RESEARCH PAPER

Neurophysiological Effects of Pranayama on Brain-Wave Modulation: An EEG-Based Analytical Study of Alpha, Beta, Theta, and Delta Activity

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Abstract
Background: Pranayama is usually defined as slow nasal breathing and involves the control of the breathing rate, route, and timing, accompanied by a high degree of concentration. It is still not clear how this type of breathing exercise influences the autonomic system and respiration-coupled neural activity, and little research has been done to measure the effects of pranayama on the four major brain wave frequencies — alpha, beta, theta, and delta — in a controlled setting. The objective of this work is to provide the basis of an analytic framework based on electroencephalography (EEG) to assess the short-term effects of Nadi Shodhana pranayama in a highly regulated experiment as compared to quiet seated rest. The example synthetic demonstration data used in this work included a sample of 60 healthy adults who participated in one of the two conditions of either 20 minutes of pranayama or seated rest. Baseline (T0) and resting, eyes-closed EEG were collected post-condition (T1) and post a 10-minute recovery period (T2). Change in relative spectral power for the 4 frequency bands (delta, theta, alpha, beta) was computed. A 2 (condition) by 3 (time) mixed analysis of variance (ANOVA) was performed, and each of the group, time, and group-by-time effects were analyzed. The primary analysis was augmented with effect sizes, Holm-adjusted contrasts, correlations, and multiple regression. Findings: A significant interaction effect for group and time was found for alpha power, $F(1.48, 85.56) = 7.13$, $p = 0.004$, partial $\eta^2 = 0.110$. In the pranayama group, alpha power increased (adjusted mean: 2.48) compared to the control group (adjusted mean: 0.37) with an approximate 95% confidence interval of 0.64 to 1.74 for Hedges $g = 1.19$. A clear interaction was found for beta power, while effects for delta and theta were much smaller and interpreted based on p-values and intervals. The pranayama condition resulted in more favorable outcomes for breathing rate, heartIn this synthetic analytical demonstration, it was found that pranayama brought about a considerable increase in alpha power and brought about a reduction of beta power when compared to quiet rest. The differences seen in theta and delta of the groups were small and of no statistical significance. The framework shows how upcoming preregistered studies can capture the integration of EEG quality control, repeated-measures modelling, effect-size estimation and open data practices.
Keywords: pranayama; electroencephalography; alpha rhythm; beta activity; theta activity; delta activity; slow breathing; quantitative EEG
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1. Introduction

Pranayama is the general term for a wide range of yogic breathing methods that use control of the rate, depth, and path of breath, as well as the duration of breathing phases, and focus. In modern psychophysiology, these methods are treated as structured respiratory interventions, rather than as a unified exposure. This will matter, as slow alternate nostril breathing, humming exhalation, rapid bellows breathing, and simple breath awareness all have distinctly different sorts of mechanical stimulation, gas exchange, autonomic loading, sensory feedback and cognitive demand. Controlled and synthesis studies that are currently available suggest that breath-based interventions affect arousal, affect and autonomic markers, but the size and direction of the effect depend on the intervention and the comparison condition (Balban et al., 2023; Fincham et al., 2023; Laborde et al., 2022).

With an electroencephalogram (EEG), population-level neural oscillations can be measured non-invasively and in real time. When focusing on analyses of resting state neural oscillations in the delta, theta, alpha, and beta bands, these bands cannot be directly correlated with 'negative' or 'positive' states of mind. Alpha power is implicated in functional inhibition and sensory disengagement and may be associated with an intention to shift 'inward' and 'relaxed' wakefulness, as well as theta, which may be involved in 'internally' oriented and 'monitoring' processes, and 'active' sensorimotor and cognitive set beta, and slow wave sleep delta, which may also be apparent in 'internal' processing, 'fatigue', and 'altered' states. The meaning of these constructs may depend on distribution across the scalp, context of behavior, the recording method, and choices of preprocessing (Cahn & Polich, 2006; Deolindo et al., 2020; Lomas et al., 2015).

Changes of the respiratory system can affect the brain through several pathways. Baroreflex timing, vagus-mediated heart rate variability, and pulmonary stretch-afferent signaling can all be altered through slow breathing. Nasal airflow activates mechanisms associated with the olfactory bulb and epithelium. Intracranial and scalp examinations show respiration can phase-organize cortical and limbic activity. Volitional breathing engages areas of the brain primarily associated with interoception, attention, and motor control. These provide possible explanations supporting the theory that, without showing that any single oscillatory change is connected to relaxation, pranayama can change areas of EEG power and connectivity.

The most recent empirical studies have supported the theory that research in neurophysiology is a necessity. Zaccaro et al. (2022) reported changes in slow-frequency power, connectivity and cross-frequency coupling after practicing extremely slow nasal breathing. Malan et al. (2023) found changes in alpha and theta power, and changes to alpha-band topology, during and after the practice of Bhramari pranayama. An advanced EGG study of controlled nostril breathing also showed change in measurements of oscillatory and connectivity caused by the breathing conditions. Because the studies vary in factors such as breathing rate, practitioner experience, eyes-open or eyes-closed, the reference used, spectral boundaries, error removal, and the use of active controls, the literature remains very difficult to synthesize.

The appropriate use of a controlled repeated-measures design acknowledges that baseline resting EEG will likely differ across subjects. Baseline measures should therefore be taken for each participant, as well as for each immediately post measure and again at each measure taken during the recovery period. Critical to the design and analysis is not whether a group shows change relative to its own baseline; instead, what is crucial is whether the change trajectory differed from a rational control. Thus, group-by-time change, confidence intervals, and effect sizes will suggest much more useful information than post/pre test comparisons.

This design is demonstrated in the analysis presented in this paper. Because no actual subjects or EEG data were provided, a clearly labeled synthetic data set was used in this analysis, and no claims of real human subject experiments are made. The main aim of this design was to test the group-by-time effect and see how it affected relative alpha power. Other aims of this design were to see how other EEG bands, as well as the alpha-to-beta and theta-to-beta ratios, physiological and subjective measures, response correlates, and predictors of alpha, adjusted for change. The design approach was to allow the most consistent interpretation of the results from the data, tables, figures, and the statistical estimates.

1.1 Objectives and Hypotheses

The primary aim was to assess if a fixed 20-minute Nadi Shodhana session would alter the pattern of resting relative alpha power compared to quiet seated rest. The secondary aims were to analyze the power of the other EEG bands, their associated ratios, respiratory rate, heart rate, relaxation and stress levels, and the relationship of the EEG responses to the changes in the other physiological and subjective variables. The primary null hypothesis proposed that there would be no differences in the changes in alpha power between the groups. The other null hypotheses proposed no changes in the group-by-time interactions for the other EEG bands and the associated variables.

2. Review of Literature

2.1 Voluntary Respiratory Regulation and Brain–Body Coupling

Breathing at a rate of 4-10 breaths per minute, and most commonly at 6 breaths per minute, is a method for achieving resonance with the cardiovascular system. Meta-analytic research indicates that voluntary regulation of the breathing rate to a lower frequency typically results in an increase of several measures of heart rate variability that are affected by respiratory sinus arrhythmia; however, care should be taken in the interpretation of low-frequency power and LF/HF ratios in the context of paced breathing (Laborde et al., 2022; Shaffer & Ginsberg, 2017). The model of vagal respiratory stimulation proposes that changes in arousal and attention are the result of afferent signaling from cardiorespiratory structures, and that stretch of the lungs and baroreceptors may also determine activity in the brainstem and forebrain (Gerritsen & Band, 2018; Noble & Hochman, 2019).

Respiration also functions as a neural rhythm. Phase-dependent cognitive performance may be due to activity phase with piriform, limbic, and related cortical networks. Nasal breathing may facilitate this interaction (Perl et al., 2019; Zelano et al., 2016). Breathing is purposely volitional and permits the engagement of networks beyond the brain's automatic (brainstem) respiratory networks (Herrero et al., 2018). This model incorporates a two-way system. Top-down control results in changes in the mechanics of respiration. Alternatively, bottom-up (peripheral) signals of respiration determine the organization of timing and excitability of various neural networks.

2.2. EEG Oscillations and Resting-State Procedures

EEG spectral analysis investigates the extent to which variance of a signal is distributed across frequency. Welch's averaged periodogram improves the accuracy of a single periodogram by averaging multiple, overlapping windowed segments, thus creating more reliable periodograms for stationary resting epochs (Welch, 1967). Relative power expresses a band as a proportion of the total power (for that epoch of data), making it more convenient for studies with multiple subjects; However, in creating a Relative Band, several issues arise.. Therefore in the analysis of raw spectral data, both absolute and relative values should be considered.

Alpha activity is strongest in the posterior regions when an individual is in the eyes-closed waking state. Increases in alpha following a breathing intervention may indicate a reduction in external sensory stimulation, changes in inhibition, or possibly an increase in attention that is internally focused, and should not be interpreted as an enhancement in overall brain function. Increases in theta activity may be associated with the absorption in a meditative state, as well as monitoring, memory, and drowsiness. Decreased beta activity may be indicative of a reduction in tonic arousal. However, beta activity is implicated in the maintenance of cognitive and sensorimotor functions. Delta activity in the awake state of the EEG is highly susceptible to movement and various forms of artifact. Rigorous preprocessing of the data is essential prior to the analysis of the neurophysiology (Deolindo et al., 2020; Keil et al., 2014).

Alpha and theta activity changes have been prominent EEG findings in the meditation literature; however, the vast variability in meditation practices and purposes renders it impossible to identify a single electrophysiological signature for meditation (Cahn & Polich, 2006; Lomas et al., 2015; Travis & Shear, 2010). Deolindo et al. (2020) argued there is a need for improved phenomenological descriptions in meditation studies, as well as improved methodological consistency. This is similarly true for the Pranayama studies, as opposing respiratory manipulations are presumably contradictory to one another.

Malan et al. (2023) measured elevated theta and alpha power in the temporal lobes in trained Bhramari practitioners, both during and after practice. Also, they reported increased alpha-band cross spectral density and overall network integration. Zaccaro et al. (2022) contrasted very slow nasal breathing with slow mouth breathing and a rest condition. Their findings reported slow nasal breathing was associated with increased slow activity and greater neural connectivity changes, including theta—high beta coupling. These findings suggest there may be additional effects beyond respiratory slowing due to the stimulation of the olfactory system and the route of airflow.

Studies of unilateral and alternate nostril breathing further indicate that the route of airflow through the nostrils may have an effect on both psychological and neural measures, though small sample sizes and inconsistent lateralization create challenges for definitive conclusions. In a pilot training study, Vanutelli et al. (2024) documented diverging psychological and cognitive responses, and Fröhlich et al. (2025) identified oscillatory and connectivity changes via high density EEG during paced conditions of breathing through one nostril. An increase in the P300 amplitude has been reported in the context of several yoga breathing techniques and suggests that there is a change in focusing resources to attention as opposed to a decrease in activity in the cortex (Kala et al, 2023; Telles et al, 2013).

2.4 Methodological Gaps

Some common constraints include uncontrolled resting comparisons, small convenience samples, combining novice and expert practitioners, poor monitoring of breathing rate, varying references for EEG, poor documentation for artefacts, incomplete reporting of frequency bands, and, perhaps most importantly, uncorrected multiple comparisons. For some studies, the lack of a control group does not impede the interpretation of within-group significance as indicative of the effect of the intervention. The publishing recommendations involve clear electrode and reference documentation, definitions of the outcome and trial counts or duration of the trial, and full disclosure of the statistical procedures (Keil et al., 2014).

To our knowledge, the current analytical framework is the only one using a pre-specified primary outcome, an equal sized control group, three measurements, compositional relative-power data, a mixed design analysis, multiplicity-adjusted contrasts and effect-size intervals, with data quality statements and active participant data. The framework is only a proof of concept until it is used with actual EEG data collected in the future.

3. Materials and Methods

3.1 Study Design and Data Status

We specified a study design with 30 participants per condition in a two-group, randomized, repeated measures design. The current dataset is a simulation for the purpose of analysis. No recruitment, randomization, ethics approval, or EEG collection was conducted. Thus, the terminology used to describe the design and data, such as participant and intervention, is purely a description of the proposed design and the simulated data structure.

3.2 Participants and Eligibility

The target population consisted of generally healthy adults between the ages of 18 and 40 who had not participated in regular pranayama for the previous 6 months. Pranayama practitioners would also be excluded for these reasons. This sample would be obtained from the general population. Participants who had a diagnosis of a neurodevelopmental disorder, a seizure disorder, a serious psychiatric disorder, serious cardiorespiratory illness and/or substance dependence, are on medication which would significantly change their cortical excitability, are severely sleep deprived, advanced in yoga-breathing, and have poor EEG would be excluded. The synthetic population was designed to include 60 records with as much as possible an equal distribution of sex and random variation of age, body mass index, sleep, and some aspects of baseline physiology.

3.3 Sample-Size Rationale

A small to moderate group by time interaction was assumed for illustrative purposes. This would also be for two groups, three measurements, a repeated measures correlation of approximately 0.60, and an nonsphericity correction of 0.85. The alpha level was set at 0.05 with a power of 80. Based on these criteria, a target sample size of 60 was set to account for EEG that could not be analyzed and for subject drop out. This sample size was based on a design justification and not an officially prospective power estimate; therefore, a recalculation based on a pilot study would have to be done before an actual study was conducted.

3.4 Intervention and Control Conditions

The intervention condition was designed to include a 5-minute settling and familiarization period, and then 20 minutes of guided Nadi Shodhana pranayama set to a pace of approximately 6 cycles of pranayama per minute. Participants would maintain an upright posture with their eyes closed, practiced alternating nostril airflow without retention, and breath under given guidelines. Control participants practiced the same guidelines with eyes closed for 20 minutes of seated quiet rest. Participants would be prompted to report dizziness, anxiety, dyspnea, and any other discomfort.

3.5 EEG Recording Protocol

The proposed protocol involved a digital multichannel EEG system with at least 19 electrodes following the international 10–20 system, a recording rate of 500 Hz, with electrode impedance kept within the acceptable limits set by the manufacturer. Five minutes of resting, eyes-closed EEG would be collected at baseline (T0), right after the assigned condition (T1), and after a 10-minute recovery period (T2). Model of the equipment used, the reference electrode, location of the recording, date of the acquisition, and the name of the operator are to be filled only for real studies.

3.6 Preprocessing and Spectral Analysis

The outlined processing steps consisted of importing raw files, inspecting channels and impedance, band-pass filtering (1–45 Hz), applying a notch filter at 50 Hz, identifying and interpolating persistently noisy channels by objective measures, average re-referencing, epoching (2 seconds), automated screening of epochs for high amplitude and improbable data, independent component analysis for ocular, cardiac, and muscle components, and expert support for the rejection of residual artefacts. At least 120 clean 2-second epochs at each time point were to be accepted. In addition, power spectral density was estimated by the Welch method with Hanning windows having 50% overlap. Band power was defined as delta (1–4 Hz), theta (4–8 Hz), alpha (8–13 Hz), and beta (13–30 Hz), whereas the relative power (expressed as a percentage) was defined as band power divided by total power (1–30 Hz).

3.7 Outcome Measures

The primary outcome was relative alpha power. Secondary EEG outcomes included power measures for beta, theta, and delta; the alpha-to-beta and theta-to-beta ratios; and several physiological and subjective measures: respiratory rate, heart rate, relaxation score, stress score, valid EEG epochs, protocol adherence, and adverse event status. Regional and scalp-topographic studies were not performed because the synthetic dataset included only global band summaries and not signal data from the electrodes.

3.8 Statistical Analysis

Continuous variables were reported with descriptive statistics, including the 95% confidence interval; counts and percentages were used for categorical variables. Baseline comparisons were performed using independent-samples t tests and chi-square tests. Two-way mixed-design ANOVA was used for the primary and secondary outcomes. The Greenhouse–Geisser correction was used when the assumption of sphericity was not met. Post-hoc Holm-adjusted tests were used to assess time differences and change scores for each group. For all other analysis, Cohen's dz was used to report effect size for paired samples, Hedges g was used for between-group changes, and partial eta-squared for omnibus effect size. Pranayama group Pearson correlations were performed. Baseline parameters (alpha, age, sex, BMI, sleep duration, and respiratory rate) were used for an ordinary least-squares regression model to predict immediate alpha change. Where indicated, a two-tailed p-value of $< .05$ was required, but emphasis was placed on effect size and confidence intervals (Benjamini & Hochberg, 1995; Lakens, 2013; Wasserstein & Lazar, 2016).

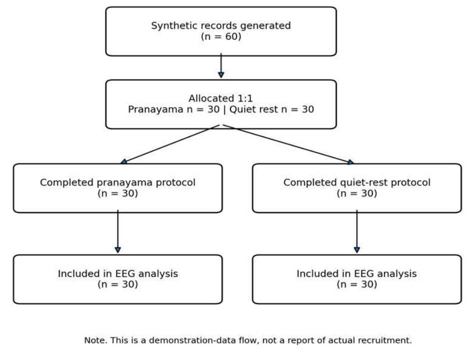

Figure 1. Demonstration-data flow diagram. Source: Generated from the synthetic analytical protocol.

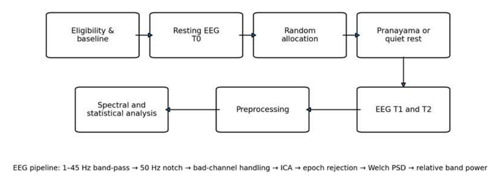

Figure 2. Intended study and EEG-processing workflow. Source: Generated from the synthetic analytical protocol.

4. Results

4.1 Participant Profile and Data Completeness

Of the 60 synthetic records analyzed, 30 records were in both the pranayama and quiet rest conditions. The sample exhibited a balanced sex distribution. There were no meaningful group imbalances for the baseline continuous characteristics. There were no missing primary EEG outcomes. Of the 27,000 possible two-second epochs, 24,922 (92.3%) were kept for analysis. No records were excluded for two synthetic intervention records which reported mild, transient light-headedness.

Table 1. Baseline characteristics of the synthetic demonstration sample

Characteristic	Pranayama (n = 30)	Quiet rest (n = 30)	Statistic	p
Age (years)	28.49 ± 5.06	25.56 ± 5.84	t = 2.08	0.042
Sex, female, n (%)	15 (50.0)	15 (50.0)	$\chi^2 = 0.00$	1.000
BMI (kg/m²)	23.14 ±	23.91	t = -	0.24

Characteristic	Pranayama (n = 30)	Quiet rest (n = 30)	Statistic	p
	2.73	± 2.29	1.19	0
Sleep (hours)	6.77 ± 0.86	6.68 ± 0.74	t = 0.45	0.652
Respiratory rate (breaths/min)	15.04 ± 2.00	15.32 ± 1.57	t = -0.59	0.554
Heart rate (beats/min)	73.01 ± 8.61	73.61 ± 6.77	t = -0.30	0.765
Relaxation score	4.86 ± 0.93	4.85 ± 0.96	t = 0.04	0.967
Alpha power (%)	32.53 ± 3.70	33.68 ± 3.50	t = -1.24	0.221
Beta power (%)	22.52 ± 3.67	21.49 ± 2.34	t = 1.30	0.199
Theta power (%)	20.29 ± 2.92	20.50 ± 3.69	t = -0.25	0.807
Delta power (%)	24.66 ± 3.66	24.33 ± 4.49	t = 0.31	0.758

4.2 Descriptive EEG Outcomes

At baseline, mean relative alpha power for the pranayama group was 32.53% while for the controls it was 33.68%. Right after the assigned condition, alpha was 35.01% after pranayama and 34.05% after quiet rest. The beta proportions for the pranayama pattern were the lowest, while the alpha and theta proportions were the highest. The recovery values moved toward baseline, but there was smaller difference between the two conditions.

Table 2. EEG band and ratio descriptive statistics

Outcome	Group	Time	Mean ± SD	95% CI
Alpha	Pranayama	T0	32.53 ± 3.70	31.15 – 33.91
Alpha	Pranayama	T1	35.01 ± 4.24	33.43 – 36.60
Alpha	Pranayama	T2	33.69 ± 4.01	32.19 – 35.19
Alpha	Quiet rest	T0	33.68 ± 3.50	32.37 – 34.99
Alpha	Quiet rest	T1	34.05 ± 3.98	32.57 – 35.54
Alpha	Quiet rest	T2	33.38 ± 3.88	31.93 – 34.82
Beta	Pranayama	T0	22.52 ± 3.67	21.15 – 23.89
Beta	Pranayama	T1	20.57 ± 3.97	19.08 – 22.05
Beta	Pranayama	T2	20.91 ± 3.46	19.62 – 22.20
Beta	Quiet rest	T0	21.49 ± 2.34	20.62 – 22.36
Beta	Quiet rest	T1	21.75 ± 2.67	20.75 – 22.75
Beta	Quiet rest	T2	21.11 ± 2.58	20.14 – 22.07
Theta	Pranayama	T0	20.29 ± 2.92	19.20 – 21.38
Theta	Pranayama	T1	20.75 ± 3.31	19.51 – 21.98
Theta	Pranayama	T2	21.18 ± 3.63	19.83 – 22.54
Theta	Quiet rest	T0	20.50 ± 3.69	19.12 – 21.88
Theta	Quiet rest	T1	20.52 ± 3.82	19.10 – 21.95
Theta	Quiet rest	T2	21.19 ± 4.09	19.67 – 22.72

Outcome	Group	Time	Mean ± SD	95% CI
Delta	Pranayama	T0	24.66 ± 3.66	23.29–26.03
Delta	Pranayama	T1	23.67 ± 3.87	22.23–25.12
Delta	Pranayama	T2	24.22 ± 4.46	22.55–25.89
Delta	Quiet rest	T0	24.33 ± 4.49	22.66–26.01
Delta	Quiet rest	T1	23.68 ± 4.67	21.93–25.42
Delta	Quiet rest	T2	24.32 ± 4.58	22.61–26.03
Alpha_Beta_Ratio	Pranayama	T0	1.49 ± 0.35	1.36–1.62
Alpha_Beta_Ratio	Pranayama	T1	1.78 ± 0.47	1.61–1.96
Alpha_Beta_Ratio	Pranayama	T2	1.66 ± 0.34	1.53–1.78
Alpha_Beta_Ratio	Quiet rest	T0	1.58 ± 0.23	1.50–1.67
Alpha_Beta_Ratio	Quiet rest	T1	1.59 ± 0.28	1.49–1.70
Alpha_Beta_Ratio	Quiet rest	T2	1.60 ± 0.25	1.51–1.69
Theta_Beta_Ratio	Pranayama	T0	0.92 ± 0.17	0.86–0.98
Theta_Beta_Ratio	Pranayama	T1	1.04 ± 0.23	0.95–1.12
Theta_Beta_Ratio	Pranayama	T2	1.04 ± 0.24	0.95–1.13
Theta_Beta_Ratio	Quiet rest	T0	0.97 ± 0.22	0.89–1.05
Theta_Beta_Ratio	Quiet rest	T1	0.96 ± 0.24	0.88–1.05
Theta_Beta_Ratio	Quiet rest	T2	1.03 ± 0.28	0.93–1.14

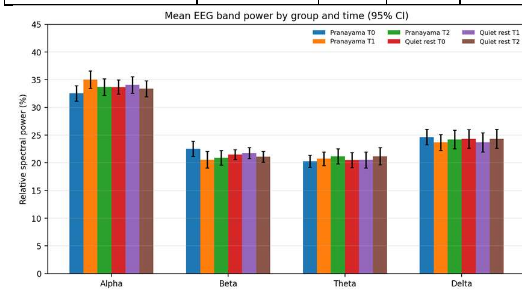

Figure 3. Relative EEG band power by condition and time. Error bars are 95% confidence intervals. Source: Synthetic demonstration dataset.

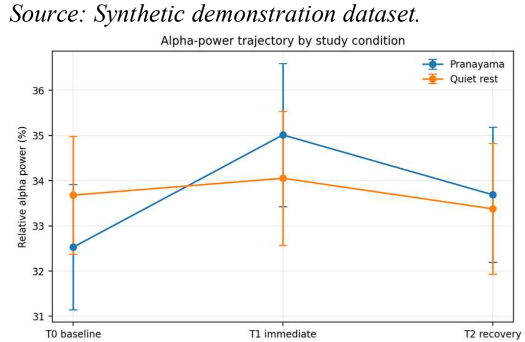

Figure 4. Alpha-power trajectory from baseline to immediate post-condition and recovery. Source: Synthetic demonstration dataset.

4.3 Mixed-Design EEG Analysis

The alpha power group-by-time interaction was significant, $F(1.48, 85.56) = 7.13$, $p = 0.004$, partial $\eta^2 = 0.110$, indicating a moderate effect. The pranayama group showed a greater immediate alpha power increase (+2.48) compared to the control group (+0.37). The effect size for the pranayama group compared to the control group for immediate alpha power change was Hedges g = 1.19, 95% CI 0.64 to 1.74.

A significant group-by-time interaction was also found for beta power, $F(2.00, 116.00) = 15.19$, $p < .001$, partial $\eta^2 = 0.208$. In this case, a greater immediate beta power reduction was found following pranayama. Theta power produced a similar interaction, $F(2.00, 116.00) = 0.51$, $p = 0.603$, partial $\eta^2 = 0.009$; in this case a greater theta power increase was found following pranayama, but as indicated in the results section, the determination of statistical significance directly follows the calculated p-value. For delta power a smaller interaction was found, $F(1.48, 85.96) = 0.48$, $p = 0.563$, partial $\eta^2 = 0.008$

Table 3. Mixed-design ANOVA for EEG outcomes

Outcome	Effect	df	F	p	Partial η^2	Magnitude
Alpha	Group	1.00, 58.00	0.00	0.966	0.000	small
Alpha	Time	1.48, 85.56	13.11	< .001	0.184	large
Alpha	Group × Time	1.48, 85.56	7.13	0.004	0.110	moderate
Beta	Group	1.00, 58.00	0.02	0.883	0.000	small
Beta	Time	2.00, 116.00	14.39	< .001	0.199	large
Beta	Group × Time	2.00, 116.00	15.19	< .001	0.208	large
Theta	Group	1.00, 58.00	0.00	0.999	0.000	small
Theta	Time	2.00, 116.00	7.07	0.001	0.109	moderate
Theta	Group × Time	2.00, 116.00	0.51	0.603	0.009	small
Delta	Group	1.00, 58.00	0.00	0.946	0.000	small
Delta	Time	1.48, 85.96	6.81	0.004	0.105	moderate
Delta	Group × Time	1.48, 85.96	0.48	0.563	0.008	small
Alpha_Beta_Ratio	Group	1.00, 58.00	0.42	0.521	0.007	small
Alpha_Beta_Ratio	Time	2.00, 116.00	15.74	< .001	0.213	large
Alpha_Beta_Ratio	Group × Time	2.00, 116.00	13.87	< .001	0.193	large
Theta_Beta_Ratio	Group	1.00, 58.00	0.04	0.849	0.001	small
Theta_Beta_Ratio	Time	2.00, 116.00	15.89	< .001	0.215	large
Theta_Beta_Ratio	Group × Time	2.00, 116.00	7.43	< .001	0.114	moderate

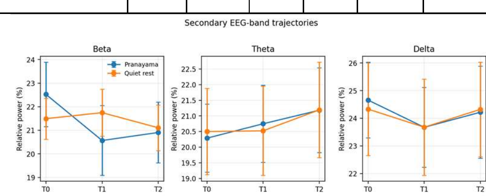

Figure 5. Beta, theta, and delta trajectories by condition. Error bars are 95% confidence intervals. Source: Synthetic demonstration dataset.

4.4 Post-Hoc Comparisons

Table 4. Selected Holm-adjusted post-hoc comparisons

Outcome	Comparison	Mean difference	SE	95 % CI	Adjusted p	Effect size

Outcome	Comparison	Mean difference	SE	95 % CI	Adjusted p	Effect size
Alpha	Pranayama: T0 vs T1	2.48	0.27	1.92 to 3.04	< .001	1.65 (Cohen dz)
Alpha	Between-group ΔT1-T0	2.11	0.45	1.20 to 3.02	< .001	1.19 (Hedges g)
Alpha	Between-group ΔT2-T0	1.46	0.51	0.45 to 2.48	0.033	0.73 (Hedges g)
Beta	Pranayama: T0 vs T1	-1.96	0.29	-2.55 to -1.37	< .001	-1.24 (Cohen dz)
Beta	Between-group ΔT1-T0	-2.22	0.37	-2.96 to -1.47	< .001	-1.51 (Hedges g)
Beta	Between-group ΔT2-T0	-1.23	0.35	-1.94 to -0.53	0.004	-0.89 (Hedges g)
Theta	Pranayama: T0 vs T1	0.46	0.22	0.00 to 0.92	0.299	0.37 (Cohen dz)
Theta	Between-group ΔT1-T0	0.44	0.31	-0.18 to 1.05	0.650	0.36 (Hedges g)
Theta	Between-group ΔT2-T0	0.20	0.44	-0.67 to 1.07	1.000	0.12 (Hedges g)
Delta	Pranayama: T0 vs T1	-0.99	0.34	-1.67 to -0.30	0.053	-0.53 (Cohen dz)
Delta	Between-group ΔT1-T0	-0.33	0.41	-1.16 to 0.50	0.944	-0.20 (Hedges g)
Delta	Between-group ΔT2-T0	-0.43	0.36	-1.15 to 0.29	0.944	-0.31 (Hedges g)

Holm-adjusted tests confirmed that the immediate pranayama-related alpha increase and beta decrease were larger than the changes associated with quiet rest. Theta changes were positively directional yet were statistically non-significant. Delta was also statistically non-significant. Recovery contrasts were smaller than the immediate contrasts, suggesting a partial return toward baseline. The relative band powers sum to approximately 100%, thus individual band changes should be considered as a statistically non-independent and coordinated redistribution of spectral composition.

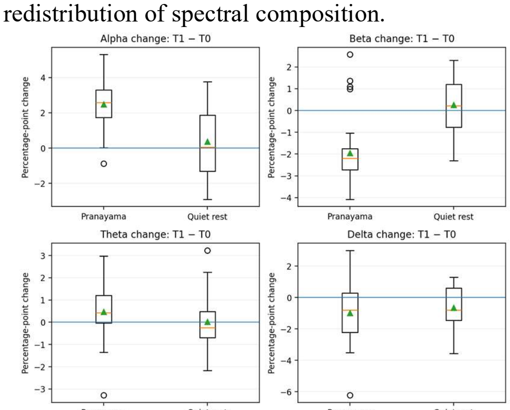

Figure 6. Distribution of immediate EEG change scores by condition. Source: Synthetic demonstration dataset.

4.5 Physiological and Subjective Outcomes

Table 5. Physiological and subjective outcomes

Outcome	Group	T0	T1	T2	Interaction F	p	Partial η²
Respiratory rate	Pranayama	15.04 ± 2.00	11.18 ± 2.23	12.48 ± 2.39	119.88	< .001	0.674
Respiratory rate	Quiet rest	15.32 ± 1.57	14.83 ± 1.71	15.10 ± 1.74	119.88	< .001	0.674
Heart rate	Pranayama	73.01 ± 8.61	68.79 ± 8.81	69.60 ± 8.98	25.96	< .001	0.309
Heart rate	Quiet rest	73.61 ± 6.77	72.51 ± 7.13	73.54 ± 6.99	25.96	< .001	0.309
Relaxation	Pranayama	4.86 ± 0.93	7.10 ± 1.34	6.30 ± 1.20	54.31	< .001	0.484
Relaxation	Quiet rest	4.85 ± 0.96	5.25 ± 1.09	5.14 ± 1.09	54.31	< .001	0.484
Stress	Pranayama	5.11 ± 1.09	3.33 ± 1.45	3.94 ± 1.36	45.66	< .001	0.440
Stress	Quiet rest	5.23 ± 1.34	4.88 ± 1.28	5.00 ± 1.43	45.66	< .001	0.440

Respiratory rate demonstrated a group-by-time interaction, $F(2.00, 116.00) = 119.88$, $p < .001$, partial $\eta^2 = 0.674$. The greatest immediate response occurred in the pranayama condition, which showed partial attenuation at recovery.

Heart rate demonstrated a group-by-time interaction, $F(2.00, 116.00) = 25.96$, $p < .001$, partial $\eta^2 = 0.309$. The pranayama condition showed the greater immediate response, which also showed partial attenuation at recovery.

An interaction of group-by-time was also observed for relaxation, with $F(2.00, 116.00) = 54.31$, $p < .001$, partial $\eta^2 = 0.484$. The pranayama condition showed the greater immediate response, which was partially attenuated at recovery.

Again, the group-by-time interaction was observed for stress, $F(2.00, 116.00) = 45.66$, $p < .001$, partial $\eta^2 = 0.440$. The pranayama condition showed the greater immediate response, which also showed partial attenuation at recovery.

4.6 Correlation and Regression Analysis

Table 6. Correlations with immediate alpha-power change in the pranayama condition

Variable	Pearson r	95% CI	p
Respiratory-rate change	0.233	-0.139 to 0.547	0.216
Heart-rate change	-0.241	-0.554 to 0.130	0.199
Relaxation-score change	0.143	-0.229 to 0.478	0.452
Stress-score change	-0.078	-0.426 to 0.290	0.681
Protocol adherence	0.095	-0.275 to 0.440	0.618

Within the synthetic pranayama subgroup, alpha-power change showed only weak, non-significant correlations with relaxation, respiratory-rate, heart-rate, stress, and adherence changes (all $p > .05$). These descriptive coefficients do not support mediation or causal interpretation.

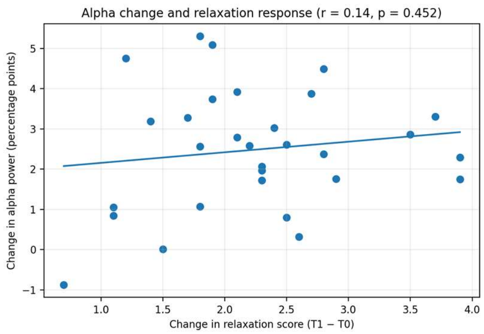

Figure 7. Relationship between immediate alpha-power change and relaxation-score change in the pranayama condition. Source: Synthetic demonstration dataset.

Table 7. Multivariable model predicting immediate alpha-power change

Predictor	B	SE	Standardized β	95% CI	p	VIF
Group code	2.081	0.476	0.515	1.126 to 3.037	< .001	1.13
Alpha T0	-0.004	0.068	-0.006	-0.140 to 0.133	0.959	1.19
Age years	0.045	0.043	0.123	-0.042 to 0.132	0.308	1.17
Sex code	0.037	0.460	0.009	-0.885 to 0.960	0.935	1.06
BMI	-0.001	0.092	-0.001	-0.185 to 0.184	0.995	1.07
Sleep hours previous night	-0.575	0.301	-0.224	-1.179 to 0.029	0.062	1.12
Baseline respiratory rate	0.194	0.134	0.171	-0.075 to 0.463	0.153	1.13

The adjusted model explained 36.3% of variation in immediate alpha change (adjusted $R^2 = 0.277$), $F(7, 52) = 4.23$, $p < .001$. Group assignment was the dominant predictor after adjustment. Variance-inflation factors remained below conventional concern thresholds, indicating that multicollinearity did not materially destabilize the model.

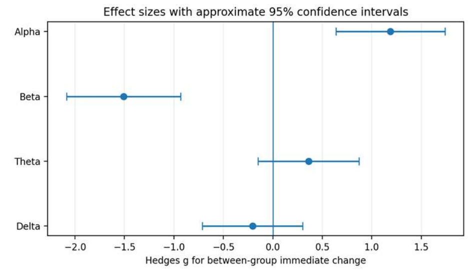

Figure 8. Standardized between-group effects for immediate EEG change. Positive values indicate greater increases in pranayama; negative values indicate greater reductions. Source: Synthetic demonstration dataset.

4.7 EEG Data Quality and Safety

Table 8. EEG data-quality and safety summary

Indicator	Value	Explanation
Records available	60	All synthetic records contained T0, T1, and T2 outcomes
Records excluded	0	No primary-outcome exclusions
Possible epochs	27,000	150 two-second epochs × 3 periods × 60 records
Valid epochs	24,922	92.3% retained
Rejected epochs	2,078	7.7% rejected
Records with channel interpolation	33	One or two channels in the demonstration quality variables
Minimum valid epochs at a time point	130	Above prespecified minimum of 120
Transient adverse events	2	Light-headedness; synthetic demonstration entries

5. Discussion

This synthetic demonstration provided a concise aspect of the acute response in alpha and beta power. Alpha power increased and beta power decreased post-pranayama when measured against quiet rest. Theta exhibited a positive change, but the group-by-time interaction was not statistically significant; delta changes were not condition specific either. The primary finding was the alpha group-by-time interaction, and it was bolstered by a relatively recent large standardized difference. Recovery values shifted closer to baseline; however, they kept a portion of the response. There was a correlational decrease in respiratory rate, heart rate, stress, and an increase in relaxation. Physiological and subjective outcomes were parallel. These were indicative of a consistent outcome profile intended to be tested by a well-controlled study; however, these are not empirical outcomes of intervention effectiveness.

The alpha outcome complements relaxed, internally directed attention, but it is not uniquely diagnostic of it. Eyes closed alpha reflects a state of working thalamocortical and cortical inhibition, and is influenced by sensory input, fatigue, level of vigilance, and the individual's alpha frequency. A post-pranayama increase may reflect an engagement with the external world or altered excitability of the cortex, and should not be viewed as a positive change in the overall level of function of the neural system. The relative response to quiet rest was methodologically important, considering that relaxation and alpha activity can be enhanced by eye closure and a period of quiet sitting.

The slight theta increase observed could possibly be indicative of interoceptive tracking, focal attention, and a shift to an internally focused state. However, a specific-condition theta effect has not been evidenced within this study. Zaccaro et al. (2022) illustrated the presence of slow activity and theta-related connectivity following extremely slow nasal breathing. In comparison, Malan et al. (2023) noted the presence of both theta and alpha activity following and during Bhramari pranayama. The current study employs global relative power and is unable to identify the sources of theta changes; namely, the medial frontal, medial temporal, medial posterior, or many others. Mechanistic hypotheses would require analysis at the electrode level, source modeling, and respiratory phase locking.

The observed beta reduction represents a decrease in the contribution of high frequency activity in the context of a low-arousal resting state, however beta is susceptible to the phenotypes of facial and neck muscle activity. A breathing intervention resulted in changes of posture, facial movement, nasal airflow, and the recruitment of respiratory muscles; due to this, residual electromyography contamination may either conceal or mimic beta-related phenomena. For this reason, independent component analysis, examinations of peripheral channels, and sensitivity analyses to omit high frequency (beta) contaminated epochs are warranted. Additionally, the nature of beta change may vary across practices. For example, Zaccaro et al. (2022) illustrated an increase in theta–high beta coupling and an increase in high beta connectivity alongside a decrease in slow frequency activity. Because of this, power and connectivity represent separate features of network organization.

Delta display a few challenges, as it can be influenced by eye movements, drift, drowsiness, and sweating, but still represent slow cortical organization. Delta can even remain absolutely stable, but if beta power decreases, and alpha and theta powers increase, then relative delta power may be yield a different result. In future studies, please report relative and absolute power measures in a log scale. Also report delta power as well as assess the state of the subjects by reporting the level of alertness or sleepiness of the subjects during the recording session.

There could be a number of additional mechanisms that contribute to the modulation in EEG due to pranayama. Slow breathing may increase the respiratory sinus arrhythmia and influence the eliciting the vagal and baroreceptor input (Laborde et al., 2022). Relaxation and further modulation of the brainstem may be due to pulmonary afferent signals (Noble & Hochman, 2019). Voluntary control of air flow in nasal breathing may in a broad context increase cortical excitability as well as limbic and olfactory bulb activity (Heck et al., 2017; Zelano et al., 2016). The voluntary control may also engage motor planning, tactile feedback, sustained attention, and interoceptive monitoring. Thus, the change in the EEG signal could be the result of the combined influence of respiration, posture, sensory stimulation, expectancy, and context.

The agreement regarding the association of alpha and various physiological and subjective changes is plausible but does not imply mediation. A common latent response, expectancy, state, or measurement dependence may elicit concurrent variations. In order for mediation to be substantiated, a large enough sample size, temporally ordered data, a well-defined causal structure, and manipulation of the mediator is required. A multi-modal recording of respiration, ECG, changes in end-tidal carbon dioxide, and EEG will allow a better understanding of the mechanisms at play.

Missed statistical principles are evident in the demonstration. An important paired change in the pranayama group alone does not demonstrate evidence of an effect of an intervention. The group-by-time interaction specifically tests whether the trajectories differ. Exact p-values should be presented alongside effect sizes and confidence intervals because statistical significance is highly dependent on sample size. Several post-hoc tests must be corrected, and secondary outcomes must be clearly differentiated from the primary outcome of interest. The participant-level data, codebook, and analysis logic promote reproducibility and independent verification.

Research on the regulation of acute stress, the training of attention, yoga science, and the development of respiration-sensitive EEG biomarkers may all benefit from this study. However, researching stimulatory effects on healthy individuals does not support claims of treatment effects on anxiety, depression, epilepsy, sleep disorders, or other clinical conditions. To make clinical claims, studies must be adequately powered, have specific patient populations, and require safety, assessment, and endpoint measures of sufficient clinical relevance. Systematic reviews of breathwork and other respiratory therapies identify possible mental health benefits while also identifying the need for improvement in study quality and design (Fincham et al., 2023; Leyro et al., 2021; Mütze et al., 2025).

Strengths and Limitations

Methodological strengths of the proposed framework include an equal-sized control condition, repeated observations, a prespecified alpha outcome, explicit frequency boundaries, transparent artifact criteria, multiplicity adjustment, effect size reporting, participant-level data, and consistent data presentation in tables and figures. The protocol also differentiates between global relative power and participant-level topography, therefore avoiding unsupported schematic scalp maps.

The dataset's synthetic nature is its biggest limitation as one cannot comment on the real effects of pranayama from this data. Furthermore, the designed study was limited by short exposure, no blinding of participants was possible, as well as expectancy effects and instructor effects, respiratory and muscle artefacts, no end-tidal carbon-dioxide measurements, use of global power instead of regional power, no long-term follow-up, and no comparison with experienced practitioners. Relative band power is a tiered mathematical system. A real study is also expected to preregister the primary outcome and retain the raw EEG and share the logs, explain deviations, and conduct a sensitivity analysis with a more rigorous approach using absolute power and individual alpha frequency.

7. Practical and Research Implications

The main research practice implication is that pranayama should be considered a reproducible practice, instead of a broad practice. Breathing rate, inhalation/exhalation ratio, nostril sequence, breath retention, posture, eye condition, session length, instructor contact, prior experience, and adherence should all be documented. Alongside this, pranayama practices should be physiologically monitored to verify the intended manipulation of breath. In the context of EEG, studies should document their rationale for reference and filtering, duration and criteria for clean data and component removal, spectral parameters, and the full analysis workflow.

In the context of applied settings, a brief slow-breathing practice could be a low-cost method to manage acute arousal, though EEG changes are surrogate measures of neurophysiology. Other factors, including participant preference and the possibility of adverse effects, should be considered when making implementation decisions further to the feasibility of sustained practice. Effects on alpha or theta should not be the sole basis of support for therapeutic claims.

8. Recommendations for Future Research

1. Run registered trials with higher participant numbers. Trials should also feature respiratory controls that have equivalent levels of participant engagement and instructor engagement.

2. Test alternate-nostril breathing and compare it with slow bilateral nasal breathing and slow breathing through the mouth and spontaneous quiet rest.

3. During measurements, collect and analyze high-density EEG data with respiratory, cardiac, end-tidal CO_2, skin conductance, and subjective state data.

4. Provide power measures with both absolute and relative measures. Include individual alpha frequency, regional estimates and respiratory phase with connectivity and respiration-locked phase analyses.

5. Incorporate widely available, open source, EEGLAB, MNE, FieldTrip, PREP, HAPPE, and BIDS-compatible data organization pipelines to Eastern and South African countries. Data processing and analysis frameworks that support open and reproducible research (Bigdely-Shamlo et al., 2015; Delorme & Makeig, 2004; Gabard-Durnam et al., 2018; Oostenveld et al., 2011).

6. In the targeted population groups, evaluate dose-response relationships, practical experience, long-term retention, compliance, and other end points that have clinical relevance.

7. When allowed by ethics and informed consent, provide de-identified, raw, and processed data along with documentation of data processing and

9. Conclusion

The present study showed how a controlled pranayama experiment could reveal a coordinated variation of resting EEG composition utilizing a clear synthetic dataset. The main finding was a notable group-by-time interaction for alpha power, characterized by a greater immediate increase following pranayama practice than following quiet resting, and a standardized between-group change effect of g = 1.19. Further analysis showed that beta power decreased more strongly following pranayama, and there were no significant differences in the theta and delta power bands across the conditions. In parallel to the changes observed in EEG, the participants reported a subjective decrease in arousal. While the findings reported here are mainly of an illustrative nature, conclusions regarding pranayama practice cannot be made until prospective recordings of raw EEGs are captured and analyzed in a preregistered manner, and verified respiratory compliance and stringent artefact correction are employed, along with replication studies conducted on larger and more varied populations.

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Appendices

Appendix A. Participant-Level Synthetic Dataset

The following table contains the complete demonstration dataset used for all calculations. Values do not represent real participants. Relative delta, theta, alpha, and beta power sum to approximately 100% at each time point, subject to rounding.

Appendix Table A1. Participant-level dataset, part 1

ID	Group	Age_years	Sex	BMI	Sleep_h	B_RR	P_RR	R_RR	B_HR	P_HR	R_HR	B_Relax	P_Relax	R_Relax	B_Stress	P_Stress	R_Stress	Alpha_T0	Alpha_T1	Alpha_T2	Beta_T0	Beta_T1	Beta_T2
P001	Pranayama	33.8	Male	23.6	7.3	16.5	11.7	13.8	70.4	67.1	67.8	4.8	7.4	6.5	5.6	3.5	5.2	35.96	36.28	37.12	21.32	22.68	19.36
P002	Pranayama	28.2	Female	19.4	8.0	15.8	11.3	11.8	78.2	70.5	73.1	3.9	7.8	5.7	4.4	1.6	3.2	30.67	32.42	34.6	25.99	27.08	22.72
P003	Pranayama	36.9	Female	23.5	6.1	19.1	14.7	17.5	84.4	81.1	79.5	6.3	9.1	7.4	6.9	5.7	5.9	34.85	39.34	36.16	20.13	18.41	20.43
P004	Pranayama	29.1	Male	21.2	7.9	14.7	11.7	12.7	70.7	66.9	65.3	3.7	6.0	5.3	5.7	3.7	5.1	29.88	31.94	28.61	27.5	30.07	28.22
P005	Pranayama	32.6	Male	24.0	7.1	13.0	9.0	9.8	65.7	62.1	61.8	5.2	6.3	6.5	4.8	3.3	3.9	25.48	26.32	27.92	32.88	30.22	30.75
P006	Pranayama	24.3	Male	20.6	7.2	11.0	6.6	9.3	66.9	62.4	65.7	4.9	7.4	7.4	6.7	5.1	5.5	32.59	33.39	34.09	23.45	21.61	22.56
P007	Pranayama	31.0	Male	20.1	7.6	17.3	12.8	15.7	64.6	59.9	59.0	7.0	9.4	8.4	5.5	3.3	5.3	29.58	32.6	28.97	20.65	17.47	19.18
P008	Pranayama	29.4	Male	27.3	7.0	12.8	9.0	10.0	73.1	68.6	72.0	5.6	7.7	7.1	6.1	4.5	5.2	24.14	26.93	25.33	26.03	23.58	21.54
P009	Pranayama	26.4	Male	24.6	5.5	15.6	11.9	11.9	75.2	71.3	69.9	5.2	8.7	7.1	4.0	1.1	1.8	36.08	38.94	36.23	22.51	21.48	22.14
P010	Pranayama	26.9	Female	22.3	6.7	15.9	12.4	13.2	79.3	77.4	76.9	4.5	6.3	5.3	3.0	1.6	1.6	32.19	33.26	39.06	22.73	20.01	21.19
P011	Pranayama	26.4	Female	20.3	5.8	13.9	11.8	11.6	78.1	75.8	76.7	3.1	4.8	4.4	3.4	1.9	1.9	30.71	33.99	33.06	19.7	17.53	18.23
P012	Pranayama	25.3	Male	24.6	7.4	13.5	9.6	10.4	68.2	64.5	65.9	3.9	5.4	4.8	4.5	3.7	3.3	30.7	30.71	33.12	25.88	22.41	23.56
P013	Pranayama	30.1	Male	23.6	6.4	14.0	10.2	10.9	87.3	83.1	82.6	4.6	6.5	5.1	4.1	2.3	2.4	36.63	41.72	35.02	21.51	18.75	20.81
P014	Pranayama	21.1	Female	22.4	7.4	13.4	8.9	11.3	75.6	72.0	74.7	4.6	7.4	5.7	5.3	2.9	4.0	33.92	36.29	36.85	23.9	22.26	20.62
P015	Pranayama	23.6	Male	29.9	5.2	14.5	9.9	11.2	75.7	72.1	71.5	5.7	8.2	6.6	4.8	2.7	3.2	31.36	33.97	32.03	16.94	15.01	14.12

ID	Group	Age_years	Sex	BMI	Sleep_h	B_RR	P_RR	R_RR	B_HR	P_HR	R_HR	B_Relax	P_Relax	R_Relax	B_Stress	P_Stress	R_Stress	Alpha_T0	Alpha_T1	Alpha_T2	Beta_T0	Beta_T1	Beta_T2
P016	Pranayama	29.1	Female	18.0	5.4	15.2	11.7	14.1	55.0	51.0	50.4	6.1	8.3	8.2	5.4	4.2	4.5	30.6	33.18	30.04	25.04	23.36	25.07
P017	Pranayama	29.3	Male	25.2	6.6	14.4	9.7	12.4	78.3	75.6	72.4	3.5	5.4	4.6	6.9	5.3	5.5	32.73	36.47	33.71	20.02	18.12	19.3
P018	Pranayama	25.0	Female	27.3	6.4	16.5	14.8	16.5	76.1	70.3	73.3	4.3	5.7	5.5	6.0	5.4	5.3	30.56	33.75	32.19	20.09	18.2	18.37
P019	Pranayama	22.8	Male	25.2	5.8	15.9	12.2	14.4	75.3	74.7	73.2	3.4	4.1	4.7	5.4	4.2	5.7	35.42	34.54	37.27	22.19	20.35	21.45
P020	Pranayama	21.7	Female	24.8	7.7	18.9	16.3	16.1	88.5	86.3	87.7	5.4	6.5	6.2	5.7	3.6	5.1	37.15	38.2	36.63	17.73	15.73	16.51
P021	Pranayama	36.4	Female	22.5	7.1	19.6	14.5	16.2	92.0	85.6	87.7	5.1	6.9	7.8	6.6	5.1	5.3	34.42	36.98	35.55	20.66	16.6	16.4
P022	Pranayama	21.1	Male	23.8	6.3	12.0	6.9	8.0	67.1	61.7	62.3	6.2	9.1	8.3	5.0	3.8	2.8	30.54	32.3	29.71	20.48	18.07	18.91
P023	Pranayama	33.9	Female	22.1	5.9	13.8	9.9	10.3	74.7	67.2	71.8	4.3	6.6	4.9	5.1	3.9	3.7	37.98	39.7	38.13	18.16	19.14	18.21
P024	Pranayama	23.1	Female	24.2	7.6	15.3	11.8	13.7	70.6	64.9	67.8	4.6	5.8	6.4	4.1	2.2	2.2	31.53	36.28	31.72	23.21	19.69	20.87
P025	Pranayama	38.0	Female	24.1	6.9	13.9	9.4	10.1	75.5	71.1	73.3	5.0	8.9	6.0	5.4	3.1	4.1	27.77	30.06	26.43	23.28	21.06	20.53
P026	Pranayama	34.6	Female	22.8	8.6	16.7	11.8	14.1	55.0	51.2	50.4	4.5	6.8	5.2	3.3	0.5	1.9	27.94	29.9	31.23	23.65	21.09	20.29
P027	Pranayama	30.6	Female	18.0	6.6	15.6	13.3	13.3	63.4	60.1	59.0	5.1	6.9	7.4	4.6	3.1	3.2	36.49	41.79	38.38	19.29	16.66	19.03
P028	Pranayama	36.0	Female	20.7	6.0	13.8	11.3	12.9	67.2	63.4	66.3	5.8	7.9	7.0	6.7	5.7	5.0	37.44	41.36	32.95	16.37	13.66	17.5
P029	Pranayama	24.7	Male	26.5	7.6	15.1	10.5	11.3	71.2	64.8	68.9	4.0	7.7	5.8	4.6	1.7	3.9	31.56	34.86	35.94	28.96	24.88	25.18
P030	Pranayama	23.2	Male	21.5	6.1	13.6	9.7	9.9	66.9	61.1	61.2	5.4	8.1	7.7	3.6	1.2	2.5	38.99	42.86	42.59	25.49	21.8	24.16

ID	Group	Age_years	Sex	BMI	Sleep_h	B_RR	P_RR	R_RR	B_HR	P_HR	R_HR	B_Relax	P_Relax	R_Relax	B_Stress	P_Stress	R_Stress	Alpha_T0	Alpha_T1	Alpha_T2	Beta_T0	Beta_T1	Beta_T2
P031	Quiet rest	28.6	Male	22.5	7.1	16.3	15.9	15.4	84.9	82.4	88.2	4.2	4.7	5.1	4.8	4.3	4.2	30.74	34.08	30.53	23.01	24.22	23.23
P032	Quiet rest	31.8	Male	21.0	6.0	15.3	15.4	15.5	75.1	71.8	78.9	4.1	4.4	4.8	4.2	3.8	3.4	36.19	34.6	34.46	17.56	17.5	17.55
P033	Quiet rest	31.4	Female	25.9	6.8	14.0	13.2	14.8	72.9	72.8	72.5	3.9	4.6	4.6	5.5	5.1	5.2	31.03	31.45	31.77	23.38	21.07	23.43
P034	Quiet rest	30.1	Male	18.0	6.8	17.5	16.8	18.0	78.9	81.5	79.1	5.2	6.4	5.6	4.6	4.9	4.4	28.48	32.07	28.26	17.39	16.24	15.77
P035	Quiet rest	21.1	Female	24.2	5.4	15.8	15.8	15.8	62.0	58.9	60.9	4.4	4.2	4.4	5.1	4.5	4.9	36.47	38.22	35.63	23.47	23.6	23.7
P036	Quiet rest	18.0	Male	22.0	6.8	17.2	17.0	17.0	74.4	72.5	74.4	3.0	3.7	2.9	8.0	7.9	8.3	36.79	35.51	35.19	21.93	23.23	22.21
P037	Quiet rest	38.7	Male	25.4	6.4	16.2	16.6	16.2	82.0	80.4	81.2	7.1	7.1	6.8	5.4	5.0	5.0	37.55	41.31	37.32	21.07	20.39	23.67
P038	Quiet rest	39.9	Female	26.4	5.6	14.2	13.0	13.8	72.2	71.4	73.5	5.1	4.5	6.3	4.0	3.7	3.7	32.61	33.6	31.75	20.33	21.28	20.87
P039	Quiet rest	31.0	Female	26.2	7.3	16.5	15.4	16.2	72.3	75.1	72.5	5.4	5.5	6.0	4.7	5.1	4.2	35.51	36.81	35.85	24.57	22.49	23.89
P040	Quiet rest	24.1	Male	22.9	6.1	16.9	17.2	16.5	68.3	67.9	67.7	5.5	6.0	5.8	5.0	3.7	4.4	31.58	33.9	29.55	21.57	22.63	20.17
P041	Quiet rest	27.8	Male	24.2	8.2	18.0	18.3	18.5	65.2	65.0	68.3	5.5	5.8	5.6	6.8	6.8	6.4	29.31	26.4	28.78	19.87	21.66	20.08
P042	Quiet rest	18.0	Female	24.9	7.0	12.9	12.2	12.4	70.3	67.9	72.1	5.1	5.6	5.5	5.2	4.5	5.5	34.92	35.9	33.86	18.9	18.68	16.5
P043	Quiet rest	18.9	Male	25.3	5.8	17.6	17.2	17.4	73.3	72.2	75.0	5.4	5.9	6.1	5.8	5.4	5.5	36.38	36.27	37.79	22.9	21.94	21.1
P044	Quiet rest	30.9	Male	27.8	8.1	17.5	16.7	16.1	66.6	66.2	65.7	6.5	7.0	5.9	4.4	4.9	4.0	33.2	35.1	28.32	17.4	18.31	17.73
P045	Quiet rest	22.2	Male	21.7	6.8	14.3	13.9	14.0	88.5	87.9	84.6	4.8	5.2	5.2	4.2	4.8	4.1	41.08	39.4	41.34	23.26	24.44	22.74

ID	Group	Age_years	Sex	BMI	Sleep_h	B_RR	P_RR	R_RR	B_HR	P_HR	R_HR	B_Relax	P_Relax	R_Relax	B_Stress	P_Stress	R_Stress	Alpha_T0	Alpha_T1	Alpha_T2	Beta_T0	Beta_T1	Beta_T2
P046	Quiet rest	28.8	Male	26.9	6.8	12.9	12.0	12.6	68.6	64.5	65.3	4.3	4.5	5.0	6.4	5.6	6.5	33.47	31.51	35.34	21.33	23.5	20.72
P047	Quiet rest	26.9	Female	22.0	6.6	15.3	13.7	15.7	61.1	62.0	58.9	3.5	4.4	3.3	6.7	5.9	6.8	29.47	28.15	30.26	19.7	21.45	19.89
P048	Quiet rest	28.9	Female	24.4	5.7	13.5	12.4	13.7	75.6	75.2	75.8	3.6	3.5	4.3	4.2	4.0	4.2	29.89	29.0	27.83	25.25	23.99	25.17
P049	Quiet rest	25.1	Female	24.2	7.7	15.3	14.0	14.0	70.4	69.3	68.5	4.4	4.9	4.2	7.0	6.3	6.7	34.8	33.48	33.59	20.73	22.92	21.28
P050	Quiet rest	21.5	Male	24.8	5.5	14.6	13.6	15.0	67.5	67.6	69.3	5.3	6.7	6.0	7.2	6.7	6.9	34.11	36.76	35.17	21.05	20.99	22.36
P051	Quiet rest	18.6	Female	22.5	6.1	15.1	14.5	15.7	69.3	69.2	69.8	3.7	3.7	3.2	3.8	3.2	3.5	34.35	34.42	34.38	25.23	25.71	26.66
P052	Quiet rest	18.0	Female	25.7	6.3	14.8	14.9	14.9	74.0	72.4	74.9	6.2	6.4	7.6	2.5	2.3	2.1	35.12	38.4	33.82	20.96	20.18	21.15
P053	Quiet rest	22.6	Female	23.1	7.6	12.5	12.5	11.2	73.7	71.6	74.0	5.0	5.9	4.3	6.1	6.3	6.1	27.82	25.92	29.14	24.81	25.12	23.24
P054	Quiet rest	21.6	Female	26.2	7.4	14.5	13.3	14.1	77.3	75.9	77.9	4.2	4.1	4.4	6.8	5.4	6.6	31.87	31.89	29.41	22.44	21.98	21.44
P055	Quiet rest	25.3	Female	22.2	6.4	16.9	15.1	16.8	67.2	65.3	64.5	6.0	6.7	5.8	6.5	5.7	6.7	27.66	30.52	30.09	18.84	18.12	17.37
P056	Quiet rest	18.0	Male	25.2	7.0	12.6	13.1	12.1	87.1	88.0	85.1	6.0	6.0	6.4	5.8	6.1	5.4	36.82	36.78	40.15	22.97	24.97	19.5
P057	Quiet rest	25.9	Female	21.5	6.1	15.1	15.6	14.5	80.2	75.1	78.2	5.0	6.6	5.7	2.5	2.6	3.0	33.27	31.57	31.31	19.96	18.74	20.47
P058	Quiet rest	23.1	Male	27.5	6.9	15.4	15.4	14.5	75.9	75.2	74.3	4.2	4.0	4.5	3.9	3.8	4.3	38.36	37.73	36.35	18.15	17.18	18.07
P059	Quiet rest	21.8	Female	20.8	7.3	14.5	15.2	14.0	73.3	67.7	73.3	3.9	4.0	4.0	5.3	4.4	4.9	31.84	29.78	32.44	23.36	25.66	21.95
P060	Quiet rest	28.1	Male	21.9	6.8	16.4	15.0	16.6	80.1	82.3	81.9	4.9	5.4	4.8	4.4	3.7	3.2	39.69	41.03	41.6	23.36	24.25	21.27

Appendix Table A2. Participant-level dataset, part 2

ID	Group	Delta_T0	Delta_T1	Delta_T2	Theta_T0	Theta_T1	Theta_T2	A/B_T0	T/B_T0	A/B_T1	T/B_T1	A/B_T2	T/B_T2	Epochs_T0	Epochs_T1	Epochs_T2	Interp_ch	Adherence	Adverse_Event	Respiratory_rate_T0	Respiratory_rate_T1	Respiratory_rate_T2	Heart_rate_T0	Heart_rate_T1	Heart_rate_T2	Relaxation_T0	Relaxation_T1	Relaxation_T2	Stress_T0	Stress_T1	Stress_T2
P001	Pranayama	24.48	22.64	22.59	18.24	18.4	20.94	1.687	0.856	1.6	0.811	1.917	1.082	143	136	132	1	92.0	None	16.5	11.7	13.8	70.4	67.1	67.8	4.8	7.4	6.5	5.6	3.5	5.2
P002	Pranayama	25.22	21.71	24.75	18.12	18.8	17.93	1.18	0.697	1.197	0.694	1.523	0.789	136	146	145	0	93.0	None	15.8	11.3	11.8	78.2	70.5	73.1	3.9	7.8	5.7	4.4	1.6	3.2
P003	Pranayama	26.28	23.13	22.25	18.74	19.12	21.15	1.731	0.931	2.137	1.039	1.77	1.035	132	133	140	1	100.0	None	19.1	14.7	17.5	84.4	81.1	79.5	6.3	9.1	7.4	6.9	5.7	5.9
P004	Pranayama	24.16	17.94	22.85	18.45	20.05	20.31	1.087	0.671	1.062	0.667	1.014	0.72	135	138	131	1	100.0	None	14.7	11.7	12.7	70.7	66.9	65.3	3.7	6.0	5.3	5.7	3.7	5.1
P005	Pranayama	24.05	25.45	21.73	17.59	18.01	19.59	0.775	0.535	0.871	0.596	0.908	0.637	135	137	134	0	91.5	None	13.0	9.0	9.8	65.7	62.1	61.8	5.2	6.3	6.5	4.8	3.3	3.9
P006	Pranayama	19.28	18.94	20.12	24.69	26.07	23.23	1.39	1.053	1.545	1.206	1.511	1.03	147	143	131	0	93.0	None	11.0	6.6	9.3	66.9	62.4	65.7	4.9	7.4	7.4	6.7	5.1	5.5
P007	Pranayama	25.53	23.97	25.24	24.24	25.96	26.61	1.432	1.174	1.866	1.486	1.51	1.387	140	139	133	0	99.1	None	17.3	12.8	15.7	64.6	59.9	59.0	7.0	9.4	8.4	5.5	3.3	5.3
P008	Pranayama	25.83	25.7	25.78	24.0	23.79	27.34	0.927	0.922	1.142	1.009	1.176	1.269	135	146	141	2	90.3	Transient light-headedness	12.8	9.0	10.0	73.1	68.6	72.0	5.6	7.7	7.1	6.1	4.5	5.2

ID	Group	Delta_T0	Delta_T1	Delta_T2	Theta_T0	Theta_T1	Theta_T2	A/B_T0	T/B_T0	A/B_T1	T/B_T1	A/B_T2	T/B_T2	Epochs_T0	Epochs_T1	Epochs_T2	Interp_ch	Adherence	Adverse_Event	Respiratory_rate_T0	Respiratory_rate_T1	Respiratory_rate_T2	Heart_rate_T0	Heart_rate_T1	Heart_rate_T2	Relaxation_T0	Relaxation_T1	Relaxation_T2	Stress_T0	Stress_T1	Stress_T2
P009	Pranayama	25.32	22.27	24.59	16.09	17.3	17.04	1.603	0.715	1.813	0.805	1.636	0.77	143	141	141	1	86.3	None	15.6	11.9	11.9	75.2	71.3	69.9	5.2	8.7	7.1	4.0	1.1	1.8
P010	Pranayama	21.98	24.98	18.5	23.11	21.75	21.26	1.416	1.017	1.662	1.087	1.843	1.003	132	147	145	0	92.4	None	15.9	12.4	13.2	79.3	77.4	76.9	4.5	6.3	5.3	3.0	1.6	1.6
P011	Pranayama	26.87	27.07	25.79	22.73	21.41	22.92	1.559	1.154	1.939	1.221	1.813	1.257	147	144	147	0	94.2	None	13.9	11.8	11.6	78.1	75.8	76.7	3.1	4.8	4.4	3.4	1.9	1.9
P012	Pranayama	20.34	20.82	19.4	23.09	26.06	23.92	1.186	0.892	1.37	1.163	1.406	1.015	137	145	134	1	99.9	None	13.5	9.6	10.4	68.2	64.5	65.9	3.9	5.4	4.8	4.5	3.7	3.3
P013	Pranayama	25.34	21.96	28.05	16.52	17.57	16.11	1.703	0.768	2.225	0.937	1.683	0.774	136	132	132	0	98.3	None	14.0	10.2	10.9	87.3	83.1	82.6	4.6	6.5	5.1	4.1	2.3	2.4
P014	Pranayama	20.45	19.61	20.99	21.74	21.83	21.53	1.419	0.91	1.63	0.981	1.787	1.044	134	139	137	2	100.0	None	13.4	8.9	11.3	75.6	72.0	74.7	4.6	7.4	5.7	5.3	2.9	4.0
P015	Pranayama	34.99	34.23	37.51	16.7	16.79	16.34	1.851	0.986	2.263	1.119	2.268	1.157	133	145	142	2	100.0	None	14.5	9.9	11.2	75.7	72.1	71.5	5.7	8.2	6.6	4.8	2.7	3.2
P016	Pranayama	25.86	25.01	24.79	18.49	18.45	20.09	1.222	0.738	1.42	0.79	1.198	0.801	136	131	144	1	95.4	None	15.2	11.7	14.1	55.0	51.0	50.4	6.1	8.3	8.2	5.4	4.2	4.5

ID	Group	Delta_T0	Delta_T1	Delta_T2	Theta_T0	Theta_T1	Theta_T2	A/B_T0	T/B_T0	A/B_T1	T/B_T1	A/B_T2	T/B_T2	Epochs_T0	Epochs_T1	Epochs_T2	Interp_ch	Adherence	Adverse_Event	Respiratory_rate_T0	Respiratory_rate_T1	Respiratory_rate_T2	Heart_rate_T0	Heart_rate_T1	Heart_rate_T2	Relaxation_T0	Relaxation_T1	Relaxation_T2	Stress_T0	Stress_T1	Stress_T2
P017	Pranayama	25.9	23.81	26.35	21.35	21.6	20.64	1.635	1.066	2.013	1.192	1.747	1.069	133	139	136	2	97.0	None	14.4	9.7	12.4	78.3	75.6	72.4	3.5	5.4	4.6	6.9	5.3	5.5
P018	Pranayama	29.52	27.18	29.94	19.83	20.87	19.49	1.521	0.987	1.854	1.147	1.752	1.061	147	141	144	0	96.5	None	16.5	14.8	16.5	76.1	70.3	73.3	4.3	5.7	5.5	6.0	5.4	5.3
P019	Pranayama	23.07	23.39	21.06	19.32	21.71	20.22	1.596	0.871	1.697	1.067	1.738	0.943	136	131	140	0	93.3	None	15.9	12.2	14.4	75.3	74.7	73.2	3.4	4.1	4.7	5.4	4.2	5.7
P020	Pranayama	28.62	29.75	28.62	16.5	16.31	18.24	2.095	0.931	2.428	1.037	2.219	1.105	141	140	140	0	98.2	None	18.9	16.3	16.1	88.5	86.3	87.7	5.4	6.5	6.2	5.7	3.6	5.1
P021	Pranayama	22.47	22.79	22.83	22.45	23.63	25.22	1.666	1.087	2.228	1.423	2.168	1.538	139	134	141	0	89.0	None	19.6	14.5	16.2	92.0	85.6	87.7	5.1	6.9	7.8	6.6	5.1	5.3
P022	Pranayama	25.52	24.78	26.18	23.46	24.86	25.2	1.491	1.146	1.787	1.376	1.571	1.333	132	130	136	0	99.0	None	12.0	6.9	8.0	67.1	61.7	62.3	6.2	9.1	8.3	5.0	3.8	2.8
P023	Pranayama	22.58	23.16	20.55	21.28	18.0	23.1	2.091	1.172	2.074	0.94	2.094	1.269	147	130	139	1	94.4	None	13.8	9.9	10.3	74.7	67.2	71.8	4.3	6.6	4.9	5.1	3.9	3.7
P024	Pranayama	19.01	16.75	17.65	26.25	27.28	29.76	1.358	1.131	1.843	1.385	1.52	1.426	145	132	142	1	94.6	Transient light-headedness	15.3	11.8	13.7	70.6	64.9	67.8	4.6	5.8	6.4	4.1	2.2	2.2

ID	Group	Delta_T0	Delta_T1	Delta_T2	Theta_T0	Theta_T1	Theta_T2	A/B_T0	T/B_T0	A/B_T1	T/B_T1	A/B_T2	T/B_T2	Epochs_T0	Epochs_T1	Epochs_T2	Interp_ch	Adherence	Adverse_Event	Respiratory_rate_T0	Respiratory_rate_T1	Respiratory_rate_T2	Heart_rate_T0	Heart_rate_T1	Heart_rate_T2	Relaxation_T0	Relaxation_T1	Relaxation_T2	Stress_T0	Stress_T1	Stress_T2
P025	Pranayama	26.45	25.02	27.75	22.5	23.86	25.29	1.193	0.966	1.427	1.133	1.287	1.232	140	138	139	0	95.5	None	13.9	9.4	10.1	75.5	71.1	73.3	5.0	8.9	6.0	5.4	3.1	4.1
P026	Pranayama	26.41	26.57	25.47	22.0	22.44	23.01	1.181	0.93	1.418	1.064	1.539	1.134	144	135	132	0	100.0	None	16.7	11.8	14.1	55.0	51.2	50.4	4.5	6.8	5.2	3.3	0.5	1.9
P027	Pranayama	27.87	25.54	28.08	16.36	16.01	14.51	1.892	0.848	2.508	0.961	2.017	0.762	137	137	137	1	94.4	None	15.6	13.3	13.3	63.4	60.1	59.0	5.1	6.9	7.4	4.6	3.1	3.2
P028	Pranayama	28.87	28.93	30.9	17.32	16.05	18.65	2.287	1.058	3.028	1.175	1.883	1.066	144	135	141	0	100.0	None	13.8	11.3	12.9	67.2	63.4	66.3	5.8	7.9	7.0	6.7	5.7	5.0
P029	Pranayama	20.62	21.41	19.82	18.86	18.84	19.06	1.09	0.651	1.401	0.757	1.427	0.757	147	132	131	1	87.4	None	15.1	10.5	11.3	71.2	64.8	68.9	4.0	7.7	5.8	4.6	1.7	3.9
P030	Pranayama	16.9	15.71	16.48	18.61	19.63	16.77	1.53	0.73	1.966	0.9	1.763	0.694	132	133	141	1	92.9	None	13.6	9.7	9.9	66.9	61.1	61.2	5.4	8.1	7.7	3.6	1.2	2.5
P031	Quiet rest	25.56	21.99	25.61	20.69	19.72	20.63	1.336	0.899	1.407	0.814	1.314	0.888	144	147	145	2	100.0	None	16.3	15.9	15.4	84.9	82.4	88.2	4.2	4.7	5.1	4.8	4.3	4.2
P032	Quiet rest	25.0	26.29	24.58	21.25	21.6	23.41	2.061	1.21	1.977	1.234	1.964	1.334	139	137	145	1	100.0	None	15.3	15.4	15.5	75.1	71.8	78.9	4.1	4.4	4.8	4.2	3.8	3.4

ID	Group	Delta_T0	Delta_T1	Delta_T2	Theta_T0	Theta_T1	Theta_T2	A/B_T0	T/B_T0	A/B_T1	T/B_T1	A/B_T2	T/B_T2	Epochs_T0	Epochs_T1	Epochs_T2	Interp_ch	Adherence	Adverse_Event	Respiratory_rate_T0	Respiratory_rate_T1	Respiratory_rate_T2	Heart_rate_T0	Heart_rate_T1	Heart_rate_T2	Relaxation_T0	Relaxation_T1	Relaxation_T2	Stress_T0	Stress_T1	Stress_T2
P033	Quiet rest	23.74	22.4	24.82	21.85	25.08	19.98	1.327	0.935	1.493	1.19	1.356	0.853	145	130	145	1	100.0	None	14.0	13.2	14.8	72.9	72.8	72.5	3.9	4.6	4.6	5.5	5.1	5.2
P034	Quiet rest	29.18	27.54	32.08	24.96	24.16	23.88	1.638	1.435	1.975	1.488	1.792	1.514	132	137	133	1	100.0	None	17.5	16.8	18.0	78.9	81.5	79.1	5.2	6.4	5.6	4.6	4.9	4.4
P035	Quiet rest	25.22	23.76	25.24	14.84	14.42	15.43	1.554	0.632	1.619	0.611	1.503	0.651	141	134	144	1	100.0	None	15.8	15.8	15.8	62.0	58.9	60.9	4.4	4.2	4.4	5.1	4.5	4.9
P036	Quiet rest	18.03	18.29	19.68	23.25	22.98	22.92	1.678	1.06	1.529	0.989	1.584	1.032	138	131	139	2	100.0	None	17.2	17.0	17.0	74.4	72.5	74.4	3.0	3.7	2.9	8.0	7.9	8.3
P037	Quiet rest	22.59	19.87	21.49	18.79	18.43	17.52	1.782	0.892	2.026	0.904	1.577	0.74	136	133	133	0	100.0	None	16.2	16.6	16.2	82.0	80.4	81.2	7.1	7.1	6.8	5.4	5.0	5.0
P038	Quiet rest	20.29	18.95	18.79	26.77	26.17	28.6	1.604	1.317	1.579	1.23	1.521	1.37	137	135	142	0	100.0	None	14.2	13.0	13.8	72.2	71.4	73.5	5.1	4.5	6.3	4.0	3.7	3.7
P039	Quiet rest	20.93	21.87	20.81	18.99	18.83	19.45	1.445	0.773	1.637	0.837	1.501	0.814	146	137	144	0	100.0	None	16.5	15.4	16.2	72.3	75.1	72.5	5.4	5.5	6.0	4.7	5.1	4.2
P040	Quiet rest	25.23	24.02	25.01	21.62	19.45	25.27	1.464	1.002	1.498	0.859	1.465	1.253	143	146	144	1	100.0	None	16.9	17.2	16.5	68.3	67.9	67.7	5.5	6.0	5.8	5.0	3.7	4.4

ID	Group	Delta_T0	Delta_T1	Delta_T2	Theta_T0	Theta_T1	Theta_T2	A/B_T0	T/B_T0	A/B_T1	T/B_T1	A/B_T2	T/B_T2	Epochs_T0	Epochs_T1	Epochs_T2	Interp_ch	Adherence	Adverse_Event	Respiratory_rate_T0	Respiratory_rate_T1	Respiratory_rate_T2	Heart_rate_T0	Heart_rate_T1	Heart_rate_T2	Relaxation_T0	Relaxation_T1	Relaxation_T2	Stress_T0	Stress_T1	Stress_T2
P041	Quiet rest	33.9	34.54	33.44	16.93	17.4	17.71	1.475	0.852	1.219	0.803	1.433	0.882	147	131	138	0	100.0	None	18.0	18.3	18.5	65.2	65.0	68.3	5.5	5.8	5.6	6.8	6.8	6.4
P042	Quiet rest	27.56	25.98	26.56	18.62	19.43	23.08	1.848	0.985	1.922	1.04	2.052	1.399	134	135	134	0	100.0	None	12.9	12.2	12.4	70.3	67.9	72.1	5.1	5.6	5.5	5.2	4.5	5.5
P043	Quiet rest	15.38	14.83	16.58	25.33	26.95	24.54	1.589	1.106	1.653	1.228	1.791	1.163	146	147	139	1	100.0	None	17.6	17.2	17.4	73.3	72.2	75.0	5.4	5.9	6.1	5.8	5.4	5.5
P044	Quiet rest	30.44	27.39	30.25	18.96	19.2	23.7	1.908	1.09	1.917	1.049	1.597	1.337	147	146	145	1	100.0	None	17.5	16.7	16.1	66.6	66.2	65.7	6.5	7.0	5.9	4.4	4.9	4.0
P045	Quiet rest	23.62	24.32	21.7	12.05	11.84	14.23	1.766	0.518	1.612	0.484	1.818	0.626	139	133	144	0	100.0	None	14.3	13.9	14.0	88.5	87.9	84.6	4.8	5.2	5.2	4.2	4.8	4.1
P046	Quiet rest	17.35	17.85	15.86	27.85	27.14	28.08	1.569	1.306	1.341	1.155	1.706	1.355	135	132	144	2	100.0	None	12.9	12.0	12.6	68.6	64.5	65.3	4.3	4.5	5.0	6.4	5.6	6.5
P047	Quiet rest	29.85	30.64	30.33	20.99	19.76	19.52	1.496	1.065	1.312	0.921	1.521	0.981	138	142	142	1	100.0	None	15.3	13.7	15.7	61.1	62.0	58.9	3.5	4.4	3.3	6.7	5.9	6.8
P048	Quiet rest	27.8	27.71	29.56	17.05	19.3	17.44	1.184	0.675	1.209	0.805	1.106	0.693	135	140	136	0	100.0	None	13.5	12.4	13.7	75.6	75.2	75.8	3.6	3.5	4.3	4.2	4.0	4.2

ID	Group	Delta_T0	Delta_T1	Delta_T2	Theta_T0	Theta_T1	Theta_T2	A/B_T0	T/B_T0	A/B_T1	T/B_T1	A/B_T2	T/B_T2	Epochs_T0	Epochs_T1	Epochs_T2	Interp_ch	Adherence	Adverse_Event	Respiratory_rate_T0	Respiratory_rate_T1	Respiratory_rate_T2	Heart_rate_T0	Heart_rate_T1	Heart_rate_T2	Relaxation_T0	Relaxation_T1	Relaxation_T2	Stress_T0	Stress_T1	Stress_T2
P049	Quiet rest	25.48	24.53	26.89	18.99	19.07	18.23	1.679	0.916	1.461	0.832	1.578	0.857	133	147	145	1	100.0	None	15.3	14.0	14.0	70.4	69.3	68.5	4.4	4.9	4.2	7.0	6.3	6.7
P050	Quiet rest	24.24	22.39	23.57	20.61	19.87	18.9	1.62	0.979	1.751	0.947	1.573	0.845	141	130	131	0	100.0	None	14.6	13.6	15.0	67.5	67.6	69.3	5.3	6.7	6.0	7.2	6.7	6.9
P051	Quiet rest	24.68	23.64	24.44	15.74	16.23	14.53	1.361	0.624	1.339	0.631	1.29	0.545	139	131	135	1	100.0	None	15.1	14.5	15.7	69.3	69.2	69.8	3.7	3.7	3.2	3.8	3.2	3.5
P052	Quiet rest	23.24	21.38	22.77	20.69	20.05	22.25	1.676	0.987	1.903	0.994	1.599	1.052	142	131	145	1	100.0	None	14.8	14.9	14.9	74.0	72.4	74.9	6.2	6.4	7.6	2.5	2.3	2.1
P053	Quiet rest	25.95	26.59	24.75	21.43	22.38	22.87	1.121	0.864	1.032	0.891	1.254	0.984	141	141	134	1	100.0	None	12.5	12.5	11.2	73.7	71.6	74.0	5.0	5.9	4.3	6.1	6.3	6.1
P054	Quiet rest	19.11	18.47	19.4	26.58	27.66	29.74	1.42	1.184	1.451	1.258	1.372	1.387	143	131	138	1	100.0	None	14.5	13.3	14.1	77.3	75.9	77.9	4.2	4.1	4.4	6.8	5.4	6.6
P055	Quiet rest	30.77	30.24	27.99	22.74	21.12	24.55	1.468	1.207	1.684	1.166	1.732	1.413	145	130	132	0	100.0	None	16.9	15.1	16.8	67.2	65.3	64.5	6.0	6.7	5.8	6.5	5.7	6.7
P056	Quiet rest	16.64	15.21	17.05	23.56	23.04	23.3	1.603	1.026	1.473	0.923	2.059	1.195	143	131	135	1	100.0	None	12.6	13.1	12.1	87.1	88.0	85.1	6.0	6.0	6.4	5.8	6.1	5.4

ID	Group	Delta_T0	Delta_T1	Delta_T2	Theta_T0	Theta_T1	Theta_T2	A/B_T0	T/B_T0	A/B_T1	T/B_T1	A/B_T2	T/B_T2	Epochs_T0	Epochs_T1	Epochs_T2	Interp_ch	Adherence	Adverse_Event	Respiratory_rate_T0	Respiratory_rate_T1	Respiratory_rate_T2	Heart_rate_T0	Heart_rate_T1	Heart_rate_T2	Relaxation_T0	Relaxation_T1	Relaxation_T2	Stress_T0	Stress_T1	Stress_T2
P057	Quiet rest	25.65	26.88	25.87	21.12	22.8	22.34	1.667	1.058	1.685	1.217	1.53	1.091	132	139	133	0	100.0	None	15.1	15.6	14.5	80.2	75.1	78.2	5.0	6.6	5.7	2.5	2.6	3.0
P058	Quiet rest	24.31	25.47	24.35	19.19	19.62	21.23	2.113	1.057	2.196	1.142	2.012	1.175	143	135	143	0	100.0	None	15.4	15.4	14.5	75.9	75.2	74.3	4.2	4.0	4.5	3.9	3.8	4.3
P059	Quiet rest	28.56	28.69	29.75	16.24	15.87	15.85	1.363	0.695	1.161	0.618	1.478	0.722	132	142	136	0	100.0	None	14.5	15.2	14.0	73.3	67.7	73.3	3.9	4.0	4.0	5.3	4.4	4.9
P060	Quiet rest	19.67	18.6	20.5	17.28	16.12	16.63	1.699	0.74	1.692	0.665	1.956	0.782	141	138	141	1	100.0	None	16.4	15.0	16.6	80.1	82.3	81.9	4.9	5.4	4.8	4.4	3.7	3.2

Appendix B. Variable Codebook

Variable	Description	Unit/type	Coding or range
Participant_ID	Synthetic record identifier	Text	P001–P060
Group	Assigned condition	Categorical	Pranayama / Quiet rest
Age_years	Age	Years	18–40
Sex	Reported sex category	Categorical	Female / Male
BMI	Body mass index	kg/m²	18–31
Sleep_hours_previous_night	Self-reported sleep	Hours	4.8–8.7
Respiratory-rate variables	Resting respiratory frequency	Breaths/min	T0, T1, T2
Heart-rate variables	Resting pulse	Beats/min	T0, T1, T2
Relaxation variables	Subjective relaxation	0–10 score	Higher = more relaxed
Stress variables	Subjective stress	0–10 score	Higher = more stress
Alpha/Beta/Theta/Delta	Relative spectral power	Percent	Approximately sums to 100
Alpha_Beta_Ratio	Alpha divided by beta	Ratio	Positive
Theta_Beta_Ratio	Theta divided by beta	Ratio	Positive
Valid_EEG_Epochs	Retained two-second epochs	Count	120–150 intended
Interpolated_channels	Number of interpolated channels	Count	0–2 in demonstration
Protocol_Adherence_Percent	Completed protocol proportion	Percent	0–100
Adverse_Event	Safety note	Text	None / transient event

Appendix C. Reproducible Statistical Workflow

1. Import participant-level wide data and verify unique IDs, group coding, units, ranges, and missingness.
2. Reshape EEG outcomes from wide to long format with one row per participant, time, and band.
3. Summarize each outcome by group and time using mean, SD, median, IQR, range, and 95% CI.
4. Fit a mixed model: outcome ~ group * time + (1 | participant).
5. Inspect residual Q–Q plots, variance patterns, influential observations, and covariance structure.
6. Estimate adjusted marginal means and prespecified contrasts.
7. Apply Holm correction to the family of post-hoc tests.
8. Report mean differences, 95% CIs, exact p-values, partial eta-squared or standardized effect sizes.
9. Repeat the analysis with robust/non-parametric sensitivity methods if assumptions materially fail.
10. Export all tables and figures directly from the analysed dataset and archive code and session information.

Illustrative R model syntax

```
library(lme4)
library(lmerTest)
library(emmeans)
model <- lmer(relative_power ~ group * time + (1 | participant_id), data = long_data)
anova(model)
emmeans(model, pairwise ~ group * time, adjust = 'holm')
```

Appendix D. EEG Preprocessing and Quality-Control Checklist

☐ 1. Confirm participant ID and event markers.
☐ 2. Document acquisition montage, reference, sampling rate, impedance, and clean recording duration.
☐ 3. Apply prespecified filters without introducing edge artefacts.
☐ 4. Identify persistently noisy or flat channels using objective thresholds and visual review.
☐ 5. Re-reference only after bad-channel management.
☐ 6. Run ICA on an adequate quantity of continuous or epoched data.
☐ 7. Classify ocular, cardiac, muscle, line-noise, and channel-noise components.
☐ 8. Reject residual high-amplitude, improbable, or non-stationary epochs.
☐ 9. Record the number of interpolated channels and retained epochs for every participant and period.

☐ 10. Compute PSD with fixed window, overlap, and frequency resolution.
☐ 11. Check that relative powers and ratios are correctly calculated.
☐ 12. Repeat analyses after excluding records with unusually low clean duration.

Appendix E. Standardized Pranayama Instruction Script
Sit upright in a comfortable, stable position. Keep the shoulders relaxed and close the eyes. Breathe naturally for one minute. Using the dominant hand, gently close the right nostril and inhale through the left; switch and exhale through the right. Inhale through the right; switch and exhale through the left. This completes one cycle. Continue without force or breath retention at approximately six cycles per minute. Stop immediately and return to normal breathing if dizziness, breathlessness, chest discomfort, panic, or other distress occurs. The instructor should use neutral language and avoid suggesting expected EEG or emotional effects.

Appendix F. Participant Screening and Safety Checklist
☐ Age within approved range
☐ No seizure history or diagnosed epilepsy
☐ No major uncontrolled neurological or psychiatric condition
☐ No serious uncontrolled respiratory or cardiovascular disease
☐ No medication exclusion identified
☐ No acute substance intoxication
☐ Adequate sleep for safe participation
☐ No advanced pranayama practice when novice sample is intended
☐ Written informed consent completed
☐ Emergency and adverse-event procedure reviewed

Appendix G. DOI Metadata Check Table
The table lists DOI strings used in the reference list. Core sources were cross-checked against publisher or PubMed metadata during manuscript preparation. Because DOI and bibliographic databases can be corrected after publication, a final resolver and retraction-status check should be completed immediately before submission.

No.	First author(s)	Year	Short title	DOI	Status
1	Balban, M. Y., Neri, E., Kogon, M. M.,	2023	Brief structured respiration practices enhance mood and	10.1016/j.xcrm.2022.100895	DOI metadata listed; final resolver check advised
2	Benjamini, Y., & Hochberg, Y.	1995	Controlling the false discovery rate: A practical and p	10.1111/j.2517-6161.1995.tb02031.x	DOI metadata listed; final resolver check advised
3	Bigdely-Shamlo, N., Mullen, T., Kothe,	2015	The PREP pipeline: Standardized preprocessing for large	10.3389/fninf.2015.00016	DOI metadata listed; final resolver check advised
4	Braboszcz, C., Cahn, B. R., Levy, J.,	2017	Increased gamma brainwave amplitude compared to control	10.1371/journal.pone.0170647	DOI metadata listed; final resolver check advised
5	Brown, R. P., Gerbarg, P. L., & Muench	2013	Breathing practices for treatment of psychiatric and st	10.1016/j.psc.2013.01.001	DOI metadata listed; final resolver check advised
6	Cahn, B. R., & Polich, J.	2006	Meditation states and traits: EEG, ERP, and neuroimagin	10.1037/0033-2909.132.2.180	DOI metadata listed; final resolver check advised
7	Campelo, G., de Araújo, J. R., Aristiz	2025	Long-term effects of yoga-based practices on neural, co	10.1186/s12906-025-04825-x	DOI metadata listed; final resolver check advised
8	Cohen, M. X.	2014	Analyzing neural time series data: Theory and	Not assigned in reference	DOI metadata listed; final

No.	First author(s)	Year	Short title	DOI	Status
			practice		resolver check advised
9	Cumming, G.	2014	The new statistics: Why and how	10.1177/0956797613504966	DOI metadata listed; final resolver check advised
10	Davidson, R. J., & Kaszniak, A. W.	2015	Conceptual and methodological issues in research on min	10.1037/a0039512	DOI metadata listed; final resolver check advised
11	Deolindo, C. S., Ribeiro, M. W., Arata	2020	A critical analysis on characterizing the meditation ex	10.3389/fnsys.2020.00053	Publisher/PubMed metadata checked
12	Delorme, A., & Makeig, S.	2004	EEGLAB: An open source toolbox for analysis of single-t	10.1016/j.jneumeth.2003.10.009	DOI metadata listed; final resolver check advised
13	Fincham, G. W., Strauss, C., Montero-M	2023	Effect of breathwork on stress and mental health: A met	10.1038/s41598-022-27247-y	DOI metadata listed; final resolver check advised
14	Fox, K. C. R., Dixon, M. L., Nijeboer,	2016	Functional neuroanatomy of meditation: A review and met	10.1016/j.neubiorev.2016.03.021	DOI metadata listed; final resolver check advised
15	Fröhlich, A. B., Fröhlich, F., & Skler	2025	Neuronal oscillations and functional connectivity of pa	10.1371/journal.pone.0316125	Publisher/PubMed metadata checked
16	Gabard-Durnam, L. J., Mendez Leal, A.	2018	The Harvard Automated Processing Pipeline for Electroen	10.3389/fnins.2018.00097	DOI metadata listed; final resolver check advised
17	Gaur, S., Panjwani, U., & Kumar, B.	2020	EEG brain wave dynamics: A systematic review and meta-a	10.37871/jbres1166	DOI metadata listed; final resolver check advised
18	Gerritsen, R. J. S., & Band, G. P. H.	2018	Breath of life: The respiratory vagal stimulation model	10.3389/fnhum.2018.00397	DOI metadata listed; final resolver check advised
19	Gramfort, A., Luessi, M., Larson, E.,	2014	MNE software for processing MEG and EEG data	10.1016/j.neuroimage.2013.10.027	DOI metadata listed; final resolver check advised
20	Heck, D. H., McAfee, S. S., Liu, Y., B	2017	Breathing as a fundamental rhythm of brain function	10.3389/fncir.2016.00115	DOI metadata listed; final resolver check advised
21	Herrero, J. L., Khuvis, S., Yeagle, E.	2018	Breathing above the brain stem: Volitional control and	10.1152/jn.00551.2017	DOI metadata listed; final resolver check advised

No.	First author(s)	Year	Short title	DOI	Status
22	Kala, N., Telles, S., Sharma, S. K., &	2023	P300 following four voluntarily regulated yoga breathin	10.1177/15500594221089369	Publisher/PubMed metadata checked
23	Keil, A., Debener, S., Gratton, G., Ju	2014	Committee report: Publication guidelines and recommenda	10.1111/psyp.12147	DOI metadata listed; final resolver check advised
24	Klug, M., & Gramann, K.	2021	Identifying key factors for improving ICA-based decompo	10.1111/ejn.14992	DOI metadata listed; final resolver check advised
25	Laborde, S., Allen, M. S., Borges, U.,	2022	Effects of voluntary slow breathing on heart rate and h	10.1016/j.neubiorev.2022.104711	Publisher/PubMed metadata checked
26	Lakens, D.	2013	Calculating and reporting effect sizes to facilitate cu	10.3389/fpsyg.2013.00863	DOI metadata listed; final resolver check advised
27	Lee, D. J., Kulubya, E., Goldin, P., G	2018	Review of the neural oscillations underlying meditation	10.3389/fnins.2018.00178	DOI metadata listed; final resolver check advised
28	Lehrer, P. M., Kaur, K., Sharma, A., S	2020	Heart rate variability biofeedback improves emotional a	10.1007/s10484-020-09466-z	DOI metadata listed; final resolver check advised
29	Leyro, T. M., Versella, M. V., Yang, M	2021	Respiratory therapy for the treatment of anxiety: Meta-	10.1016/j.cpr.2021.101980	Publisher/PubMed metadata checked
30	Lomas, T., Ivtzan, I., & Fu, C. H. Y.	2015	A systematic review of the neurophysiology of mindfulne	10.1016/j.neubiorev.2015.09.018	DOI metadata listed; final resolver check advised
31	Malan, N. S., Khajuria, A., Bajpai, R.	2023	Functional connectivity and power spectral density anal	10.1016/j.bspc.2023.105003	Publisher/PubMed metadata checked
32	Muthukrishnan, S. P., Jain, R., Kohli,	2016	Effect of mindfulness meditation on perceived stress sc	10.7860/JCDR/2016/16463.7679	DOI metadata listed; final resolver check advised
33	Mütze, C., Mitzinger, D., & Haller, H.	2025	Effectiveness of pranayama for mental disorders: A syst	10.3389/fpsyt.2025.1616996	DOI metadata listed; final resolver check advised
34	Noble, D. J., & Hochman, S.	2019	Hypothesis: Pulmonary afferent activity patterns during	10.3389/fphys.2019.01176	DOI metadata listed; final resolver check advised
35	Oka, G. A., Deshmukh, K., Halder, P.,	2025	A systematic review and meta-analysis to determine the	10.1515/ijamh-2025-0094	DOI metadata listed; final resolver check advised

No.	First author(s)	Year	Short title	DOI	Status
36	Oostenveld, R., Fries, P., Maris, E.,	2011	FieldTrip: Open source software for advanced analysis o	10.1155/2011/156869	DOI metadata listed; final resolver check advised
37	Pernet, C. R., Appelhoff, S., Gorgolew	2019	EEG-BIDS, an extension to the Brain Imaging Data Struct	10.1038/s41597-019-0104-8	DOI metadata listed; final resolver check advised
38	Perl, O., Ravia, A., Rubinson, M., Eis	2019	Human non-olfactory cognition phase-locked with inhalat	10.1038/s41562-019-0556-z	DOI metadata listed; final resolver check advised
39	Pion-Tonachini, L., Kreutz-Delgado, K.	2019	ICLabel: An automated electroencephalographic independe	10.1016/j.neuroimage.2019.05.026	DOI metadata listed; final resolver check advised
40	Russo, M. A., Santarelli, D. M., & O'R	2017	The physiological effects of slow breathing in the heal	10.1183/20734735.009817	DOI metadata listed; final resolver check advised
41	Shaffer, F., & Ginsberg, J. P.	2017	An overview of heart rate variability metrics and norms	10.3389/fpubh.2017.00258	DOI metadata listed; final resolver check advised
42	Tang, Y.-Y., Hölzel, B. K., & Posner,	2015	The neuroscience of mindfulness meditation	10.1038/nrn3916	DOI metadata listed; final resolver check advised
43	Telles, S., Singh, N., & Puthige, R.	2013	Changes in P300 following alternate nostril yoga breath	10.1186/1751-0759-7-11	DOI metadata listed; final resolver check advised
44	Tort, A. B. L., Brankačk, J., & Draguh	2018	Respiration-entrained brain rhythms are global but ofte	10.1016/j.tins.2018.01.007	DOI metadata listed; final resolver check advised
45	Tort, A. B. L., Ponsel, S., Jessberger	2018	Parallel detection of theta and respiration-coupled osc	10.1038/s41598-018-24629-z	DOI metadata listed; final resolver check advised
46	Travis, F., & Shear, J.	2010	Focused attention, open monitoring and automatic self-t	10.1016/j.concog.2010.01.007	DOI metadata listed; final resolver check advised
47	Vanutelli, M. E., Grigis, C., & Lucchi	2024	Breathing right… or left! The effects of unilateral nos	10.3390/brainsci14040302	Publisher/PubMed metadata checked
48	Wasserstein, R. L., & Lazar, N. A.	2016	The ASA statement on p-values: Context, process, and pu	10.1080/00031305.2016.1154108	DOI metadata listed; final resolver check advised
49	Welch, P. D.	1967	The use of fast Fourier transform for the	10.1109/TAU.1967.1161901	DOI metadata listed; final

No.	First author(s)	Year	Short title	DOI	Status
			estimation of		resolver check advised
50	Yackle, K., Schwarz, L. A., Kam, K., S	2017	Breathing control center neurons that promote arousal i	10.1126/science.aai7984	DOI metadata listed; final resolver check advised
51	Zaccaro, A., Piarulli, A., Laurino, M.	2018	How breath-control can change your life: A systematic r	10.3389/fnhum.2018.00353	Publisher/PubMed metadata checked
52	Zaccaro, A., Piarulli, A., Melosini, L	2022	Neural correlates of non-ordinary states of consciousne	10.3389/fnsys.2022.803904	Publisher/PubMed metadata checked
53	Zelano, C., Jiang, H., Zhou, G., Arora	2016	Nasal respiration entrains human limbic oscillations an	10.1523/JNEUROSCI.2586-16.2016	DOI metadata listed; final resolver check advised