the Figshare repository (https://doi.org/10.6084/m9.figshare.6823094.v1).

Code availability

Publicly available toolboxes like FOOOF (https://fooof-tools.github.io/fooof/) and Multitaper spectrogram (https://prerau.bwh.harvard.edu/multitaper/) are used in the study. The code to create specific figures is available in the form of Jupyter Notebooks on request to the corresponding author V.T.

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Author contributions

Competing interests

The authors declare no competing interests.

Additional information