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EXPLORING THE NEUROBIOLOGICAL AND PSYCHOLOGICAL IMPACTS OF YOGA: PERSPECTIVES FROM fNIRS

Explorando los impactos neurobiológicos y psicológicos del yoga: perspectivas desde fNIRS

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DEDICATION

To the pain that cracked me open and taught me to perceive the world in two directions: outward, through the microscope of the scientific method, and inward, through the inquiries of yoga and meditation. To the generations of teachers and researchers who preserved, refined, and continue to transmit these two traditions.

Two paths, one longing: to see through illusion and ease suffering.

May these directions of inquiry converge in this work and illuminate future research into the complexity, transformation, and flourishing of the human BEING.

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RESUMEN

Descripción general: Esta tesis doctoral examina los efectos agudos y longitudinales del yoga *āsana* mediante tres estudios que combinan neuroimagen compatible con el movimiento con medidas bioquímicas, endocrinas, posturales y experienciales.

Objetivo: La investigación avanzó desde el desarrollo de un protocolo reproducible de fNIRS hasta el análisis de cambios agudos en la actividad prefrontal y la conectividad funcional en reposo, y de cambios asociados con un programa de yoga de 30 días.

Métodos: El primer estudio estableció un protocolo de espectroscopia funcional de infrarrojo cercano (fNIRS) para medir la actividad hemodinámica cortical durante inversiones y extensiones hacia atrás, controlando artefactos de movimiento y registrando la conectividad antes y después de la práctica. El segundo lo aplicó a 27 adultos sanos durante una sesión de *āsana* de 23 minutos con diseño por bloques y tres posturas. El tercero evaluó a 29 adultos tras un programa de 30 días, combinando fNIRS durante tareas de retención de la respiración, imágenes afectivas y reposo con marcadores bioquímicos y endocrinos, evaluación postural baropodométrica, cuestionarios y entrevistas semiestructuradas.

Resultados: La práctica aguda se asoció con mayor oxigenación prefrontal, especialmente en la corteza prefrontal derecha, y con menor conectividad funcional posterior, principalmente en la corteza prefrontal medial izquierda. Tras el programa de 30 días, se observaron cambios en HbO y HbR en regiones prefrontales bilaterales y en la conectividad de una red frontal inferior derecha. Disminuyeron el colesterol total y la oxitocina, mejoró la alineación postural mediolateral y los participantes informaron mayor conciencia corporal, menos dolor, mejor sueño, mayor bienestar psicológico y relaciones interpersonales más sólidas.

Conclusión: Los estudios respaldan la viabilidad de fNIRS para investigar el yoga *āsana* en contextos naturalistas y basados en el movimiento. Los hallazgos sugieren que puede comprenderse como una práctica reguladora corporal compleja, no reducible a un único mecanismo. Para reconocer sus orígenes históricos y filosóficos, los resultados se interpretan desde la psicofisiología contemporánea junto con los marcos yóguicos de los cinco *kośas* y los ocho miembros. Esta perspectiva transdisciplinaria integra cerebro, cuerpo, postura y experiencia vivida, y abre nuevas líneas de investigación sobre sus interacciones.

Palabras clave: yoga *āsana*; fNIRS; corteza prefrontal; conectividad funcional; encarnación; métodos mixtos; postura física

ABSTRACT

Overview: This doctoral thesis investigates the acute and longitudinal neurobiological, physiological, and experiential effects of yoga *āsana* through three linked studies combining movement-compatible neuroimaging with biochemical, endocrine, postural, and first-person measures.

Aim: The studies progressed from establishing a reproducible fNIRS protocol to examining acute changes in prefrontal cortical activity and resting-state functional connectivity during and following a 23-minute *āsana* sequence, and finally to investigating changes associated with a 30-day yoga program across neural, biochemical, postural, and experiential domains.

Methods: The first study established a reproducible protocol for using functional near-infrared spectroscopy (fNIRS) to measure cortical hemodynamic activity during physically demanding postures, specifically inversions and backbends, while addressing motion artifacts and incorporating pre- and post-practice resting-state connectivity measurements. The second study applied this protocol to 27 healthy adults during a 23-minute block-design yoga session involving three distinct postures to examine acute changes in cortical activity and connectivity. The third study extended the investigation through a 30-day yoga program completed by 29 adults. It integrated fNIRS measurements during breath-holding, affective-image, and resting-state paradigms along with biochemical and endocrine markers, baropodometric postural assessments, questionnaires, and semi-structured interviews.

Results: The acute practice was associated with increased prefrontal oxygenation, particularly in the right prefrontal cortex, together with reduced post-practice resting-state functional connectivity, most prominently in the left medial prefrontal cortex. Following the 30-day program, task-dependent changes in HbO and HbR were observed across bilateral prefrontal regions, along with altered connectivity within a right inferior frontal network. Total cholesterol and oxytocin decreased, mediolateral postural alignment improved, and participants reported greater body awareness, reduced pain, improved sleep, enhanced psychological well-being, and stronger interpersonal relationships.

Conclusion: Taken together, the studies support the feasibility of using fNIRS to examine yoga *āsana* in naturalistic, movement-based contexts. The findings suggest that yoga *āsana* may be best understood as a multidimensional, embodied regulatory practice rather than through any single mechanism. To acknowledge and preserve the integrity of yoga's historical and philosophical origins, the findings are interpreted through contemporary psychophysiology alongside the yogic frameworks of the five *kośas* and eight limbs. This transdisciplinary perspective offers a multilayered understanding of the observed changes across brain, body, posture, and lived experience, while opening important avenues for further research into how these dimensions may interact.

Keywords: yoga *āsana*; fNIRS; prefrontal cortex; functional connectivity; embodiment; mixed methods; physical posture

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LIST OF ACRONYMS AND ABBREVIATIONS

ANOVA	analysis of variance
ANS	autonomic nervous system
BCE	before Common Era
BIDS	Brain Imaging Data Structure
BMI	body mass index
BOLD	blood-oxygen-level-dependent
CAM	complementary and alternative medicine
CBSI	correlation-based signal improvement
CI	confidence interval
CIACYT	Coordinación para la Innovación y la Aplicación de la Ciencia y la Tecnología
CMR	Complementary Medicine Research
CONAHCYT	Consejo Nacional de Humanidades, Ciencias y Tecnologías
DICIM	Doctorado Institucional en Ingeniería y Ciencia de Materiales
DLPFC	dorsolateral prefrontal cortex
DMN	default mode network
DPF	differential pathlength factor
EEG	electroencephalography
fMRI	functional magnetic resonance imaging
fNIRS	functional near-infrared spectroscopy
GABA	gamma-aminobutyric acid
GAD	generalized anxiety disorder
GLM	general linear model
HbO	oxygenated hemoglobin
IFG	inferior frontal gyrus
IL-6	interleukin-6
IQR	interquartile range
JoVE	Journal of Visualized Experiments
LOC	locus of control
MDD	major depressive disorder
MNI	Montreal Neurological Institute
mPFC	medial prefrontal cortex
NBS	network-based statistic
NIR	near-infrared
NIRS	near-infrared spectroscopy
PCA	principal component analysis
PET	positron emission tomography
PFC	prefrontal cortex
PSSD	post-SSRI sexual dysfunction
PTSD	posttraumatic stress disorder
rIFG	right inferior frontal gyrus
rsFC	resting-state functional connectivity
rTMS	repetitive transcranial magnetic stimulation
SD	standard deviation
SECIHTI	Secretaría de Ciencia, Humanidades, Tecnología e Innovación
SEM	standard error of the mean
SKY	Sudarshan Kriya Yoga

HbR	deoxygenated hemoglobin
HbT	total hemoglobin
HPA	hypothalamic–pituitary–adrenal
HRF	hemodynamic response function
HRV	heart rate variability
IAPS	International Affective Picture System
ICA	independent component analysis
SNIRF	Shared Near Infrared Spectroscopy Format
SNRI	serotonin–norepinephrine reuptake inhibitor
SSRI	selective serotonin reuptake inhibitor
TCCA	temporally embedded canonical correlation analysis
TDDR	temporal derivative distribution repair
UASLP	Universidad Autónoma de San Luis Potosí
VLPFC	ventrolateral prefrontal cortex

Introduction

"If I have seen further, it is by standing on the shoulders of Giants."
— Isaac Newton, letter to Robert Hooke, February 5, 1676

From Antiquity to the Present:

The Evolution of Yoga Across Time and Cultures

Yoga is a millennia-old contemplative and physical discipline rooted in South Asian traditions, with textual foundations traceable to the Vedas (c. 1500–1000 BCE) and systematized by Patañjali's Yoga Sūtras (c. 2nd century BCE–5th century CE) into an eightfold path integrating ethical practice, posture, breath regulation, and meditation [1], [2]. Postural practice (*āsana*) as it is widely recognized today emerged through centuries of cross-pollination among Śaiva, haṭhayogic, and Tantric traditions, later codified in texts such as the Haṭha Yoga Pradīpikā (15th century), and introduced to Western audiences following Swami Vivekananda's 1893 address and 20th-century teachers such as Krishnamacharya and Iyengar [1], [3]. From these foundations, modern yoga has become a clinically relevant practice within complementary and alternative medicine (CAM), with a growing body of evidence supporting its benefits for mental, emotional, and physical health [4], [5].

Despite the widespread adoption of yoga, the potential mechanisms and associations through which yoga *āsana* may contribute to reported therapeutic effects remain incompletely understood across multiple levels of analysis. At the neurophysiological level, prefrontal hypoactivity and rigid patterns of functional connectivity have been implicated in depression and anxiety-related conditions [6]–[8]. However, relatively little research has directly examined whether and how physical yoga postures influence these cortical systems. Studies reporting the psychological benefits of yoga seldom include measures of neural activity, whereas neuroimaging studies of contemplative practices rarely incorporate physically demanding, movement-based protocols, assess participants' subjective experiences of the intervention, or investigate how physical posture itself may contribute to the observed changes.

This gap is partly methodological. Conventional neuroimaging techniques impose substantial restrictions on posture and movement, making them poorly suited to the investigation of *āsana* as an embodied and dynamic practice. Consequently, it remains uncertain whether portable and ecologically valid methods such as functional near-infrared spectroscopy (fNIRS) can adequately measure cortical hemodynamic activity during demanding postures, including inversions and backbends. Beyond the neural level, yoga has been associated with changes in autonomic regulation, neuroendocrine function, interoception, affect, postural alignment, and subjective experience [9]–[12]. These domains, however, are typically investigated separately. Neurobiological changes and lived experience have rarely been examined within a unified empirical framework [13], [14]. This fragmentation makes it difficult to determine whether changes across domains represent separate therapeutic effects or interrelated components of a coordinated, multidimensional regulatory process. Such integration is especially important in the study of yoga, whose traditional frameworks describe human experience through the five *kośas* as interacting dimensions of body, breath, mind, discernment, and awareness being affected by the eight limbs, a system of ethical, postural, respiratory, interoceptive, and meditative practices. A comprehensive investigation of yoga *āsana* must therefore address two related challenges: the methodological difficulty of studying an inherently movement-based practice and the conceptual difficulty of examining its neural, physiological, postural, and experiential effects within a unified framework.

To address these interconnected challenges, this doctoral research comprises three linked studies that progress from methodological feasibility to acute and longitudinal investigation. The first evaluates the use of fNIRS during yoga *āsana* practice; the second examines changes in prefrontal cortical oxygenation and resting-state functional connectivity following an acute sequence of inversions and backbends; and the third investigates sustained yoga practice across neural, biochemical, postural, and experiential domains.

One of the principal contributions of this thesis is the development and methodological validation of a reproducible fNIRS protocol for measuring cortical hemodynamic activity during physically demanding yoga *āsana* under controlled, movement-based conditions, while situating the resulting neurophysiological data within a broader experiential context.

The overarching aim is not to determine the clinical efficacy of yoga, but to examine candidate neurobiological and psychophysiological mechanisms, pathways, and associations that may help explain the improvements in mood, depression, anxiety, stress regulation, and subjective well-being documented over more than 25 years of research in clinical and nonclinical populations [11], [15]–[19].

Drawing on contemporary neuroscience and psychology, while employing yogic philosophy as a complementary interpretive lens, this thesis integrates acute and longitudinal findings to examine how changes in cortical activity, biochemical function, posture, and lived experience may be interrelated. The inclusion of yogic philosophical concepts also reflects the scholarly principle of acknowledging the intellectual traditions that have contributed to the development of knowledge.

Although frameworks such as the five *kośas* and eight limbs may be unfamiliar within contemporary Western scientific discourse, they represent historically and culturally situated accounts of embodied and psychological experience, expressed through the philosophical and metaphorical language of their time. Some of the phenomena described within these traditions are now beginning to be examined empirically through modern neuroscientific and psychophysiological methods. These concepts are therefore included not as direct equivalents to contemporary neurobiological models, but as complementary interpretive frameworks that may provide broader historical, cultural, and experiential context for understanding the measured findings.

The Present Inquiry:

Research Questions, Objectives, and Overview of Published Studies

Although a growing body of research supports the potential benefits of yoga for mood, self-regulation, and well-being, the first two articles address a more specific methodological and neurophysiological inquiry. The acute pilot study on which these articles are based had two primary aims: first, to examine whether inversions and backbends increase prefrontal cortical oxygenation and hemodynamic activity, given the relevance of prefrontal hypoactivity in depression and anxiety research; and second, to assess whether fNIRS can feasibly measure cortical activity during physically demanding, movement-based yoga *āsanas*. The first two articles therefore contribute both methodological evidence regarding the use of fNIRS in embodied yoga research and preliminary evidence regarding the neural effects of selected postures.

Building on this foundation, the third article presents a longitudinal investigation of yoga as a multidimensional health system. This study extends the inquiry beyond isolated outcome measures by examining candidate mechanisms and associations that may help explain previously reported improvements in psychological health and well-being. It addresses a significant gap in the yoga research literature, in which subjective experience and neurobiological, physiological, psychological, and postural changes have rarely been examined within a unified empirical framework. Rather than conceptualizing these outcomes as separate domains, the study investigates how they may interact over time to support self-regulation, psychophysiological health, and well-being.

Specific Objectives

1: To evaluate the feasibility of using functional near-infrared spectroscopy (fNIRS), together with appropriate signal filtering, motion-artifact correction, and statistical analysis, to measure cortical hemodynamic activity during physically demanding yoga *āsana* postures, including inversions and backbends.

2: To examine the acute effects of yoga *āsana* practice, particularly inversions and backbends, on prefrontal cortical oxygenation and resting-state functional connectivity, and to assess whether the observed changes are consistent with a potential body-to-brain regulatory pathway.

3: To examine neural, biochemical, postural, and experiential changes associated with sustained yoga practice across pre- and post-practice assessments

Hypotheses

H1 / Article 1: Functional near-infrared spectroscopy, when applied with appropriate signal filtering, motion-artifact correction, and statistical analysis, will be capable of detecting cortical hemodynamic activity during yoga *āsana* practice, including physically demanding postures such as inversions and backbends.

H2 / Article 2: Acute yoga *āsana* practice, particularly inversions and backbends, will be associated with increased prefrontal cortical oxygenation and activity.

H3 / Article 3: Sustained yoga practice will be associated with significant changes across multiple domains, including cortical activity, resting-state functional connectivity, biochemical markers, postural alignment, and subjective well-being.

Together, the three studies form a progressive and mutually reinforcing empirical arc: first, by establishing the feasibility of measuring acute cortical responses during yoga *āsana*; second, by examining acute neurophysiological changes and possible pathways through which physical posture may be associated with cortical activity; and third, by evaluating sustained yoga practice longitudinally as a multidimensional intervention. In doing so, this thesis contributes to a more integrative understanding of yoga *āsana* as both an embodied contemplative practice and a measurable psychophysiological intervention situated at the intersection of yogic philosophy, neuroscience, and psychophysiological health.

Conceptual and Structural Organization of the Thesis

This thesis is organized around a progression from historical and philosophical grounding, through methodological and empirical differentiation, to integrative interpretation. Two complementary yogic frameworks—the five-*kośa* model described in the *Taittirīya Upaniṣad* and Patañjali's eight-limbed (*aṣṭāṅga*) path—provide historically and culturally grounded lenses through which the findings are considered. The *kośas* represent layered dimensions of human experience, while the eight limbs describe practical pathways through which bodily, respiratory, ethical, attentional, and contemplative processes may be cultivated.

These frameworks are brought into dialogue with contemporary neuroscience, psychology, and psychophysiology. Scientific methods are used to examine measurable neural, physiological, postural, and experiential processes, whereas yogic philosophy provides a broader interpretive framework for understanding embodiment, perception, regulation, and lived experience. The proposed correspondences are heuristic and interpretive rather than claims of causal or direct empirical equivalence.

The thesis is structured as follows:

1. **Literature Review.** Establishes the historical and philosophical foundations necessary to situate the research within yoga's broader intellectual, contemplative, and embodied tradition. In doing so, it gives appropriate scholarly recognition to a body of knowledge with roots extending over four millennia, while synthesizing the existing scientific evidence and theoretical frameworks relevant to the doctoral inquiry. The five *kośas* and eight limbs are developed here as complementary interpretive frameworks for understanding the empirical findings.

2. **Methodological Review.** Examines functional near-infrared spectroscopy and mixed-methods integration as the principal methodological foundations of the research. It reviews the optical and physiological basis of fNIRS, signal interpretation, motion-artifact correction, functional-connectivity analysis, and the integration of objective and first-person measures.

3. **Research Articles.** Presents the three studies comprising the doctoral research:
   - **Article 1:** *Resting-State Connectivity and Neuroimaging of Prefrontal Cortex Activity During a Block-Design Yoga Asana Practice Using fNIRS [20]*
   - **Article 2:** *Yoga Asana Increases Prefrontal Cortex Activity and Reduces Resting-State Functional Connectivity [21]*
   - **Article 3:** *Neural, Biochemical, Postural, and Subjective Outcomes Following a 30-Day Yoga Program: A Multimodal Mixed-Methods Study [22]*

4. **Discussion.** Integrates the findings across the three publications and interprets them in relation to both contemporary scientific models and the yogic perspectives established in the Literature Review. The findings are first differentiated across neural, biochemical, postural, and experiential domains and are then considered through the *kośas* and eight limbs as complementary lenses for understanding their possible interrelationships.

5. **Conclusion.** Synthesizes the principal findings, acknowledges the methodological and interpretive limitations of the research, and considers its clinical and public health implications, as well as directions for future investigation.

Literature Review

"Dividing the united, uniting the divided, is the whole work of nature."

-Johann Wolfgang von Goethe

Yoga: A Multifaceted System of Well-Being

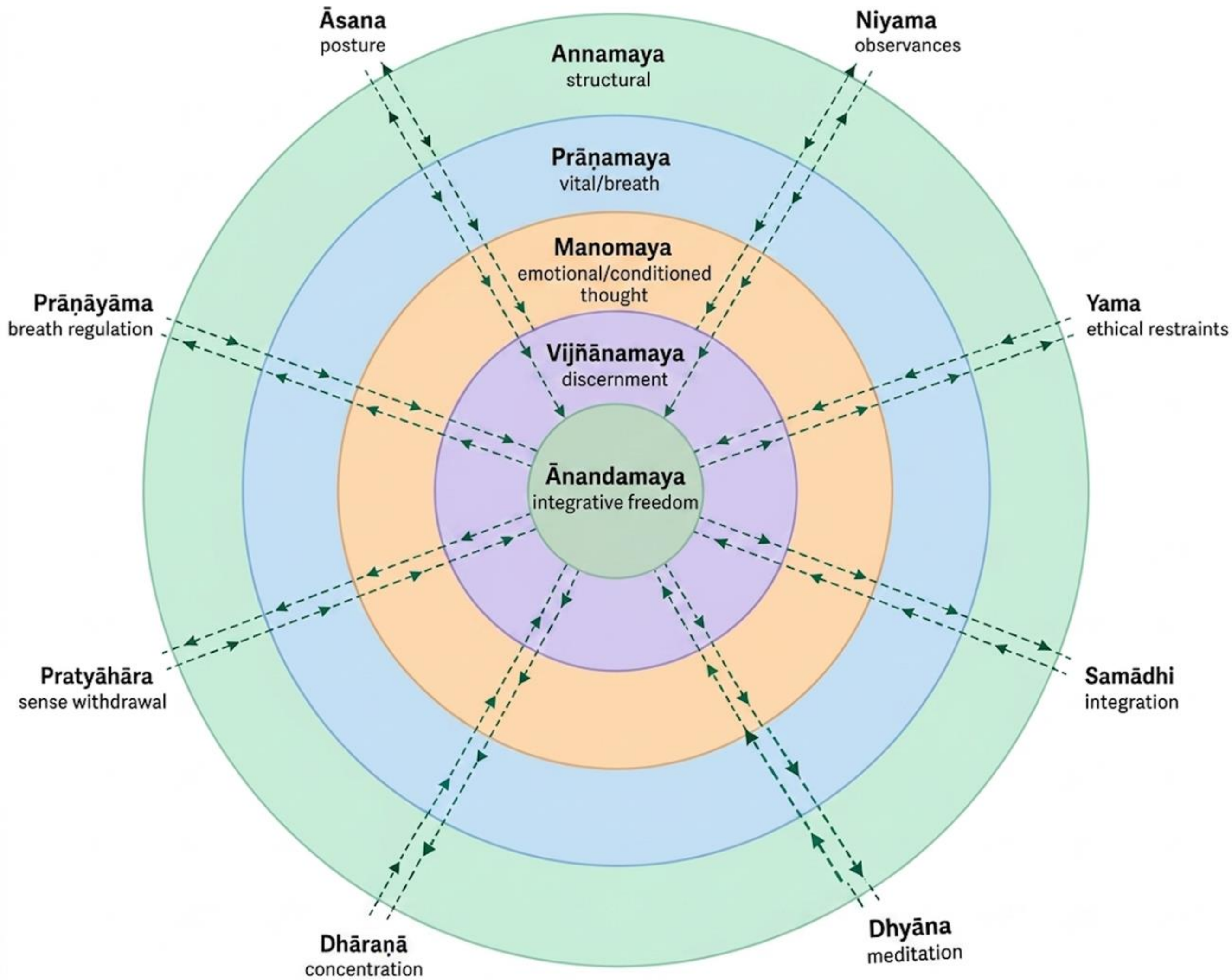
The Eight Limbs and Five *Kośas* as a Reciprocal System

The eight limbs (*aṣṭāṅga*) integrate ethical disciplines (*yamas* and *niyamas*), posture (*āsana*), breath regulation (*prāṇāyāma*), sensory withdrawal (*pratyāhāra*), concentration (*dhāraṇā*), meditation (*dhyāna*), and absorption (*samādhi*) within a reciprocal system of body–mind regulation.

Although often presented sequentially, the limbs function as a reciprocal and multidirectional system, as illustrated in Figure 1. Each limb builds upon and conditions the others, collectively offering a coherent methodology for attenuating mental fluctuations (*vṛtti*) and cultivating self-awareness, regulation, and agency across multiple dimensions of experience. In this thesis, these limbs are understood to interact across the five *kośas*, not in a strictly linear manner, but through reciprocal influences among body, breath, mind, discernment, and integrative awareness.

Annamaya Kośa, the structural-physiological domain, encompasses postural alignment, musculoskeletal organization, and the embodied substrate of experience. Within this interpretive framework, the *guṇas*—*tamas* (inertia), *rajas* (agitation), and *sattva* (clarity)—can be heuristically compared with dynamic regulatory tendencies in endocrine, autonomic, and affective systems, rather than mapped directly onto specific biological markers. *Prāṇamaya Kośa* corresponds to autonomic and respiratory regulation; *Manomaya Kośa* to affective and cognitive processing; *Vijñānamaya Kośa* to metacognitive and executive functioning; and *Ānandamaya Kośa* to integrative coherence and trait-level well-being expressed as embodied self-agency.

As sustained practice of the eight limbs of yoga deepens, these reciprocal processes may increasingly support coordinated regulation across all five layers metaphorically represented by the *kośas*.



*Note: This figure, representing the five-kośa model, is created by the author and is open-access with proper attribution.

Figure 1. Multidirectional Interaction of the Eight Limbs of Yoga Across the Five *Kośas*

Figure 1 illustrates the reciprocal relationship between Patañjali's eight limbs of yoga and the five-*kośa* model. The concentric layers represent the *kośas*, extending from Annamaya as the structural-physiological body, through Prāṇamaya, Manomaya, and Vijñānamaya, toward Ānandamaya as integrative freedom. The radial arrows indicate that each limb, including *yama*, *niyama*, *āsana*, *prāṇāyāma*, *pratyāhāra*, *dhāraṇā*, *dhyāna*, and *samādhi*, acts multidirectionally across all layers rather than operating in a strictly linear sequence. Together, the model presents yoga as an integrated regulatory system in which ethical practice, posture, breath, sensory refinement, attention, meditation, and integration mutually shape embodied self-awareness, regulation, and agency.

Locus of Control (LOC) and the Yogic Path to Self-Governance

Locus of Control and Self-Agency

The concept of locus of control (LOC), defined as the extent to which individuals perceive themselves as having agency in their own lives, is a foundational concept in psychotherapy and is closely associated with trauma-related and mood disorders. While its expression varies across cultural contexts, with collectivist societies and spiritual frameworks distributing a sense of control across community, ancestry, or faith rather than locating it solely within the individual, the underlying construct remains clinically meaningful across cultures.

Individuals with a predominantly external locus of control often experience helplessness and powerlessness, reflecting diminished self-agency and a strong association with posttraumatic stress disorder (PTSD), depression, and anxiety. Trauma is therefore often understood as involving a diminished sense of agency.

Yoga and Embodied Agency

A growing body of research suggests that yoga may meaningfully shift this dynamic. Regular practice has been shown to increase self-efficacy and personal agency, fostering movement from helplessness toward empowerment [23], [24]. Empirical studies further show that yoga practitioners report higher internal and lower external health locus of control scores than non-practitioners [25], and that continued practice strengthens internal control beliefs alongside self-determined motivation [26].

Gard et al. [9] propose a systems-based explanation for these effects, suggesting that yoga integrates top-down and bottom-up self-regulatory mechanisms through *āsana* (posture), *prāṇāyāma* (breath regulation), and sensory withdrawal and meditative practices (*pratyāhāra*, *dhāraṇā*, *dhyāna*). Together, these practices enhance interoceptive awareness and may strengthen perceived agency over bodily states and ruminative mental patterns.

Contemporary psychological research on posture and psychological states aligns with this view by demonstrating that bodily posture can influence affective states, cognition, and self-regulatory capacity. In depressed inpatients, a slumped posture increased the recall of negative words, whereas an upright posture supported more balanced recall and improved affective tone [27]. Likewise, Wilson and Peper [28] reported that 92% of participants found it easier to generate positive thoughts when sitting upright. Studies of postural awareness further indicate that improved alignment reduces musculoskeletal pain and correlates with enhanced mood and emotional regulation [29], [30].

Classical yoga similarly frames deliberate posture, breath regulation, and sustained attention as practices that may strengthen self-regulation and perceived agency through the regulation of *citta*, understood here as the mind–body complex.

Yoga, Trauma, and Autonomic Regulation

Trauma as Embodied and Autonomic Dysregulation

Trauma may involve the involuntary disruption of precisely this internal LOC. Whereas yoga may strengthen an internal LOC through deliberate engagement of the autonomic nervous system (ANS), trauma may disrupt this process through involuntary dysregulation, imprinting patterns of physiological arousal that persist long after the initiating threat has passed.

Modern trauma theory increasingly conceptualizes trauma not merely as a psychological event but as a transdiagnostic risk factor associated with persistent autonomic, interoceptive, affective, and embodied dysregulation. Systematic reviews and meta-analyses link trauma exposure, particularly chronic childhood adversity, with later depression, anxiety disorders, somatoform conditions, and functional somatic syndromes, suggesting that posttraumatic dysregulation may be expressed through both psychological and bodily symptoms [31]–[37].

At the physiological level, individuals with trauma histories consistently show autonomic dysregulation marked by lower resting heart rate variability (HRV), lower parasympathetically mediated HRV indices, higher baseline heart rate, and altered stress reactivity. Together, these patterns suggest reduced vagal regulation and relative sympathetic dominance [38]–[40]. Prospective evidence further indicates that short-term increases in PTSD symptoms predict subsequent reductions in HRV, supporting a dynamic link between trauma-related symptom burden and autonomic imbalance [41].

Collectively, these findings suggest that trauma-related ANS dysregulation may help explain why trauma-related conditions frequently present with overlapping depressive and anxious symptoms, as well as hyperarousal, hypoarousal, insomnia, dissociation, and diminished interoceptive awareness [42], [43]. Trauma-related dysregulation therefore links psychological suffering with measurable autonomic disruption.

Yoga-Based Pathways to Autonomic Regulation

As outlined in Figure 2, *āsana* (posture) and *prāṇāyāma* (breath regulation), together with *pratyāhāra* (sensory withdrawal/interoceptive awareness), may provide somatic pathways through which body, breath, and embodied awareness are integrated in support of nervous system regulation. Within Polyvagal Theory, slow, rhythmic breathing and mindful movement are proposed to facilitate vagal regulation and parasympathetic engagement [35], [44], [45]. Empirical research is consistent with this framework, suggesting that yoga and breath-based practices are associated with changes in vagal activity, heart rate variability, and autonomic balance [44], [45].

Clinical studies provide evidence that yoga-based interventions may support mental health outcomes and nervous-system regulation. Van der Kolk et al. [37] found that a 10-week trauma-informed yoga program was associated with significant reductions in PTSD symptom severity compared with a health-education control condition. Similarly, Seppälä et al. [46] reported clinically meaningful decreases in anxiety and depression following a Sudarshan Kriya Yoga (SKY) intervention among 21 veterans diagnosed with PTSD. Meta-analyses further suggest that yogic breath and movement practices are associated with improved autonomic regulation and may function as adjunctive interventions for depression and anxiety [47], [48].

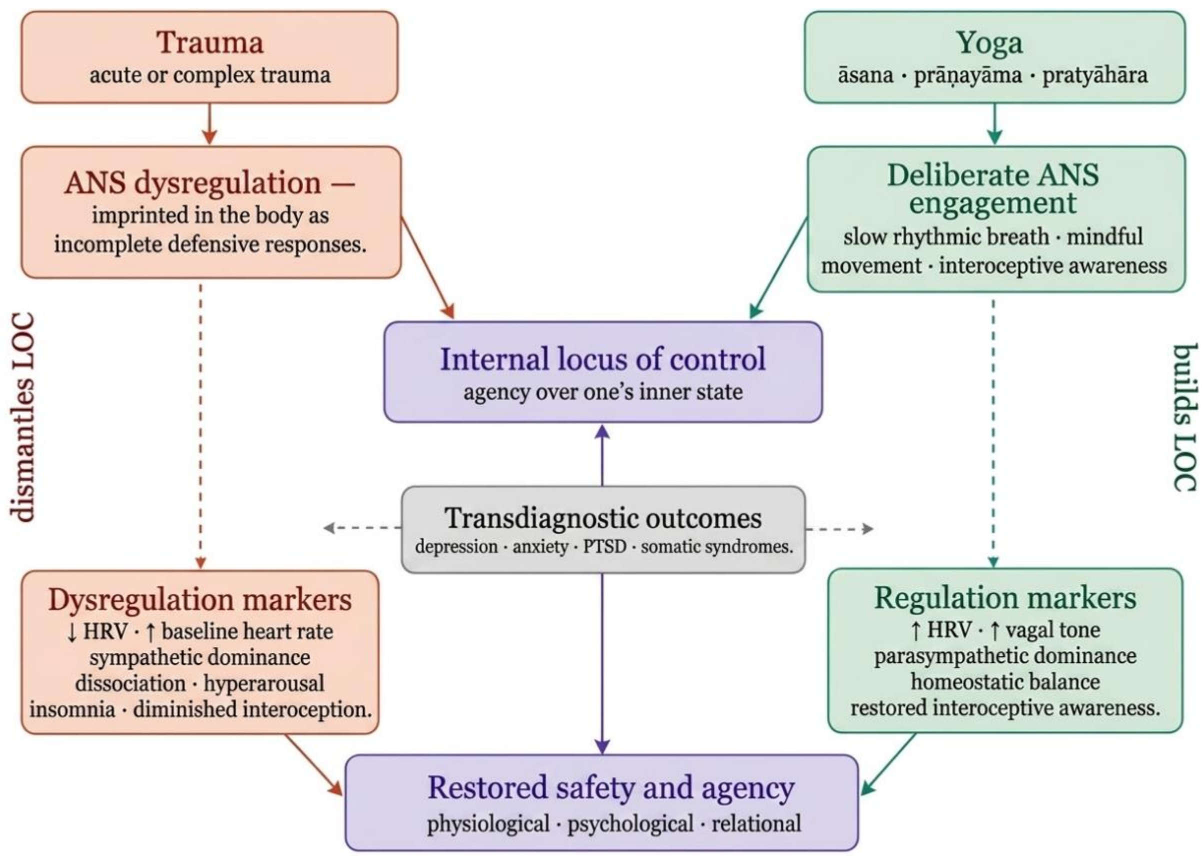


Figure 2. Agency (LOC), Trauma, and Yoga: Autonomic Nervous System Pathways Toward or Away from Self-Agency. Trauma is represented as promoting persistent autonomic dysregulation, reduced interoception, and diminished agency. In contrast, *āsana*, *prāṇāyāma*, and *pratyāhāra* may support vagal

regulation, homeostasis, and restored safety and self-agency through mindful movement, breath, and interoceptive awareness.

Neuroendocrine and Psychophysiological Pathways: Western and Yogic Perspectives

Neuroendocrine Dysregulation and Homeostasis

Within contemporary physiology, physical and psychological disorders may be understood through endocrine and neurochemical patterns. Suppressed vitality, disrupted cortisol rhythms, and low serotonergic tone are associated with depressive states; elevated norepinephrine, sympathetic dominance, and hyperarousal are associated with anxiety; and a regulated balance between these poles characterizes adaptive stress functioning.

PTSD offers a clear illustration of how these systems become dysregulated. Chronic trauma may not simply sustain elevated cortisol but may ultimately suppress it. Individuals with PTSD often present with lower baseline cortisol, elevated inflammatory markers such as IL-6, decreased heart rate variability (HRV), and a blunted acute stress response with slower recovery, reflecting hypothalamic–pituitary–adrenal (HPA) axis exhaustion following prolonged negative feedback sensitization [49]. This neuroendocrine profile is marked by both hyperarousal and depleted regulatory capacity—a system that is simultaneously overactivated and exhausted.

This same pattern of autonomic, inflammatory, and stress response dysregulation helps explain the frequent overlap between PTSD, depression, and anxiety, which often share transdiagnostic features such as impaired stress recovery, affective dysregulation, rumination, and a diminished sense of control [49]–[51]. Under healthy conditions, cortisol follows a circadian rhythm, rising in the morning and declining in the evening. When this rhythm is disrupted, the body loses some of its capacity to regulate stress, sleep, metabolism, emotion, and cognitive function, contributing to reduced well-being [52]–[55]. In this sense, sleep disturbance, endocrine dysregulation, impaired stress recovery, depression, and anxiety may be better understood not as separate problems, but as interconnected expressions of disrupted psychophysiological homeostasis.

Conventional Treatment Limitations and Complementary Approaches

Such findings warrant careful comparison with conventional pharmacological approaches, particularly in mild-to-moderate depression, where antidepressant effects relative to placebo may be more modest than commonly assumed. Limitations in the efficacy and tolerability of conventional treatments have also contributed to growing interest in complementary interventions that may influence multiple regulatory systems [56]–[58].

Meta-analytic evidence suggests that yoga may offer antidepressant effects alongside broader benefits across multiple regulatory systems, supporting its consideration as a complementary intervention. Randomized trials and systematic reviews indicate that yoga reduces depressive and anxiety symptoms, improves sleep quality, supports stress physiology, enhances parasympathetic regulation, and improves overall well-being and quality of life [11], [16]–[19]. Regular yoga practice has been associated with stabilization of circulating cortisol and norepinephrine, as well as changes in serotonergic and oxytocinergic markers, with these changes linked to stress reduction, mood stabilization, empathy, and interpersonal bonding [12]. Streeter et al. [59] reported that a single session of yoga *āsana* was associated with an approximately 27% acute increase in gamma-aminobutyric acid (GABA), accompanied by improvements in mood and anxiety. Subsequent studies further support yoga's capacity to enhance parasympathetic activity and GABAergic tone, mechanisms implicated in reduced anxiety and improved affect regulation [10], [60]. Astutik et al. [61] similarly observed hormonal stabilization in primiparous postpartum women, suggesting that yoga-related regulatory effects may extend across diverse physiological contexts.

Noetel et al. [19], in a network meta-analysis of 218 randomized controlled trials involving 14,170 participants, found that exercise interventions, including yoga, reduced depressive symptoms and identified yoga as a clinically feasible option because of its acceptability and tolerability. Together with evidence that yoga may influence endocrine function, sleep, stress regulation, and affect, these findings support the examination of yoga as a multidomain practice that may contribute to restoring psychophysiological homeostasis rather than targeting a single presumed deficit [11], [12], [15], [19], [62]. In this view, coordinated changes in sleep, autonomic regulation, stress recovery, interoceptive awareness, and emotional stability may reinforce one another, allowing physiological balance to support psychological well-being.

The *Guṇas* as a Heuristic Model of Regulation

Within the yogic framework illustrated in Figure 3, *tamas*, *rajas*, and *sattva* describe tendencies toward inertia, activation, and regulatory balance, respectively. *Sattva* does not imply the absence of *tamas* or *rajas*, but their flexible regulation, closely paralleling homeostasis as an active, self-correcting equilibrium. These guṇic qualities are compared heuristically—not causally—with endocrine, autonomic, and affective tendencies: *tamas* with depletion and withdrawal, *rajas* with hyperarousal and reactivity, and *sattva* with regulatory flexibility and psychophysiological stability. This comparison provides an interpretive bridge between yogic philosophy and contemporary models of homeostatic regulation.

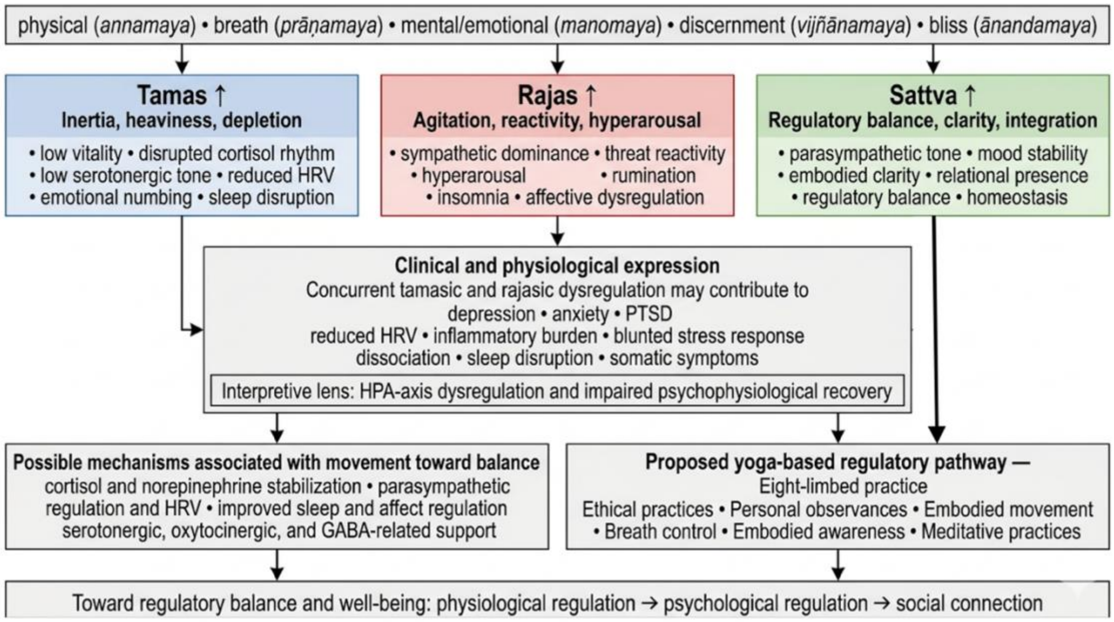


Figure 3. Proposed *Guṇa–Kośa* Model of Neuroendocrine Dysregulation and Yogic Regulation. Figure 3 links guṇic imbalance across the *kośas* with psychophysiological dysregulation. *Tamas* and *rajas* represent depletion and hyperarousal, while eight-limbed yoga is proposed as a systems-level pathway toward autonomic, affective, neuroendocrine, and relational regulation.

Community (*Sangha*), Embodiment, and Ethical Practice

Sangha—and, in some contexts, *satsang*—refers to the relational community within which yoga is practiced. In *Aṣṭāṅga* Yoga, the eight limbs form an integrated system in which ethical principles are embodied through *āsana*, *prāṇāyāma*, and meditation and extended into conduct and relationships [63], [64]. Without this dimension, yoga risks being reduced to "mere acrobatics" [64]; when practiced as a whole, however, it may support the belonging, social cohesion, and relational connection associated with human flourishing [65]–[68].

Empirical findings align with this perspective. Group-based yoga has been associated with empathy, attunement, belonging, self-compassion, and relationship quality—factors that may support trauma recovery and emotional well-being [69]–[71]. Yoga practice has also been linked to friendship, inclusion, mutual support, stronger relationships, higher self-esteem, and more adaptive stress regulation [23], [24]. As illustrated in Figure 4, the integrated cultivation of the eight limbs may therefore strengthen not only self-regulation but also the capacity to perceive and respond to the emotional states of others.

Siegel [72] describes this convergence of self-regulation and social connection as integrated awareness, a coherent mode of being in which both emerge from the same embodied foundation.

Yoga may thus be understood as both an individual and a relational practice, in which inner cultivation and social engagement mutually reinforce one another.

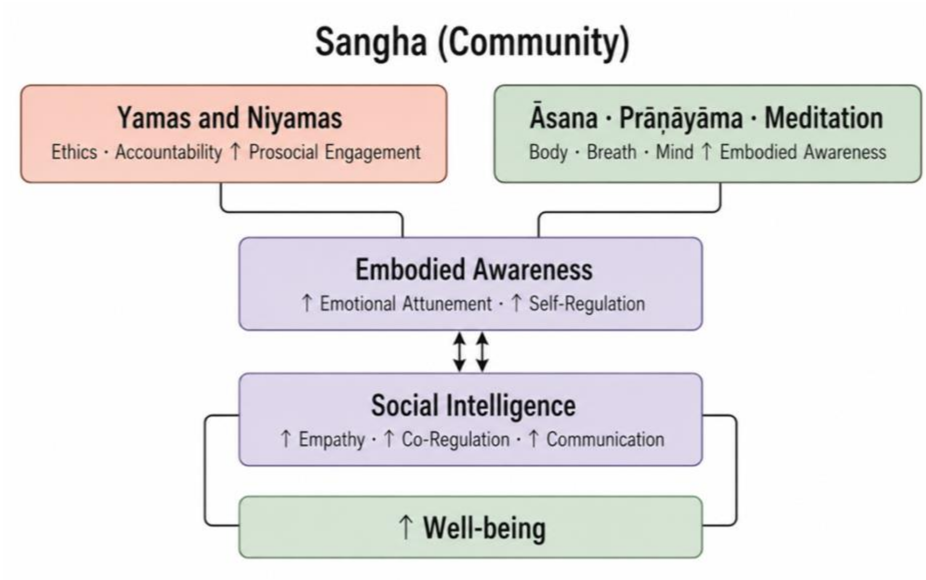


Figure 4. The Eight Limbs of Yoga as Embodied Ethics and Relational Intelligence. Conceptual model illustrating how the *yamas* and *niyamas*, together with *āsana*, *prāṇāyāma*, and meditation, form an integrated practice in which ethical cultivation, embodied awareness, and *Sangha* support relational attunement, self-regulation, empathy, and social connection.

Māyā: Distributed Network Dysfunction, Hemispheric Specialization, and Perceptual Narrowing

Within the yogic framework used here, *māyā* refers to conditioned or distorted perception that obscures reality and contributes to suffering. Contemporary neuroscience similarly associates psychological dysfunction with maladaptive perceptual processing arising from disrupted coordination across distributed brain networks rather than impairment in a single region. [73]–[76]. The therapeutic effects of stimulation applied to either hemisphere further suggest that recovery depends on network-level reorganization rather than correction of one deficient site [8], [77], [78].

This perspective challenges reductionist accounts that locate psychological disturbance in a single brain area, hemisphere, or chemical process. Healthy functioning instead depends on flexible coordination among specialized systems that cooperate, constrain, and inhibit one another. When this coordination becomes rigid, perception may narrow around self-reinforcing patterns. McGilchrist's Divided Brain Theory similarly proposes that the hemispheres support distinct but complementary modes of attention and perception. Neither is inherently superior or pathological;

coherent experience depends on their dynamic integration rather than the dominance of either hemisphere [79]–[82].

In McGilchrist's account, the left hemisphere favors analysis, categorization, abstraction, predictability, and control, whereas the right is more attuned to context, novelty, embodied cues, relational meaning, and the wholeness of lived experience [79], [81], [82]. Although complementary, excessive reliance on left-hemisphere processing may generate rigid, self-reinforcing interpretations detached from embodied and contextual information—a condition described here as "hallucinated certainty" [79], [80], [82]. From this perspective, *māyā* may be understood not simply as inaccurate thought, but as perceptual narrowing in which abstract representations are mistaken for the fuller reality they only partially describe.

As illustrated in Figure 5, left-lateralized prefrontal and language systems contribute more strongly to verbal, categorical, and executive regulation, whereas right-hemisphere systems contribute more substantially to affective prosody, facial expression, nonverbal emotional context, and embodied awareness [83]–[88]. Disruption of hemispheric and broader network coordination may therefore contribute to obsessive cognition, delusional rigidity, diminished empathy, impaired contextual and emotional understanding, and disturbances of self-awareness in schizophrenia-spectrum conditions, depersonalization, anxious paranoia, and some depressive presentations [79], [89]–[91].

Interoception and Embodied Self-Awareness

The right hemisphere is particularly important for embodied awareness and accurate self-appraisal. Right-hemisphere lesions are associated with anosognosia, impaired recognition of personal limitations, and overestimation of one's capacities [92]–[94]. Within this broader system, the right anterior insula supports interoception, somatic feeling, emotional awareness, and body-based social cognition [95]–[97]. In dissociative PTSD, excessive corticolimbic inhibition may involve hyperactivation of the medial prefrontal cortex and dorsal anterior cingulate cortex, while reduced right anterior insula activation suggests that impaired access to interoceptive information contributes to emotional numbing, disembodiment, and alexithymia [42], [98].

Contemplative Practice and Network Reintegration

Embodied contemplative practices may help restore more integrated perception by reconnecting analytic and self-referential processing with contextual, affective, and interoceptive awareness. Yoga practices such as *āsana* and *prāṇāyāma* cultivate sustained attention to bodily sensations and may strengthen access to interoceptive signals that are diminished or disrupted in dissociative states. Interoceptive training can alter cortical representations of bodily attention, and the right anterior insula is consistently implicated in body awareness, emotional experience, and mental health [95]–[97]. Meditation and yoga are also associated with reduced activation and altered connectivity within the default mode network, suggesting more flexible integration among self-referential, attentional, and interoceptive systems rather than the simple suppression of self-related processing [99]–[102].

By redirecting attention toward immediate bodily and contextual experience, yoga may therefore interrupt rigid, self-reinforcing interpretations and support greater neural flexibility. Within the present framework, this process may reduce the perceptual narrowing associated with *māyā* by promoting integrated awareness and supporting the restoration of interoceptive function, hemispheric coordination, and large-scale network functioning in trauma and depression [95], [101], [102].

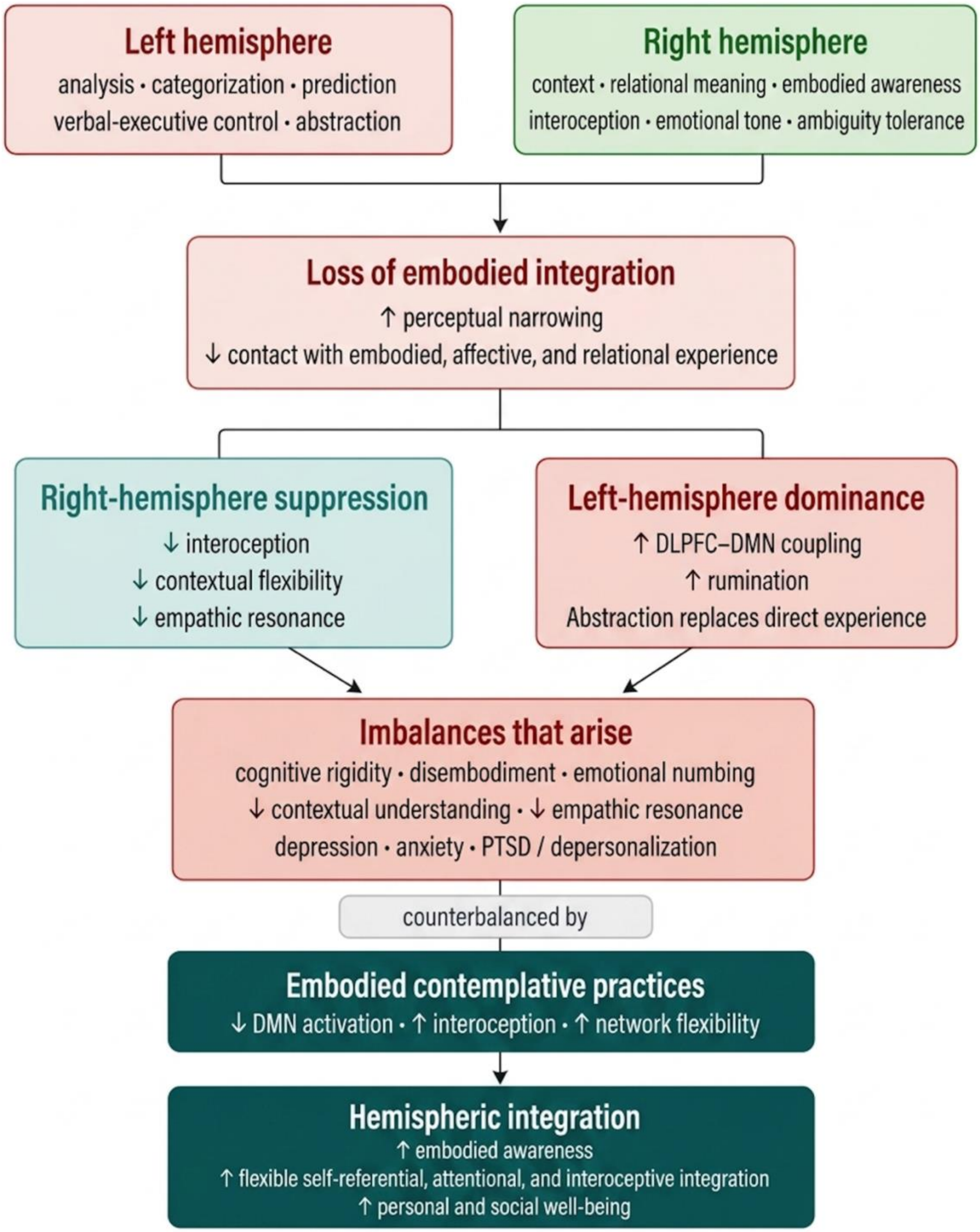


Figure 5. Proposed Model of Hemispheric Imbalance, Embodied Disconnection, and the Integrative Effects of Contemplative Practice. Conceptual model summarizing how embodied contemplative practices may support hemispheric and network-level balance through interoception, DMN modulation, and more flexible integration of self-referential, attentional, and relational processing.

Literature Review Summary

"It is easier to act yourself into a new way of thinking than to think yourself into a new way of acting"

(Jones, as cited in Mowrer [103, p. 139])

The reviewed literature suggests that yoga may support a shift away from rigid, over-controlled, and ruminative patterns of cortical processing associated with excessive left-hemispheric dominance toward a more embodied, flexible, relational, and context-sensitive mode of regulation. As outlined in Figure 6, within the yogic framework, this process is systematically cultivated through the eight limbs of yoga, which span ethical, postural, respiratory, sensory, attentional, and meditative dimensions. These practices may be understood as addressing multiple layers of dysregulation that yogic philosophy describes in terms of disturbed prāṇic flow, guṇic imbalance, and distortion across the *kośas*. At the center of this disturbance is a diminished sense of agency over one's internal state, which the tradition associates with *māyā*, or distorted perception, and which may be expressed clinically as emotional rigidity, relational withdrawal, rumination, and the disembodiment characteristic of anxiety and depression.

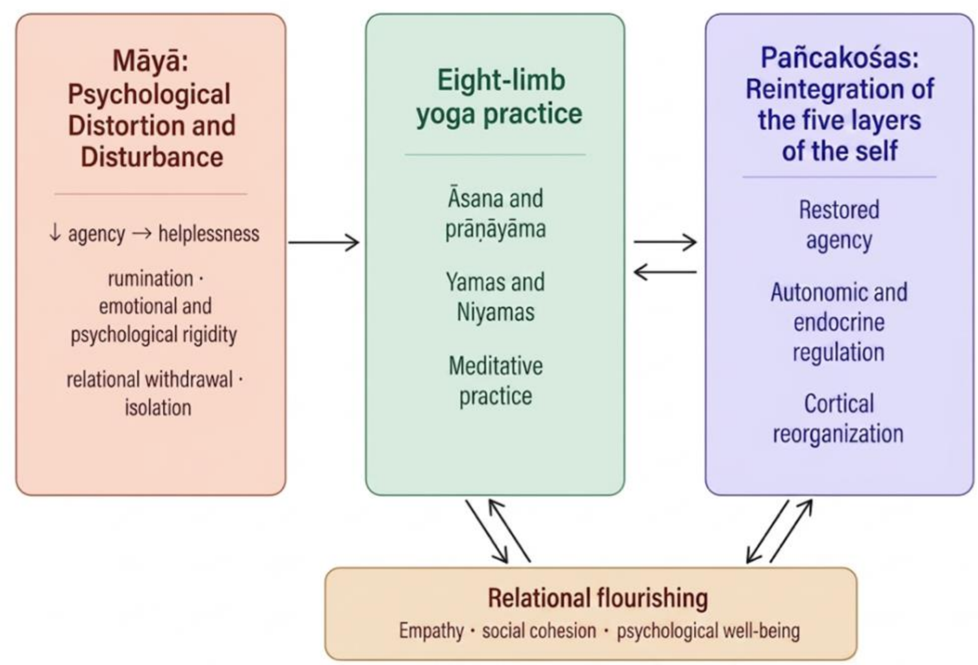


Figure 6. A Model of Yoga as Therapeutic Intervention. An integrated framework illustrating the multidirectional relationship between psychological disturbance, eight-limb yoga practice, mind–body reintegration, and relational flourishing, as well as the reciprocal feedback loop through which each dimension reinforces the others.

Yoga may address these disembodied patterns through posture, breath regulation, and interoceptive attention, immediate domains of self-regulation. Through these practices, yoga may support autonomic balance and homeostatic regulation, thereby facilitating affect regulation and greater integration across self-referential, attentional, and interoceptive networks. Within the yogic framework, this process may be understood as the rebalancing of the *guṇas*, the regulation of prāṇic flow, and the refinement of the *kośas* through which experience is perceived and organized. Importantly, this process is not limited to individual self-regulation. As embodied awareness increases, perception may shift from isolated self-focus toward greater relational awareness. This shift may strengthen empathy, self-compassion, and adaptive social engagement, while healthier relational functioning may further reinforce internal regulation. Thus, yoga may operate through a reciprocal process in which self-awareness and relational awareness mutually support psychological flexibility and well-being.

Methodological Review

From Jöbsis's Experiments to Modern Neuroimaging

"The most exciting phrase to hear in science, the one that heralds new discoveries, is not 'Eureka!' but 'That's funny...'"
— Isaac Asimov

The origins of functional near-infrared spectroscopy (fNIRS) can be traced to the pioneering work of Frans F. Jöbsis in the mid-1970s. While experimenting with near-infrared light, Jöbsis observed that light in the near-infrared spectrum could penetrate biological tissue and that transmitted light varied systematically according to oxygenation levels. This observation established that near-infrared light, particularly within the 650–950 nm optical window, could penetrate several centimeters into tissue and carry quantifiable information about hemoglobin oxygenation. In 1977, Jöbsis published his landmark paper in *Science*, demonstrating the noninvasive monitoring of cerebral oxygen sufficiency and laying the empirical foundation for what would later become an established neuroimaging modality [104].

By the 1990s, fNIRS had progressed from single-channel feasibility experiments to multi-channel systems capable of recording cortical hemodynamic changes across broader regions of the brain [105]. These changes, typically reflected in oxygenated hemoglobin (HbO), deoxygenated hemoglobin (HbR), and total hemoglobin (HbT), are used as indirect indices of neural engagement rather than direct measures of neuronal firing. Subsequent technological advances led to high-density systems with large numbers of source and detector optodes, allowing improved spatial sampling and, in some cases, three-dimensional cortical image reconstruction through diffuse optical tomography [106]. Contemporary fNIRS systems are increasingly wearable, wireless, and portable, with temporal sampling rates that vary by device configuration but are generally sufficient to capture dynamic changes in cortical oxygenation. This trajectory has positioned fNIRS as an increasingly established neuroimaging modality, particularly for ecological, developmental, clinical, rehabilitation, and movement-based research [105].

A defining advantage of fNIRS is its capacity to study cortical hemodynamics under naturalistic conditions. Unlike fMRI, which requires participants to remain still within a scanner, fNIRS can be used during tasks involving posture, movement, social interaction, and real-world behavior. fNIRS studies have recorded cortical activity during walking, driving, musical performance, and face-to-face communication, all of which are difficult or impossible to examine under conventional MRI conditions [106]. The technique is also well suited to populations for whom MRI may present practical or clinical barriers, including infants, young children, claustrophobic individuals, and medically vulnerable patients [105], [106]. Owing to its portability, safety, relatively low cost, comparatively high temporal resolution relative to functional magnetic resonance imaging (fMRI) and positron emission tomography (PET), and compatibility with naturalistic tasks, functional near-infrared spectroscopy (fNIRS) has become increasingly relevant across cognitive neuroscience, developmental psychology, clinical research, and embodied approaches to brain function. Unlike PET, fNIRS does not require radiotracers or exposure to ionizing radiation, and unlike conventional fMRI and PET, it does not require participants to remain motionless within a scanner. Compared with electroencephalography (EEG), fNIRS has lower temporal resolution but offers better spatial localization and is less susceptible to electrical and muscular interference, making it particularly well suited to measuring localized cortical activity during natural posture, whole-body movement, and physically demanding tasks.

The Physiological and Optical Basis of fNIRS

The physiological foundation of fNIRS rests on neurovascular coupling, the dynamic relationship between neuronal activity, metabolic demand, and regional cerebral blood flow. When a cortical region becomes more metabolically active, local vascular responses increase the delivery of oxygenated blood to that region. This produces a characteristic hemodynamic response, typically involving an increase in oxygenated hemoglobin (HbO) and a concurrent decrease in deoxygenated hemoglobin (HbR). fNIRS does not measure neural activity directly. Rather, it measures optical changes associated with hemoglobin oxygenation, which are interpreted as indirect hemodynamic correlates of cortical activity through the principle of neurovascular coupling. This relationship is conceptually related to the fMRI blood-oxygen-level-dependent (BOLD) signal, which is also influenced by local changes in HbR [107].

As illustrated in Figure 7, the measurement process begins when near-infrared light is emitted into the scalp by source optodes and then received by detector optodes. In the published articles of this thesis, the fNIRS system used dual-wavelength light-emitting diodes centered at 757 and 843 nm, with 3-cm source–detector separations. As light travels through scalp, skull, and superficial cortical tissue, it undergoes absorption and scattering. Absorption occurs when photons are captured by chromophores, while scattering occurs when photons are deflected by tissue inhomogeneities. The two dominant chromophores in the near-infrared optical window are HbO and HbR, each of which has a distinct wavelength-dependent absorption spectrum quantified by its molar extinction coefficient (ϵ) [105], [108]. HbR absorbs more strongly at shorter near-infrared wavelengths, around 760 nm, whereas HbO absorbs more strongly at longer wavelengths, around 850 nm. The two absorption spectra intersect near an isosbestic point around 800 nm, where both chromophores absorb light similarly [109], [110].

This difference in absorption spectra allows fNIRS to estimate changes in both HbO and HbR. If fNIRS relied on a single wavelength, any measured change in light attenuation would reflect an unknown combination of HbO and HbR, making the two contributions mathematically inseparable. By measuring attenuation at a minimum of two wavelengths, one more sensitive to HbR and one more sensitive to HbO, the system generates independent equations weighted by the known extinction coefficients of each chromophore. These equations can then be solved simultaneously to estimate relative changes in HbO and HbR. This chromophore separation is implemented through the modified Beer–Lambert law, which models how changes in optical density relate to changes in chromophore concentration while accounting for tissue scattering [108], [109], [111].

$$\Delta A(\lambda) = \sum \epsilon \cdot \Delta c \cdot L \cdot DPF + G \quad (1)$$ [1]

As shown in equation (1) above, $\Delta A(\lambda)$ represents the dimensionless change in optical density at wavelength λ (nm), ϵ denotes the molar extinction coefficients for HbO and HbR ($M^{-1} \cdot cm^{-1}$), Δc represents the change in chromophore concentration (M, commonly reported as μM), L is the source–detector separation (cm), DPF is the dimensionless differential pathlength factor accounting for scattering, and G reflects dimensionless geometry-dependent constants. Through this process, fNIRS converts changes in detected light intensity into estimates of relative hemoglobin concentration changes over time.

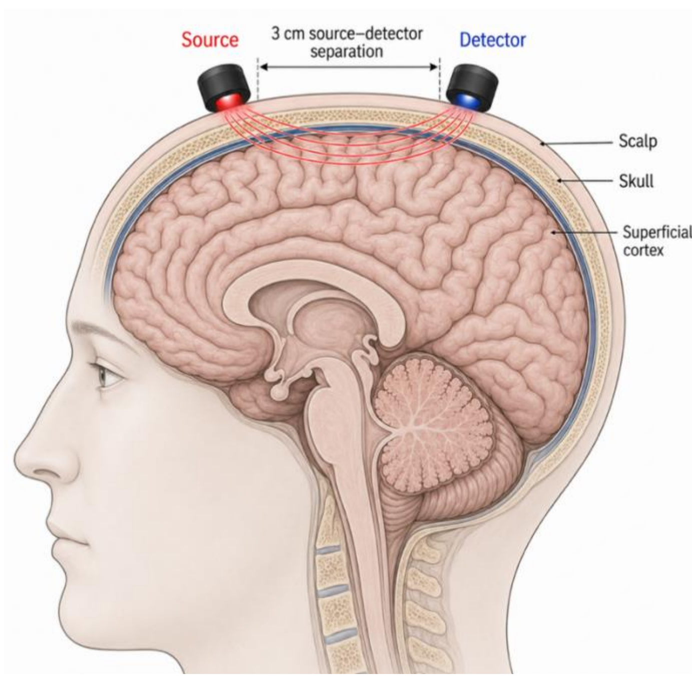


Figure 7. How fNIRS Measures Cortical Activity. Near-infrared light travels from a source optode to a detector optode through superficial head tissues, allowing fNIRS to estimate changes in cortical oxygenation.

[1] $\Delta A(\lambda)$:change in light attenuation at wavelength λ ; $\varepsilon_i(\lambda)$: extinction coefficient of chromophore i ; Δc_i: change in its concentration ; L: source–detector distance ; DPF: differential pathlength factor ; G: scattering-related constant

Strengths, Applications, and Spatial Limitations

Relative to fMRI and PET, fNIRS offers several practical advantages, including portability, silent operation, lower cost, and greater tolerance of movement. These features make it especially suitable for pediatric, psychiatric, rehabilitation, social interaction, and movement-based research. However, these advantages come with important limitations. Standard fNIRS has lower spatial resolution than fMRI and is limited to superficial cortical regions; penetration depth depends on source–detector separation and tissue properties. It cannot image deep subcortical structures, which remains a significant limitation for studies requiring precise anatomical localization or whole-brain coverage [112].

The prefrontal cortex was selected as the region of interest because of its central role in emotion regulation and executive control, as well as the well-documented alterations in prefrontal activity and connectivity associated with anxiety and depression. This choice also reflected the practical and technical constraints of the available fNIRS configuration, which did not permit whole-brain coverage. More comprehensive optical imaging approaches, such as diffuse optical tomography, require denser instrumentation and are substantially more costly and heavier. The present design therefore prioritized a clinically relevant and accessible superficial cortical region that could be measured reliably during yoga *āsana*, while recognizing that other cortical areas and subcortical structures involved in emotional regulation and executive control could not be assessed directly.

Although fNIRS is more tolerant of movement than many other neuroimaging modalities, it is not immune to motion-related signal distortion. Its relative flexibility makes it valuable for studies involving naturalistic behavior, but careful attention must still be given to scalp-optode coupling, channel quality, and motion-artifact correction. fNIRS can also be combined with EEG, allowing the comparatively better spatial resolution of fNIRS to complement the superior temporal resolution of EEG and thereby integrate hemodynamic and electrophysiological signals for improved spatiotemporal interpretation [112].

One methodological response to the spatial limitations of standard fNIRS has been the development of high-density diffuse optical tomography. This approach uses dense source–detector arrays to reconstruct three-dimensional cortical images and has demonstrated localization errors below 5 mm in fMRI validation studies [113]. These refinements improve localization but do not remove the need for careful signal-quality control.

Systemic Physiological Contamination

A central methodological challenge in fNIRS is systemic physiological contamination. Because near-infrared light must pass through extracerebral tissues before reaching the cortex, the recorded signal includes contributions from the scalp, skull, and superficial vasculature, as well as from cortical tissue. Cardiac pulsation, respiratory fluctuation, and Mayer waves, slow spontaneous oscillations in arterial blood pressure, can produce optical-density changes that resemble the cortical hemodynamic response [114]–[116]. This is especially problematic because a large proportion of the measured fNIRS signal may originate from extracerebral tissue rather than from the cortex itself [117]. Systemic physiology-augmented fNIRS (SPA-fNIRS) has been developed to address this limitation by recording fNIRS concurrently with systemic physiological measures, such as heart rate, respiration, arterial blood pressure, and oxygen saturation, which can then be used to identify, model, or remove physiological confounds from the cerebral signal [118]. However, the additional sensors, synchronized recording equipment, and increased setup requirements make SPA-fNIRS more expensive and cumbersome than conventional fNIRS.

The primary methodological response to systemic contamination is short-separation channel regression. In this approach, additional source–detector pairs are placed at short distances, such that the detected light samples superficial tissue without substantially penetrating cortical regions. Short-separation channels are used to capture extracerebral hemodynamic fluctuations from the scalp, skull, and superficial vasculature, which can then be regressed from long-separation channels used to estimate cortical activity. This improves spatial specificity by reducing the shared superficial component of the fNIRS signal [119], [120]. In the present thesis, a 3-cm source–detector separation was used for long-separation channels and a 1.0-cm source–detector separation was used for short-separation channels. Accurate interpretation of HbO and HbR therefore requires preprocessing approaches that may include short-separation regression, component analysis, and physiological signal modeling to reduce superficial contamination and improve cortical specificity [121], [122].

Task-Based fNIRS Analysis and Motion-Artifact Correction

Motion-artifact correction presents an equally important preprocessing challenge in fNIRS research, and the principal stages of this process are outlined in Figure 8. Artifacts may arise from head movement, postural transitions, facial muscle activity, breathing-related displacement, or changes in scalp-optode coupling. These issues are especially consequential in paradigms where movement and physiological modulation are intrinsic to the experimental conditions [123]. In movement-based studies, respiration, autonomic tone, posture, and extracerebral hemodynamics may shift systematically across task phases, producing signal variance that partially or wholly overlaps with the hemodynamic response of interest. Because such physiological fluctuations are inherent to the intervention rather than incidental, their contribution to the measured fNIRS signal cannot be treated as noise and requires explicit modeling during analysis.

Before preprocessing is applied, signal quality should be evaluated systematically. This includes inspection of raw intensity data, scalp-optode coupling, channel signal-to-noise ratio, and the presence of saturated or excessively noisy channels. Poor-quality channels should be documented and, where appropriate, excluded prior to statistical analysis. This step is especially important in movement-based and yoga-related fNIRS paradigms, where changes in posture, facial tension, respiration, and optode contact may influence the recorded signal. In these cases, physiological fluctuations are not random noise but structured signals that may vary across task phases.

The appropriate motion-correction strategy should be guided by the temporal structure of the artifact rather than by methodological convention alone. Spline interpolation is well suited for discrete, clearly bounded baseline shifts because it replaces contaminated segments while preserving adjacent clean data [124]. Wavelet-based methods are more appropriate for spike-like artifacts with sharp temporal profiles because they identify and attenuate abnormal wavelet coefficients without requiring manual rejection of entire segments [125].

Hybrid spline–Savitzky–Golay filtering was developed for artifacts that combine baseline shifts with residual high-frequency spikes, first correcting the baseline displacement and then smoothing the remaining spike-like component [126]. Temporal Derivative Distribution Repair (TDDR) provides another robust option because it attenuates both abrupt and gradual motion-related distortions without requiring extensive user-defined parameter tuning [127].

Other commonly discussed approaches include principal component analysis (PCA), targeted PCA, correlation-based signal improvement (CBSI), Kalman filtering, moving-average or low-pass smoothing, and independent component analysis (ICA), although their suitability depends on the artifact type, experimental design, and whether the goal is task-evoked HRF estimation or resting-state functional connectivity analysis [128]–[130]. Method choice should therefore be guided by the signal problem rather than a fixed preprocessing convention.

Importantly, temporally embedded canonical correlation analysis (TCCA) is not simply a motion-correction filter; it is a physiological-noise regression approach implemented within the general linear model (GLM). Von Lühmann et al. [131] proposed TCCA as a multimodal GLM extension that uses temporally lagged auxiliary or nuisance signals to model systemic physiological variance in fNIRS data, including delayed cardiovascular, respiratory, and autonomic fluctuations that may propagate through superficial and cortical channels over time.

By embedding these signals across multiple time lags, TCCA can capture not only simultaneous physiological contamination but also delayed, distributed systemic effects, making it especially relevant when physiological changes are structured by the experimental condition rather than appearing as isolated motion spikes. This distinction is important for movement-based and yoga-related fNIRS paradigms, where respiration, posture, autonomic tone, facial tension, and extracerebral hemodynamics may vary systematically across task phases.

The model described by von Lühmann et al. [131] incorporates regularized temporally embedded canonical correlation analysis into the supervised GLM, allowing flexible integration of auxiliary physiological signals into fNIRS noise regression. TCCA is therefore best understood as a modeling strategy for structured physiological variance.

Recent comparisons continue to show that no single method is universally optimal; wavelet filtering, spline-based approaches, PCA/CBSI variants, and TDDR can all improve signal quality, but the choice should be justified based on the expected artifact profile and analysis objective [130], [132], [133].

In the present thesis, this distinction was especially important because the first two yoga *āsana* studies involved sources of variance that were not limited to isolated motion artifacts. Respiration, autonomic tone, posture, and extracerebral hemodynamics could change systematically across task phases, requiring explicit physiological modeling rather than simple artifact removal. To address this, each participant's pre-task resting-state recording was used as a subject-specific baseline physiological regressor before movement began. This strategy was applied in the first two studies presented in this thesis, both of which measured prefrontal cortex activity before, during, and after yoga *āsana* practice.

By contrast, hybrid spline-Savitzky-Golay filtering was appropriate for the third experiment, in which the breath-holding task produced sharp signal spikes, most likely related to eyebrow elevation during inhalation, superimposed on broader baseline shifts. The preprocessing approach therefore followed the structure of the artifact in each study.

Resting-State Functional Connectivity

Activity and connectivity describe different levels of fNIRS analysis. As outlined above, activity refers to task-evoked changes in cortical hemodynamics, usually estimated from changes in HbO and HbR during or after a stimulus or movement. These changes are commonly modeled with a GLM to estimate the hemodynamic response function and features such as amplitude, peak latency, area under the curve, mean response, or slope.

In contrast, functional connectivity refers to the temporal association between spontaneous fNIRS signals from different channels or cortical regions, typically examined within the low-frequency hemodynamic range of approximately 0.01–0.10 Hz [134]. Coordinated activity within this range persists across wakefulness, sleep, and anesthesia and has been observed in humans and other mammalian species, although network organization varies across states and species [135], [136]. Following preprocessing, physiological-noise correction, and band-pass filtering, connectivity is commonly quantified using channel-to-channel or region-to-region Pearson correlation matrices, with coefficients transformed using Fisher's z for statistical analysis.

In summary, fNIRS activity asks, "Where and how strongly did the cortex respond?" whereas fNIRS connectivity asks, "How strongly did regions fluctuate together over time?" Within resting-state functional connectivity (rsFC), intrahemispheric connectivity refers to temporal coupling among regions within the same hemisphere, such as correlations between two left prefrontal or two right motor regions. Interhemispheric connectivity refers to temporal coupling between regions across hemispheres, often between homologous or functionally related left and right cortical areas.

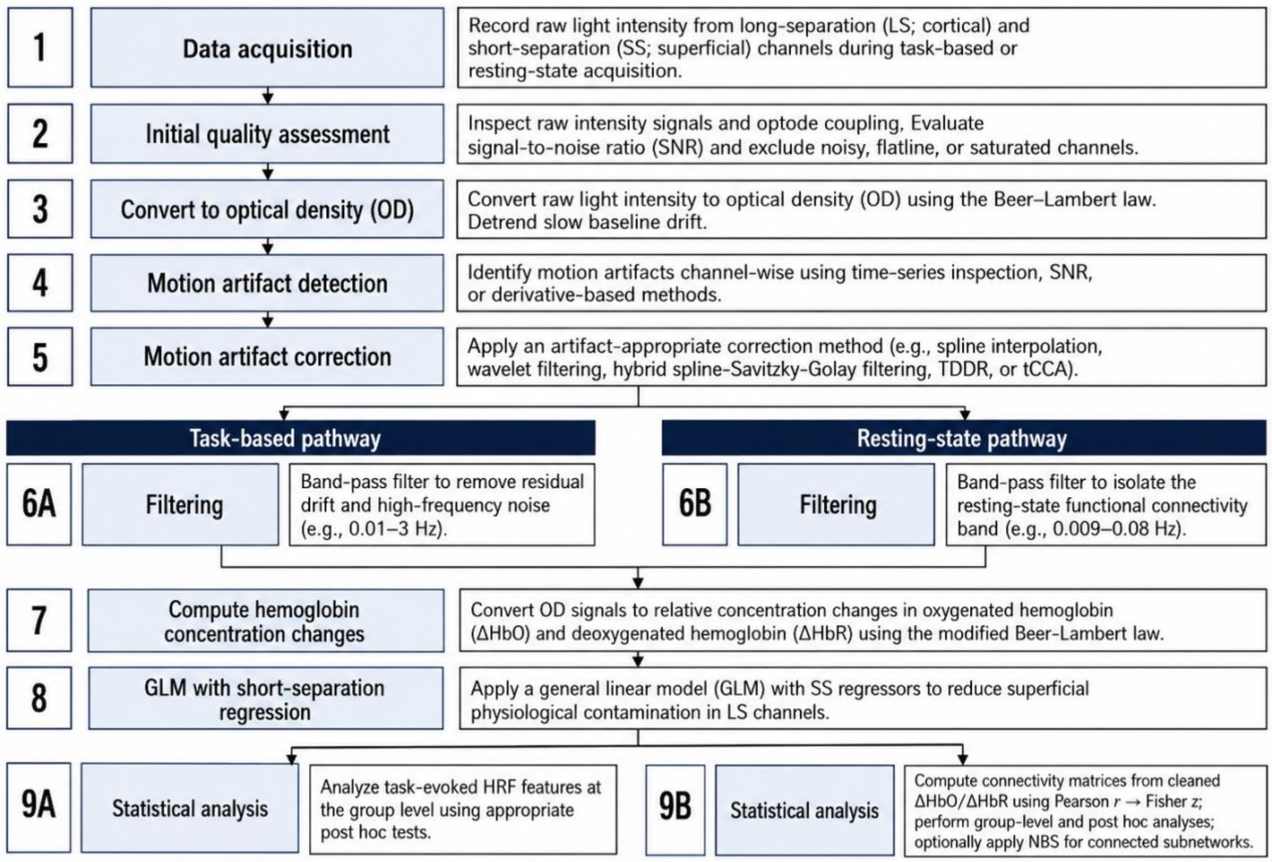
Resting-state connectivity analysis is especially useful when the objective is to examine intrinsic coordination among cortical regions rather than stimulus-evoked activation. In this framework, fNIRS channels, optode-defined cortical regions, or reconstructed regions of interest are treated as nodes, while statistical associations between oxygenated hemoglobin (HbO), deoxygenated hemoglobin (HbR), or total hemoglobin (HbT) time series are treated as edges.

Pairwise functional connectivity is typically estimated using Pearson correlation coefficients and then normalized using Fisher's z transformation before statistical testing. However, when the expected effect is distributed across multiple connected edges rather than localized to a single channel pair, network-based statistical (NBS) analysis can provide greater sensitivity than interpreting individual Pearson or Fisher-z-transformed connections in isolation.

NBS was originally introduced for structural and functional brain networks and is applicable to BOLD-fMRI, diffusion-based connectivity, and fNIRS functional connectivity when the data can be represented as a node-edge matrix [137]. Rather than testing each connection independently, NBS first performs edgewise statistical tests across the connectivity matrix, applies a primary threshold to identify suprathreshold edges, and then searches for connected components among those edges.

The significance of each component is assessed through permutation testing, allowing family-wise error control at the network-component level rather than at each individual edge [137]. This component-level approach preserves sensitivity to coordinated network-level changes that may be missed by edgewise analyses alone, particularly in resting-state or task-modulated connectivity analyses where group or condition effects may emerge as distributed subnetworks.

In fNIRS research, NBS has been used to identify group-level differences in functional connectivity networks, including altered motor-cortex connectivity in Parkinson's disease and prefrontal connectivity changes in mild cognitive impairment [138], [139]. Accordingly, NBS belongs in the connectivity-analysis pathway after hemoglobin concentration estimation, connectivity-band filtering (i.e., filtering to the frequency band used for rsFC analysis), superficial signal correction, connectivity matrix construction, and Fisher's z transformation, but before final group-level interpretation.



Note. GLM = general linear model; SS = short-separation; LS = long-separation; SNR = signal-to-noise ratio; OD = optical density; HRF = hemodynamic response function; TDDR = temporal derivative distribution repair; tCCA = temporally embedded canonical correlation analysis; NBS = network-based statistic.

Figure 8. fNIRS Preprocessing and Statistical Analysis Pipeline. Figure 8 summarizes the preprocessing workflow for task-based and resting-state fNIRS data, from raw intensity acquisition through quality control, optical-density conversion, motion-artifact correction, filtering, hemoglobin concentration estimation, GLM-based short-separation regression, and pathway-specific statistical analysis.

Signal Interpretation, Standardization, and Reporting

No single preprocessing pipeline is universally optimal for fNIRS. Instead, preprocessing decisions should be matched to the study design, the characteristics of the recorded signal, and the analytic objective [108], [123], [140]. This analytical flexibility has important implications for reproducibility: a recent study in which 38 research teams independently analyzed the same two fNIRS datasets found relatively high agreement for well-established group-level effects but substantially lower agreement at the individual level, with reproducibility influenced by data quality, analysis-pipeline choices, and researcher experience [141]. The field has begun to address these challenges through greater standardization and transparency. Community data formats, including the Shared Near-Infrared Spectroscopy Format (SNIRF) and the Brain Imaging Data Structure (BIDS), have improved the consistency of data organization, sharing, and reporting. In parallel, best-practice guidelines have emphasized the need for clearer documentation of preprocessing choices, quality-control procedures, channel-exclusion criteria, and analytic assumptions [105], [108].

Standardization efforts address the consistency of preprocessing decisions, but they do not fully resolve the problem of distinguishing neural from systemic signal contributions. This interpretive challenge is partly addressed by a recent emphasis on jointly examining both chromophores. fNIRS is distinctive in its ability to estimate changes in both HbO and HbR, and reporting both signals provides a more complete representation of the hemodynamic response than either chromophore alone.

HbO is generally stronger and more sensitive to regional blood flow changes, but it is also more vulnerable to systemic physiological contamination, including changes in heart rate and blood pressure [142]. HbR is typically weaker and noisier, but it may provide greater spatial specificity and be less affected by extracerebral physiology [117], [143], [144].

For this reason, a cautious interpretive strategy is to examine HbO and HbR together, particularly when the expected pattern of increased HbO and decreased HbR appears within the same channel. Such convergence can strengthen the inference that the observed response reflects neurovascular coupling rather than systemic artifact [145]. Dual-chromophore interpretation therefore improves both interpretive caution and clarity. The typical dual-chromophore hemodynamic response is illustrated in Figure 9.

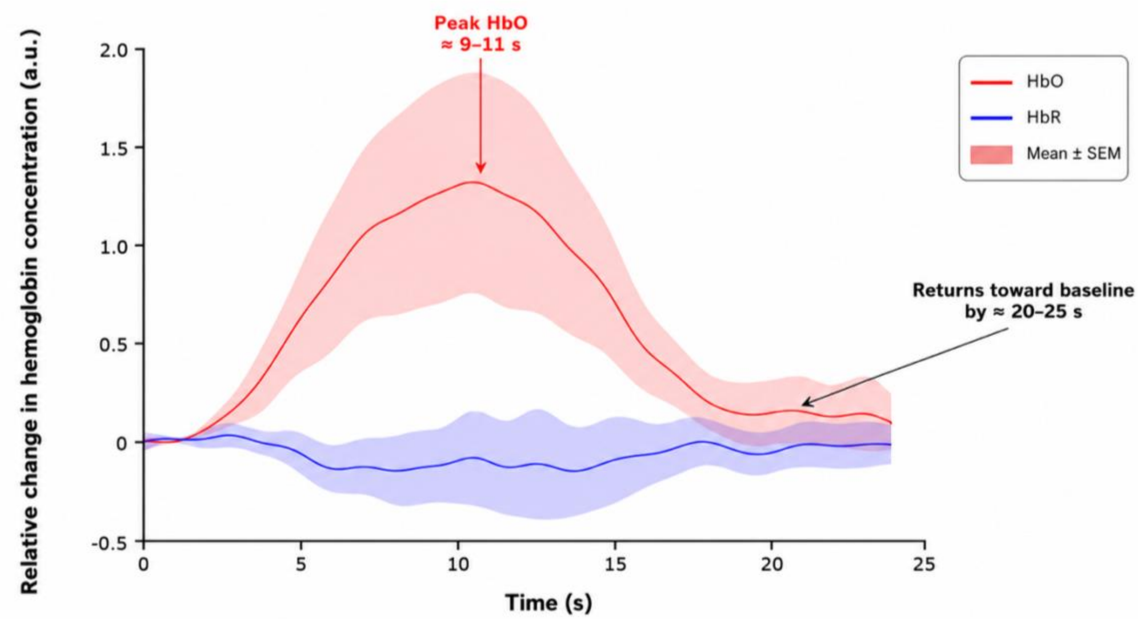


Figure 9. Representative Hemodynamic Response Measured by fNIRS. The increase in oxygenated hemoglobin (HbO; red) is typically larger than the accompanying decrease in deoxygenated hemoglobin (HbR; blue). In this example, the response develops over several seconds, peaks at approximately 10 s, and returns toward baseline within approximately 20–25 s. Solid lines represent the mean response, and shaded regions indicate the standard error of the mean.

Study-Specific fNIRS Reproducibility Information

For Article 1, *Resting-State Connectivity and Neuroimaging of Prefrontal Cortex Activity During a Block-Design Yoga Asana Practice Using fNIRS*, and Article 2, *Yoga Asana Increases Prefrontal Cortex Activity and Reduces Resting-State Functional Connectivity*, fNIRS data were acquired using the Brite MKII system at dual wavelengths of 757 and 843 nm and a sampling frequency of 25 Hz. The optode configuration comprised 22 long-separation channels with a source–detector distance of 3.0 cm and two short-separation channels with a source–detector distance of 1.0 cm. Signal quality and experimental event markers were monitored using OxySoft.

Preprocessing was conducted in HOMER3 within MATLAB. Channel pruning was performed using an intensity range of 1×10^{-7} to 1×10^{7}, a signal-to-noise ratio threshold of 2, and a source–detector distance range of 0.45–45 mm. Motion detection used an amplitude threshold of 0.5 and a standard-deviation threshold factor of 15 within a 1-s detection window and a 1-s masking period. Task-related hemodynamic responses were estimated using a general linear model with an analysis window extending from −2 to 23 s.

Resting-state functional connectivity analysis used a 0.009–0.08 Hz band-pass filter, short-separation regression with Tikhonov regularization, Pearson correlation coefficients, Fisher z transformation, and false-discovery-rate correction. Origin(Pro), version 2018, was used for the reported analysis of variance. The analysis code and supporting data for Articles 1 and 2 are openly available through Zenodo under the dataset *Yoga Asana Increases Pre-Frontal Cortex Activity and Reduces Resting State Functional Connectivity* (DOI: 10.5281/zenodo.11098996).

For Article 3, *Neural, Biochemical, Postural, and Subjective Outcomes Following a 30-Day Yoga Program: A Multimodal Mixed-Methods Study*, fNIRS data were acquired using the Brite MKII system and monitored in OxySoft at dual wavelengths of 757 and 843 nm and a sampling frequency of 25 Hz. Preprocessing was performed in HOMER3 (RRID: SCR_009586) using MATLAB R2023b. Channel pruning used an intensity range of 1×10^{-7} to 1×10^{7}, a signal-to-noise ratio threshold of 2, and a source–detector distance range of 0–45 mm.

Motion artifacts were corrected using spline interpolation and Savitzky–Golay filtering. Hemodynamic responses were estimated using a general linear model incorporating short-separation regression, and resting-state time series were filtered within the 0.009–0.08 Hz frequency range. Full preprocessing parameters, analysis commands, scripts, and supporting data are available in Zenodo [146].

fNIRS Methodological Summary

Functional near-infrared spectroscopy is a portable neuroimaging technique that estimates cortical hemodynamic activity by emitting near-infrared light through scalp-mounted source optodes and detecting returning light with detector optodes. These changes reflect wavelength-specific absorption by oxygenated and deoxygenated hemoglobin, allowing fNIRS to estimate relative changes in cortical oxygenation associated with neurovascular coupling. From its origins in the work of Jöbsis [104], fNIRS has developed into a flexible modality that is particularly valuable for studying brain function in ecological, developmental, clinical, rehabilitation, social, and movement-based contexts.

The central strength of fNIRS is its capacity to measure dynamic cortical oxygenation in settings that are difficult to access with more restrictive neuroimaging methods. However, its signals are limited to superficial cortical regions and are vulnerable to extracerebral physiological contamination, including cardiac, respiratory, blood-pressure, and autonomic fluctuations. Motion artifacts also remain a major challenge, particularly in paradigms involving posture changes, breathing tasks, facial movement, or altered scalp-optode coupling.

For this reason, preprocessing must be adapted to the study design, signal characteristics, and analytic objective rather than applied through a universal pipeline. Current best practices emphasize quality control, motion correction, short-separation regression, physiological modeling, standardized data formats, dual-chromophore analysis, and transparent reporting.

In the context of this thesis, these considerations are especially important because yoga-based paradigms involve precisely those physiological and postural processes that can influence fNIRS signals. The methodological value of fNIRS therefore lies not only in its portability and ecological validity, but also in the rigor with which optical measurement, physiological contamination, and signal interpretation are handled.

Beyond the Brain as a Dataset: Subjective Experience and Mixed-Methods Integration

Current research supports the use of physical activity and mind–body interventions, including yoga, meditation, tai chi, and qigong, as adjunctive approaches in mental health care, particularly for depression, anxiety, and stress-related symptoms [19], [147]–[152]. At the same time, this growing evidence base highlights the need for mixed-methods and multimodal frameworks capable of integrating neurophysiological, behavioral, psychometric, and first-person forms of evidence to more adequately capture the effects of mind–body interventions [14], [153]. This need is not merely methodological but epistemological. It concerns what kinds of evidence are considered valid when studying practices whose effects are simultaneously biological, psychological, embodied, relational, and experiential.

Although fNIRS can indicate when and where cortical hemodynamic changes occur, it cannot determine what those changes mean subjectively for the participant. A shift in prefrontal activation or connectivity may suggest altered cortical engagement, but it cannot reveal whether the participant experienced calm, effort, discomfort, emotional release, dissociation, boredom, or embodied presence. The hemodynamic signal therefore requires interpretation within the psychological and experiential context in which it occurs. Without this context, there is a risk of treating the brain as a dataset separated from the lived experience of the person generating the signal.

Psychological scales help address this limitation, but they are also incomplete. Standardized questionnaires can quantify changes in mood, anxiety, perceived stress, body awareness, or well-being, yet they necessarily reduce complex subjective experiences into predefined categories. They depend on the participant's interpretation of items, memory, self-awareness, willingness to disclose, and ability to translate lived experience into numerical responses. In contemplative and movement-based interventions, this is especially limiting because some of the most relevant changes may be subtle, reflective, somatic, relational, or difficult to name. A participant may show limited change on a scale while nevertheless describing a meaningful shift in how they inhabit the body, regulate emotion, relate to others, or experience inner safety.

This limitation is particularly consequential in yoga research because yoga itself is a multimodal discipline. As discussed previously, yoga addresses human health and well-being through multiple, integrated pathways, including ethical orientation, embodied practice, breath regulation, attentional training, sensory withdrawal, meditation, self-inquiry, and relational awareness. Many of these dimensions can be differentiated within Western psychology into separate categories such as affect regulation, interoception, attentional control, embodied cognition, stress physiology, social connection, and meaning-making. In yoga, however, these domains are not treated as isolated mechanisms, but as interdependent aspects of a unified transformative practice.

For this reason, the phenomenological dimension of yoga is not incidental to the intervention, but central to interpreting its possible pathways of effect. The quality of attention, the felt sense of the body, the regulation of breath, the emergence and dissolution of affective states, and the participant's changing relationship to discomfort all form part of the therapeutic process. These dimensions may not be adequately captured by neuroimaging or psychometric scales alone. For example, observed post-intervention changes in prefrontal connectivity may reflect deepened embodied presence, effortful concentration, emotional suppression, dissociative numbing, or task fatigue. The neural signal cannot adjudicate among these possibilities without reference to subjective, behavioral, and contextual evidence.

This position is consistent with a growing methodological argument in contemplative neuroscience that first-person data should be treated as primary rather than supplementary [13], [154]–[156]. Varela and colleagues' neurophenomenological approach proposes that rigorous investigation of subjective experience, conducted with the same methodological rigor as objective measurement, is not a concession to imprecision, but a necessary condition for valid knowledge about mind. Applied to contemplative and clinical neuroscience, this entails designing studies in which participants' experiences are systematically elicited, recorded, and analyzed as data in their own right, rather than appended as anecdotal support or face-validity confirmation for quantitative findings.

Accordingly, participants should not only complete validated scales but also be invited to describe what changed in their own terms. This includes what they noticed in their bodies, how their affective life shifted, how their relational world changed, and what felt different in their inner experience. Such accounts do not replace quantitative measures, but can clarify their meaning. They may reveal whether a change in cortical activity corresponds to increased embodied awareness, improved emotional regulation, attentional effort, discomfort, dissociation, or another experiential process that would remain invisible within the neurophysiological signal alone.

The present study adopts this mixed-methods orientation by treating fNIRS-derived cortical measures, psychometric outcomes, physiological indicators, behavioral observations, and participants' phenomenological accounts as complementary, integrated, and nonhierarchical sources of evidence (see Figure 10). Rather than assuming that neural activity, questionnaire scores, or subjective reports alone provide a complete account of change, this framework examines how these dimensions converge, diverge, and mutually inform one another.

fNIRS is particularly well suited to this design given its portable and movement-tolerant properties, which allow cortical hemodynamic activity to be recorded during movement-based practices such as yoga *āsana* and during post-practice periods of integration. Neural data, however, are interpreted alongside subjective, physiological, behavioral, and psychometric evidence. This reflects the central position of the thesis: in an intervention where body, breath, attention, and lived experience are interdependent, no single modality of measurement is sufficient on its own.

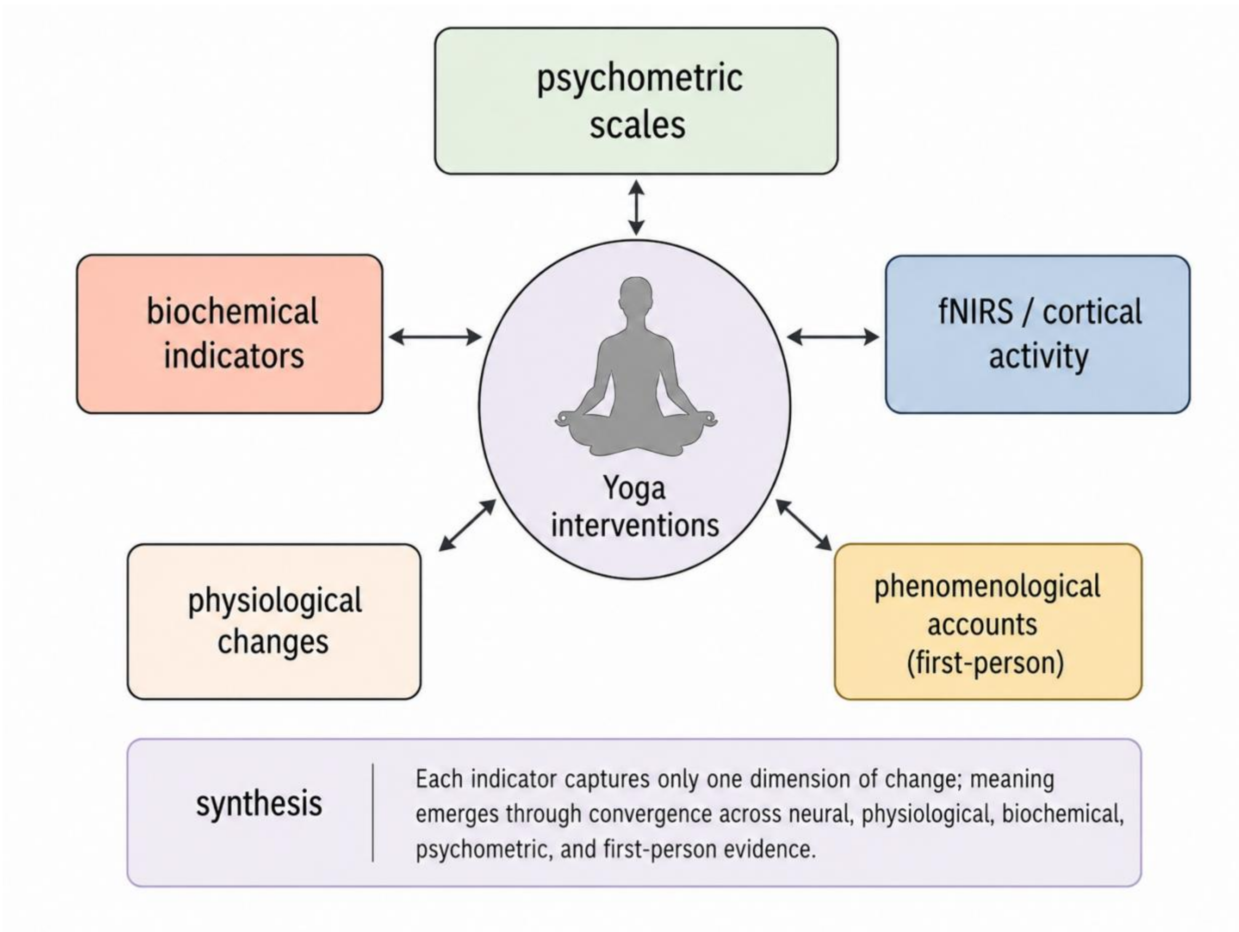


Figure 10. Integrated Model for Yoga Research. Figure 10 shows a multi-source framework for studying change in yoga research, placing lived embodied experience at the center of psychometric, neural, physiological, biochemical, and first-person evidence. Meaning emerges through convergence across indicators rather than from any single measure alone.

Research Articles

Presents the three articles that constitute the empirical core of the thesis. Table 1 summarizes the purpose, methodological contribution, and role of each article within the overall research progression. Together, the studies advance from establishing the feasibility of using fNIRS during yoga *āsana*, to examining acute posture-related changes in cortical activity and resting-state functional connectivity, and finally to investigating the multidimensional changes associated with a 30-day yoga program.

Table 1. Article Map

Article	Design	Measures / Variables	Main finding	Function within the thesis
Article 1: Journal of Visualized Experiments (JoVE) Resting-State Connectivity and Neuroimaging of Prefrontal Cortex Activity During a Block-Design Yoga Asana Practice Using fNIRS	Methodologic al/protocol article using an acute block-design yoga *āsana* session	fNIRS measurement of prefrontal cortical activity; HbO/HbR preprocessing; motion-artifact correction; statistical analysis; resting-state functional connectivity procedures. n = 27	Demonstrated that fNIRS can be used to measure cortical hemodynamic activity during movement-based yoga *āsana* practice in a real-world setting	Establishes the methodological foundation of the thesis by showing that embodied yoga postures can be studied using mobile neuroimaging
Article 2: Complementary Medicine Research (CMR). Yoga Asana Increases Prefrontal Cortex Activity and Reduces Resting-State Functional Connectivity	Acute within-subject pilot study examining pre-, during-, and post-practice neural changes	Prefrontal cortical oxygenation and activity during inversions and backbends; pre- and post-practice resting-state functional connectivity. n = 27	Yoga *āsana* increased prefrontal cortical activity, particularly in the right PFC, and reduced resting-state functional connectivity, primarily in the left medial PFC	Provides acute neural evidence consistent with a possible bottom-up body-to-brain regulatory pathway
Article 3: Journal of Integrative Medicine (JIM):Neural, Biochemical, Postural, and Subjective Outcomes Following a 30-Day Yoga Program: A Multimodal Mixed-Methods Study	Longitudinal mixed-methods intervention study	fNIRS during resting-state, breath-related, and affective-image tasks; biochemical markers; postural alignment; questionnaires; semi-structured interviews. n = 29	Sustained yoga practice was associated with measurable changes across neural, biochemical, postural, and subjective domains	Extends the acute findings into a multidimensional regulatory model for interpreting relationships among body, brain, physiology, posture, and lived experience

Resting-State Connectivity and Neuroimaging of Prefrontal Cortex Activity During a Block-Design Yoga Asana Practice Using fNIRS

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Abstract

This study aimed to use functional near-infrared spectroscopy (fNIRS) mobile neuroimaging technology to examine changes in prefrontal cortex (PFC) activity before, during, and after yoga asana (physical yoga postures). A total of 27 healthy adults participated in a 23 min yoga asana session using a block design. Before and after the sequence, participants completed two 6 min, task-independent resting states. PFC activity was continuously recorded using the fNIRS instrument, positioned on the frontal area of the skull. The session included a control posture alternating with three active postures. Each active posture was held for 30 s, followed by a 25–30 s control posture interval, and repeated eight times. This block design resulted in 25 control posture intervals and 24 active-posture repetitions in total (eight repetitions of each active posture). Analysis included preprocessing of raw fNIRS data to calculate concentrations of oxyhemoglobin (HbO) and deoxyhemoglobin (HbR), motion artifact correction, and statistical evaluation using ANOVA with Bonferroni corrections. Connectivity analyses examined interhemispheric and intrahemispheric correlations in the prefrontal cortex. In conclusion, this study demonstrates the utility of fNIRS in real-world, movement-based contexts and provides neurological insights into the effects of yoga asana.

Introduction

Yoga is an ancient Indian practice that integrates physical postures (asana), breathing exercises (pranayama), meditation, and ethical principles to promote holistic physical and mental well-being. In recent years, yoga has become increasingly recognized as a complementary intervention for mental health conditions, supported by a growing body of scientific research. Numerous studies have shown that regular yoga practice can significantly reduce symptoms of anxiety, depression, and stress, while enhancing mood, emotional regulation, and overall psychological resilience [157]–[159]. Meta-analyses and randomized controlled trials have further substantiated yoga's efficacy as an adjunct therapy for depression and posttraumatic stress disorder, with evidence also suggesting improved quality of life and cognitive function [160]–[164].

Despite this promising evidence base, the neural mechanisms underlying movement-based yoga practices, particularly the physical postures (asana), remain poorly understood [165], [166]. This gap in knowledge has hindered efforts to integrate yoga into neurocognitive models of intervention. The goal of the present study is to investigate brain activity associated with yoga asana practice in real time, thereby contributing to a mechanistic understanding of how movement-based contemplative practices impact cortical function.

To accomplish this, we employed functional near-infrared spectroscopy (fNIRS), a non-invasive, portable neuroimaging technique that measures hemodynamic responses in the cerebral cortex [167]. The rationale for using fNIRS is rooted in its ability to monitor brain activity during naturalistic, upright movement—an approach not possible with conventional imaging methods such as fMRI or PET, which require participants to remain motionless in artificial environments [112].

Compared to these alternatives, fNIRS offers several advantages: it is silent, motion-tolerant, and allows for the study of ecologically valid tasks in real-world environments [129]. Consequently, it has been widely used in studies of motor learning, cognitive workload, infant development, gait and balance, and mindfulness practices, producing reliable insights into prefrontal cortex activity during both static and dynamic conditions [168]–[172]. Its application in naturalistic settings, particularly during movement, has opened new avenues for studying embodied cognition and the neural substrates of integrative health interventions.

However, few studies have applied this technique to yoga asana specifically, and even fewer have done so across the full temporal arc of a session—from pre- to during to post-practice—with a population-representative sample. To address this, the current study employed a block-design protocol using fNIRS to examine cortical activity and resting-state connectivity before, during, and after a structured yoga asana sequence. The study was conducted in a naturalistic setting and included 27 native Spanish-speaking participants from Mexico, thereby addressing a significant gap in the literature concerning the effects of yoga in Latin-Spanish-speaking populations. Participants ranged in age from 18 to 65 and included both male and female individuals with a wide range of yoga experience, from complete beginners to practitioners with up to 15 years of regular practice. All participants reported no severe psychological or physiological conditions that would prevent them from completing the 23 min yoga session.

Individuals with severe psychiatric disorders or mobility-limiting physical conditions were excluded. While participants were not screened for specific medical pathologies such as hypertension or diabetes, it was clearly explained prior to the session that they could stop at any time should they feel unwell or uncomfortable. It was agreed in advance that any incomplete sessions would be excluded from analysis.

Of the original 30 participants, no one withdrew due to discomfort during the yoga practice. However, three were excluded from the final analysis due to excessive signal noise likely caused by hardware interference or technical software malfunction. By including a demographically diverse and representative sample and allowing for real-time, motion-tolerant imaging, this study enhances both the ecological validity and generalizability of findings. Researchers and clinicians seeking to investigate the neural dynamics of movement-based contemplative practices may find this method especially relevant for applications in cognitive neuroscience, rehabilitation science, and integrative mental health research.

Protocol

Experimental procedures were performed in accordance with the Declaration of Helsinki, reviewed and approved by the Coordinación para la Innovación y la Aplicación de la Ciencia y la Tecnología (CIACYT), Universidad Autónoma de San Luis Potosí Ethics Committee Institutional Review Board [CIACYT-CEI-003]. All participants provided signed informed consent.

1. Participant recruitment and demographics

1. Recruit participants through word-of-mouth and social media platforms, including Facebook and Instagram. Inform potential participants about the study objectives, requirements, and their right to withdraw at any time without penalty.

2. Collect self-reported demographic information, including age, weight, height, biological sex, education, and yoga experience with in-person interviews (Table 2). Assign each participant a unique numbered code for anonymity and record their information in an encrypted spreadsheet file.

3. Include participants aged 18–65 with varying levels of yoga asana experience. Exclude individuals with neurological or psychiatric conditions or those unable to perform yoga poses due to physical limitations. This study included participants aged 18 to 65 with varying levels of yoga asana experience, while excluding individuals with known neurological or psychiatric conditions, as well as those with physical limitations that would prevent them from safely performing the yoga postures. Currently, the protocol does not include variations for excluded participants, though exploring such adaptations represents a valuable direction for future research.

4. Ensure all procedures comply with institutional ethical guidelines and are in accordance with the Declaration of Helsinki. All participants provide signed informed consent. Inform participants that they will receive no financial compensation and that they can terminate the experiment at any time.

2. Experimental procedure

1. Use the portable fNIRS device for data collection. The device operates with dual wavelengths of 760 nm and 850 nm, providing continuous-wave near-infrared light for the assessment of changes in oxygenated (HbO) and deoxygenated (HbR) hemoglobin concentrations. The system supports up to 27 channels and records at a sampling rate of 50 Hz, allowing for reliable detection of cortical activation during naturalistic tasks.

1. Prepare the fNIRS setup by positioning light sources (S) and detectors (D) into the cap holders according to the bilateral prefrontal cortex (PFC) layout provided by the manufacturer (see Figure 11). Ensure a source-detector (S-D) separation of 3.0 cm to optimize cortical signal detection.
2. In addition, include two short-separation channels (1.0 cm) to account for and regress out superficial hemodynamic signals, such as scalp blood flow, which can confound cortical measurements. The use of short-separation channels is a validated method to improve signal specificity by isolating cortical hemodynamic responses from extracerebral contamination [173].

2. Select four yoga asanas for this study that are foundational postures commonly practiced across all styles of Hatha Yoga. They form the core of the widely known Surya Namaskar (Sun Salutation) sequence, which is globally recognized and practiced annually on June 21 during the International Day of Yoga [174]. These poses were intentionally chosen not only for their accessibility and standardization across yoga traditions, but also to allow for specific investigation into the effects of inversions (postures where the head is below the heart) and back extensions on brain activity—two physical forms often recommended in therapeutic yoga protocols for depression and mood disorders [175], [176].

3. Design the presentation during the experiment in PowerPoint format, which is also a visual and auditory guide for participants. Ensure each slide displays the photo and name of one posture, written in the participant's native language (Spanish) with the original Sanskrit name in parentheses: Posture A (Tadasana), Posture B (Uttanasana), Posture C (Adho Mukha Svanasana), and Posture D (Urdhva Mukha Svanasana).

4. Cycle the presentation through images of postures B, C, and D automatically every 30 s in randomized order, while the experimenter simultaneously called out the name of the posture aloud to reinforce the cue.

5. Randomly organize the active asanas, ensuring that the baseline posture is interspersed between each one. This arrangement provides a balanced sequence while maintaining a variable inter-stimulus interval to reduce potential practice and habituation effects.

6. For data management and consistency, standardize all visual materials—including images and fonts-in size and style across participants. Size images of the yoga postures appropriately with high resolution, and clear labels in both their native Spanish names and their traditional Sanskrit.

7. Ensure that each participant can read and see the presentation prompt clearly before beginning. The active asanas and baseline asanas to be performed are described below:
   - Tadasana - Mountain Pose (Baseline Posture): A standing upright, neutral posture.
   - Uttanasana - Forward Bend (Active Posture): A forward fold from the hips with the head below the heart.

- Adho Mukha Svanasana - Downward-Facing Dog (Active Posture): An inverted V position, with hands and feet on the ground and hips elevated.
- Urdhva Mukha Svanasana - Upward-Facing Dog (Active Posture): Chest lifted in a back extension with the gaze moved upward.

8. Prepare the experimental area by setting up a yoga mat, a wall-mounted yoga rope system (see Table of Materials), and a presentation screen positioned in front of the participant—close enough for clear visibility of the postures, yet far enough to avoid obstructing movement. The setup is illustrated in Figure 12. Confirm visibility and readability of the screen before beginning the session.

9. Calibrate the fNIRS system by ensuring all components, including the cap, optodes, and recording software, are fully charged, functional, and compatible with the data acquisition system. To calibrate, accurately position the optodes on the participant's scalp according to the international 10–20 system, ensuring consistent anatomical targeting of prefrontal regions. Adjust the cap and optode holders to accommodate individual head shapes and hair density, minimizing light attenuation and motion artifacts. Use the system's signal quality interface (e.g., signal-to-noise ratio, and scalp coupling index) to verify that each channel meets recommended thresholds.

   NOTE: This process is essential to ensure reliable and reproducible hemodynamic measurements and to minimize data loss or misinterpretation due to poor sensor contact or signal dropout [170], [177]–[179].

10. With the participant seated in a chair, ensure their feet are flat on the ground, hands resting gently in their lap, and their back lightly supported by the chair. Confirm verbally that the participant is seated comfortably before proceeding.

11. Use a 3-D digitizer, an optical tracking device designed to capture the spatial location of optodes on the scalp, to record the cap placement. This process generates Montreal Neurological Institute (MNI) coordinates, use these to identify and standardize the anatomical brain regions underlying each measurement channel.

   NOTE: Accurate digitization ensures consistency across participants and enables precise mapping of fNIRS data onto cortical structures for group-level analysis.

12. Secure the optode cap using the chin strap and manually adjust each optode by gently parting the hair with a bamboo stick to ensure direct scalp contact (Figure 13A). Figure 13B shows hair obstructing the optode, while Figure 13C illustrates successful removal of the obstruction using a bamboo stick. Use the DAQ value module in the acquisition software to assess signal quality. Always confirm participant comfort by asking if there is any pain or discomfort and adjust the optode positions as needed to optimize signal clarity without compromising comfort.

   NOTE: Based on empirical observations during the measurement process, this step can take up to 30 min, depending on the participant's hair type. Individuals with thick, dark, or *curly hair often require additional time and adjustments to ensure proper optode-scalp contact. In these cases, securing the fNIRS cap with a surgical bandage was found to be effective in maintaining stable optode placement. Participants who arrived with gel in their hair presented further challenges, as the product interfered with optode adherence. Through trial and error, we observed that creating a tight ponytail or using hairpins to hold the hair in place was more effective than relying on any type of hair fixative. These adjustments significantly improved signal quality and data reliability.*

3. Resting state, yoga asana block design, and measurement practice

NOTE: As illustrated in Figure 14, each of the dynamic postures (B, C, D) was held for 30 s and interleaved with Posture A as a baseline condition, held for 25–30 s. This baseline served as a physiological reference point to isolate and compare brain activity specific to the other poses. To minimize fatigue and ensure the study focused on form rather than exertion, participants were supported in each posture using Kurunta ropes, a method from therapeutic Iyengar Yoga that allows holding postures without strain. Additionally, resting-state measurements were recorded for 6 min both before and after the asana sequence, during which participants were seated with eyes closed to capture pre- and post-practice brain connectivity.

1. Connect the fNIRS cap to the software using Bluetooth to monitor real-time signal acquisition during both pre- and post-resting states, as well as throughout the yoga asana practice.
2. With the fNIRS cap held securely in place while participants sit in a chair, perform the pre-asana resting state measurement. Instruct participants to relax with their feet on the ground, their hands on their laps, and to sit still with their eyes closed for 6 min. Collect fNIRS data at 25 Hz.
    1. To ensure minimal movement and make sure that the measurements are of the resting state and not a sleep state, inform participants not to raise their eyebrows or scratch their faces during the resting state. Also, ask them to avoid falling asleep and double-check if this occurred by asking them if they fell asleep after completing the resting state.
3. After completing the first resting state, remove the chair and have participants stand and make sure that there is still a clear signal. Instruct participants to follow and perform the pre-programmed presentation with the paradigm instructions as it progresses automatically.
4. Provide verbal guidance to the participants during the presentation and manually record the predetermined posture markers—labeled A, B, C, and D—as each slide transitions. These markers correspond to specific phases of the yoga sequence and were used to segment the fNIRS data for analysis: A indicates the baseline posture (Tadasana), while B, C, and D represent the subsequent active postures (Uttanasana, Adho Mukha Svanasana, and Urdhva Mukha Svanasana, respectively), as outlined in Figure 14. The markers were recorded manually using the event annotation feature in the acquisition software (OxySoft, Artinis

Medical Systems) at the moment each posture slide was presented and the participant transitioned into the posture. This manual event marking has been widely used and validated in fNIRS studies to facilitate stimulus-locked analysis of hemodynamic responses [177]–[179].

5. Post measurement, review that the correct markers were used during the measurement process by matching the manually marked timestamps with the automatic presentation time stamps to ensure accurate data labeling.

6. Make sure that the fNIRS cap is still held securely in place and the signal is still clear, have participants sit in a chair to perform the post-asana resting state measurement. Instruct participants to relax with their feet on the ground, their hands on their laps and to sit still with their eyes closed for 6 min. Collect fNIRS data at 25 Hz.

7. It can take 2–5 min post-asana to make sure that the fNIRS setup is correctly calibrated without signal interference before performing the post-asana resting state. Provide the same instruction to participants as in the pre-resting state measurement to ensure minimal movement and make sure that the measurements are of resting state and not a sleep state.

4. fNIRS data analysis of hemodynamic response function during yoga asana

NOTE: Functional near-infrared spectroscopy (fNIRS) measures changes in cortical hemodynamics through two primary parameters: oxygenated hemoglobin (HbO) and deoxygenated hemoglobin (HbR). These biomarkers are vascular correlates of neural activity mediated by the principle of neurovascular coupling. Increased neuronal activation results in an increased oxygen consumption rate, overcompensated by an elevated regional cerebral blood flow, typically resulting in a concurrent increase in HbO and a decrease in HbR. In this study, both parameters were recorded using a multi-channel fNIRS system to quantify hemodynamic responses during yoga asana practice. Measuring mean HbO values provides a

robust and reliable indicator of activation, particularly during movement-based tasks, as it is less sensitive to noise and modeling assumptions than model-derived beta coefficients [180]. However, while HbO is often prioritized due to its higher signal-to-noise ratio, incorporating HbR is critical for enhancing the physiological interpretation of the data. HbR signals complement HbO by offering insight into the brain's metabolic response and oxygen extraction dynamics [181]. Simultaneous analysis of both HbO and HbR helps to avoid oversimplification and strengthens the validity of the observed neural patterns [182].

1. To evaluate the hemodynamic response function (HRF) during yoga asana, start by converting raw functional near-infrared spectroscopy (fNIRS) data into optical density (O.D.) and process it using the HOMER3 toolbox (RRID:SCR_009586). Use the modified Beer-Lambert law (MBLL) to calculate changes in HbO and HbR concentrations, per equation [183]. MBLL accounts for the scattering properties of biological tissue and relates changes in light absorption (ΔA) to changes in chromophore concentration ($\Delta\mu a$), allowing for the quantification of

hemoglobin dynamics from measured light intensity. rsd denotes the source-detector distance and DPF is the differential pathlength factor. This linear approximation enables the estimation of relative concentration changes in oxygenated and deoxygenated hemoglobin. Include short-channel regression to minimize the influence of superficial vascular activity and better isolate cortical signals.

2. Analyze the data in MATLAB. Calculate block averages for each participant, channel, and condition to maintain consistency. Begin quality control by excluding readings with significant optical density fluctuations, low signal-to-noise ratios (SNR), or large source-detector distances. Use the hmrR_PruneChannels function and set parameters such as a valid range of 1×10^{-7} to 1×10^{7}, an SNR threshold of 2, and a source-detector distance of 0.45 mm to 45 mm.

3. Detect motion artifacts for each channel with the hmrR_MotionArtifactByChannel function. Flag segments if the signal amplitude exceeds 0.5 (AMPthresh) or if the standard deviation increases by more than a factor of 15 (SDthresh) within a 1 s time window (tMotion). Exclude flagged segments, each lasting 1 s (tMask).

4. Apply a General Linear Model (GLM) with a time window spanning from 2 s before to 23 s after the stimulus onset. The GLM is a statistical method used to explain variation in a set of observed data by modeling it as a combination of one or more known variables (predictors) and an error term. It estimates how much each predictor contributes to the observed outcome, allowing researchers to isolate the effects of interest while accounting for noise. In this context, use the GLM to apply short-span (SS) regressors to long-span (LS) channels to reduce systemic physiological noise, and more accurately isolate brain activity for hemodynamic response function (HRF) estimation [117], [119], [121], [173], [184], [185].

5. Solve the GLM using ordinary least squares. To further address motion artifacts, apply regularized embedded Canonical Correlation Analysis (TCCA) with participants' resting-state data (30–210 s) as a regressor [131]. After this, estimate HRFs for each channel, condition, and participant, ensuring reliable neural response estimates with an improved signal-to-noise ratio.

6. Use Origin to perform a one-way repeated measures ANOVA. Assess differences in mean HbO values across long channels by comparing the baseline posture A (Tadasana), a neutral standing pose that promotes alignment and stability, to posture B (Uttanasana), a standing forward fold in which the head is positioned below the heart, classifying it as an inversion; posture C (Adho Mukha Svanasana), commonly known as Downward-Facing Dog, a semi-inverted pose that elongates the spine and activates the upper body; and posture D (Urdhva Mukha Svanasana), or Upward-Facing Dog, a back extension that opens the chest and strengthens the posterior chain.

7. Assess differences between postures B, C, and D. Check for normal data distribution using the Shapiro–Wilk test. Perform post hoc pairwise comparisons with Bonferroni corrections for

multiple tests, using a p-value threshold of <0.05 for significance. Calculate effect sizes for significant differences in HbO response using Cohen's d [186], [187].

5. fNIRS data analysis of resting-state functional connectivity

1. To analyze resting-state functional connectivity (rsFC), evaluate connectivity within each hemisphere (intrahemispheric) and between hemispheres (interhemispheric) for each participant. Base this on the statistical dependency between time series, reflecting the co-activation of brain regions.

   NOTE: Measuring rsFC provides insight into the brain's intrinsic functional organization in the absence of external stimuli and is increasingly recognized as a valuable tool for identifying subtle neural alterations and biomarkers of function or dysfunction. Previous research has demonstrated that rsFC patterns have been proposed as predictive biomarkers of antidepressant treatment response in patients with major depressive disorder [188], underscoring the utility of resting-state analysis in capturing trait-like neural signatures. By assessing both intra- and interhemispheric connectivity, this approach enables a more comprehensive understanding of the brain's functional integration and lateralization, particularly in the context of interventions like yoga, which may modulate these resting-state networks [188], [189].

2. Select a 6 min resting-state period for the analysis, as this falls within the commonly accepted range of 5–10 min, with sufficient rsFC typically achieved after 5 min [131], [180]–[182]. Take advantage of reduced noise levels during resting-state measurements compared to active asanas to assess HbO, HbR, and HbT concentrations [121], [140], [190].

3. Start by identifying and correcting motion artifacts in the data. Once corrected, apply a bandpass filter (0.009–0.08 Hz) to the time series to isolate the functional connectivity frequency range, then convert the filtered signals into hemoglobin concentrations using the modified Bouguer-Beer-Lambert law for further analysis [122], [140], [191]. Focus on time points free from motion artifacts (using the MotionArtifactByChannel function) to preserve the integrity of inter-hemispheric connectivity [192].

4. To account for spontaneous fluctuations common across all channels, apply short separation channel (SSC) signal regression. Begin by calculating the average time course across all SSCs, then regress the SSC signal from the measured fNIRS time series using the Tikhonov regularization method [191].

5. Use the resulting residual time series to construct connectivity matrices by computing Pearson correlations between all pairs of channels.

6. For intrahemispheric connectivity, calculate the average correlation coefficients between channels within the left hemisphere and within the right hemisphere separately. For interhemispheric connectivity, compute the average correlations between each channel and its contralateral counterpart [189].

7. When performing statistical analysis, transform Pearson's r values into Fisher z-scores before conducting Wilcoxon-Mann-Whitney tests. Correct for multiple comparisons using the false discovery rate (FDR) method.

   NOTE: The code and data that were used in this study are openly available in Zenodo [193] at https://zenodo.org/ records/11098997 with DOI: 10.5281/zenodo.11098996.

Representative Results

The preliminary analysis of active channels revealed significant differences between control posture A and the postures B and C (Figure 15A-B). A one-way repeated measures ANOVA was then performed to evaluate statistical differences in the mean HbO values of the estimated hemodynamic response function (HRF) across channels using the software package Origin(Pro), Version 2018. The assumption of normality was assessed using the Shapiro–Wilk test.

When using multichannel functional near-infrared spectroscopy (fNIRS), data collection from many channels necessitates performing numerous statistical tests. This naturally increases the likelihood of Type I errors, where at least one true null hypothesis may be mistakenly rejected due to the volume of comparisons [108]. To address this, a post hoc pairwise comparison with Bonferroni correction was applied to adjust for multiple comparisons, considering a significance threshold of $p < 0.05$. The Bonferroni correction modifies the significance threshold based on the number of tests conducted to help manage the family-wise error rate (FWER). Although the Bonferroni method is known for being highly conservative, potentially resulting in a higher rate of Type II errors or missed true effects, it is appropriate in this study. Our central concern is to avoid false positives that could distort the interpretation of neural activation patterns. As such, minimizing Type I errors takes precedence, even if it means that some genuine effects may go undetected. Additionally, Cohen's d was calculated to determine the effect sizes for channels exhibiting significant differences in HbO response.

Significant increases in PFC activity were observed during all three active yoga postures (B, C, and D) compared to the baseline posture (A), with activity particularly pronounced in the right hemisphere (Figure 16A-C). Analysis of HbO levels demonstrated that posture B elicited the largest effect sizes in the right inferior and medial frontal cortex ($d = 1.90$, $d = 2.89$), while posture C activated the greatest number of channels bilaterally. Posture D exhibited the fewest significant channel changes following the one-way ANOVA analysis, along with smaller effect sizes, indicating a reduced impact on PFC activation. These findings align with yoga therapy assertions that backbends and inversions increase oxygen delivery to the brain.

In comparison to the pre-asana rsFC state, the post-asana rsFC state revealed a reduction in PFC connectivity, mainly in the left hemisphere and more specifically in the medial PFC, a region associated with the default mode network (DMN) and often hyperconnected in individuals with depression or anxiety (Figure 16D and Figure 17A-I). These results confirm that yoga asana modulates PFC activity and suggest that reduced rsFC in the left medial PFC may underline the calming effects reported by practitioners.

The fNIRS technique proved reliable in capturing these dynamic changes during movement and rest in a naturalistic environment, underscoring its utility for studying real-world mind-body interventions.

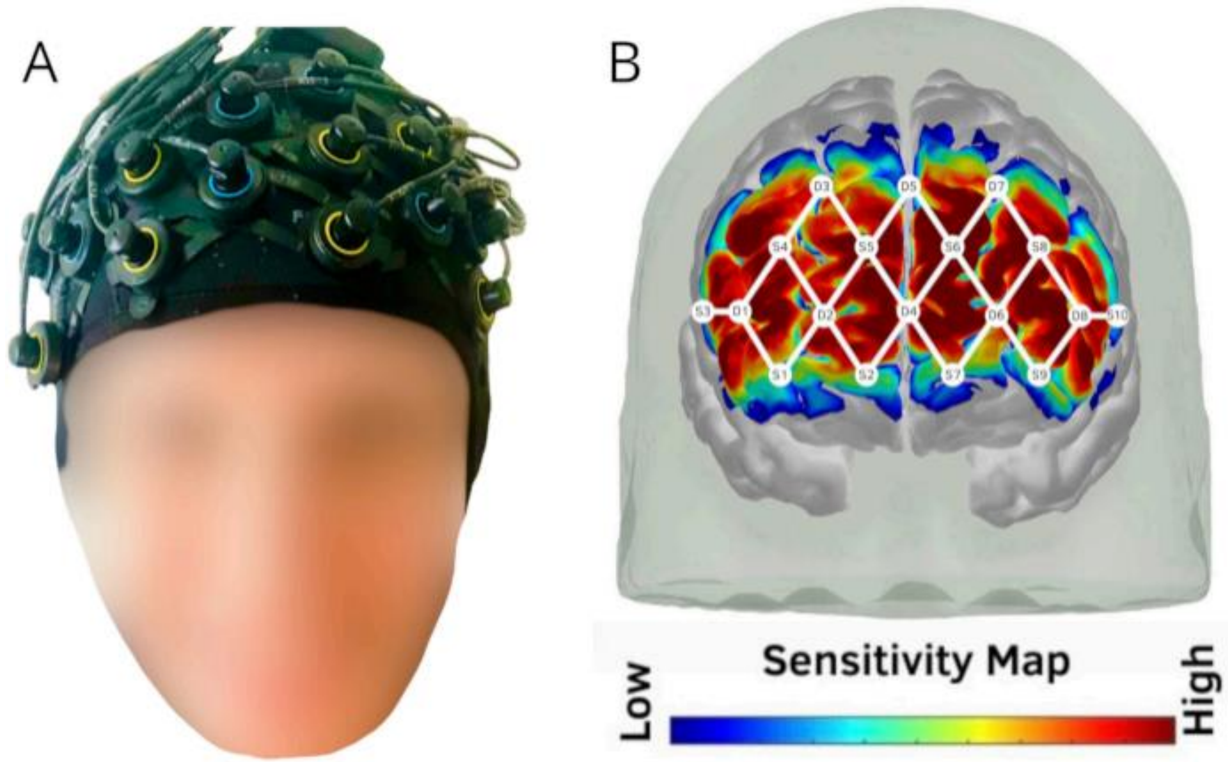

Figure 11. fNIRS cap configuration and sensitivity map. (A) fNIRS cap configuration. (B) Illustration of fNIRS cap configuration and sensitivity map. Consent for publication of the human image was obtained from Michelle Goodrick, featured in the pictures, and the first author of this paper.

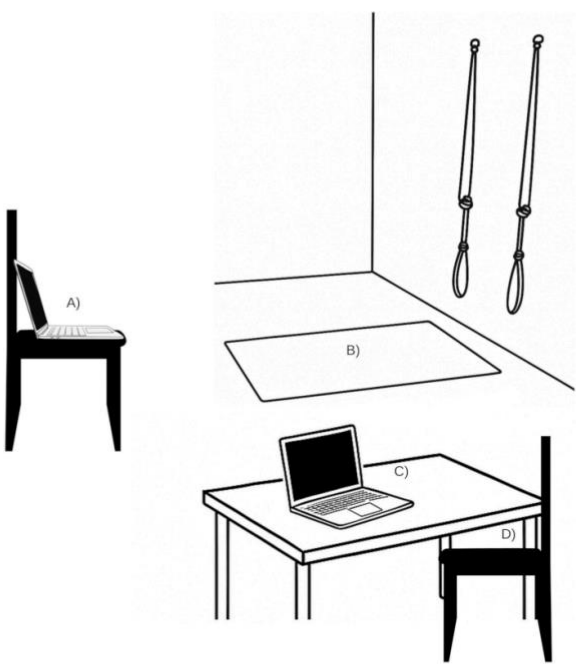

Figure 12. fNIRS experimental setup for measuring PFC activity during yoga asana. Graphical description of the experimental set-up: (A) the placement of the presentation screen, (B) the participant's position on the yoga mat, centered between the yoga ropes and the presentation screen, (C) the location of the computer running the software, which receives the Bluetooth signal from the fNIRS device, and (D) the researcher's position, enabling them to monitor both the participant and the presentation while recording each pose in real time using the interface.

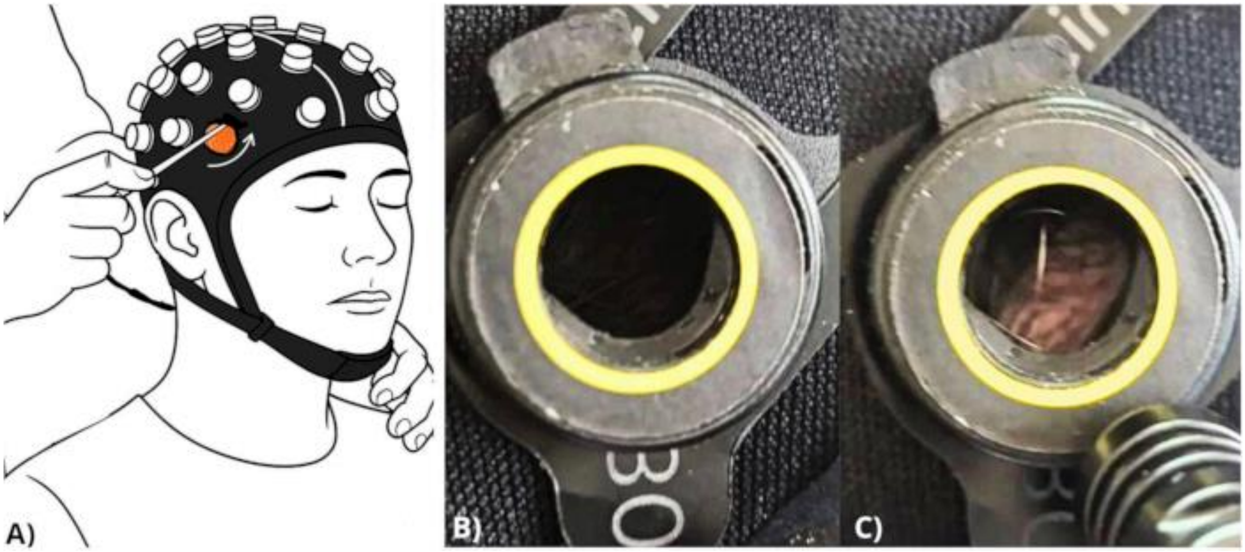

Figure 13. Secure fNIRS placement and hair adjustment technique. (A) Fasten the optode cap with a chin strap and use a bamboo stick to gently part the hair for direct scalp contact. (B) Hair obstructing the optode; (C) obstruction removed.

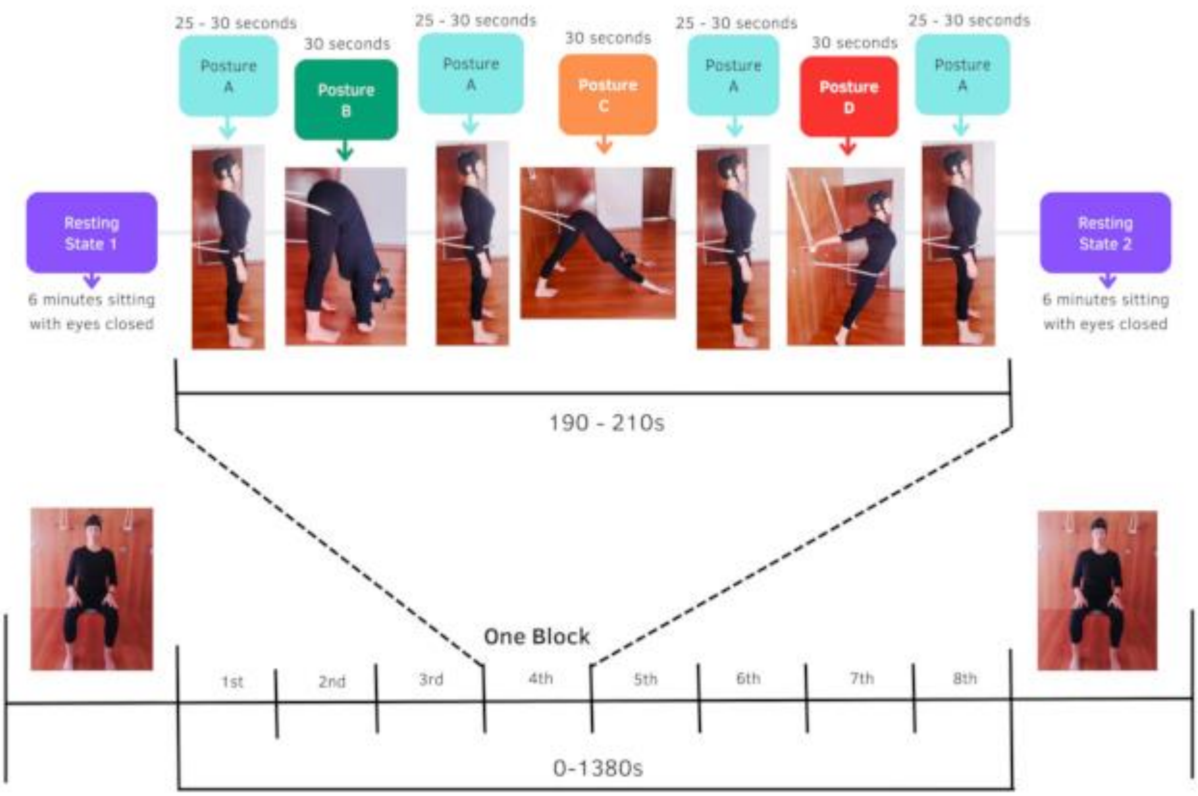

Figure 14. Experimental block design and yoga posture sequence. Experimental block design with resting state and images of yoga postures executed.

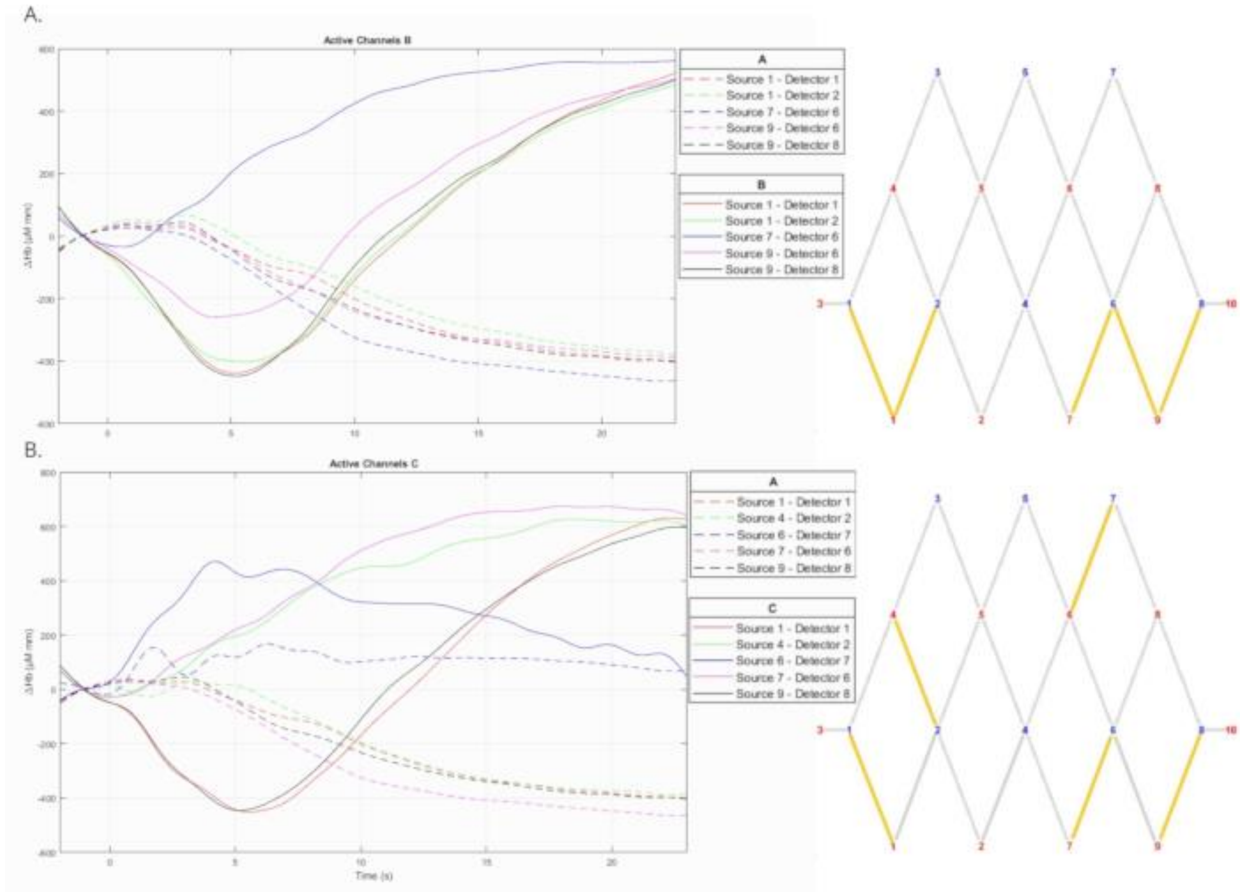

Figure 15. Significant channel activation versus baseline during yoga asana. (A) Significant differences in active channels of posture B and baseline posture A. (B) Significant differences in active channels of posture C and baseline posture A. Active-channel locations in the fNIRS PFC configuration are shown to the right of the corresponding graphs. Source numbers are indicated in red, while detectors are blue.

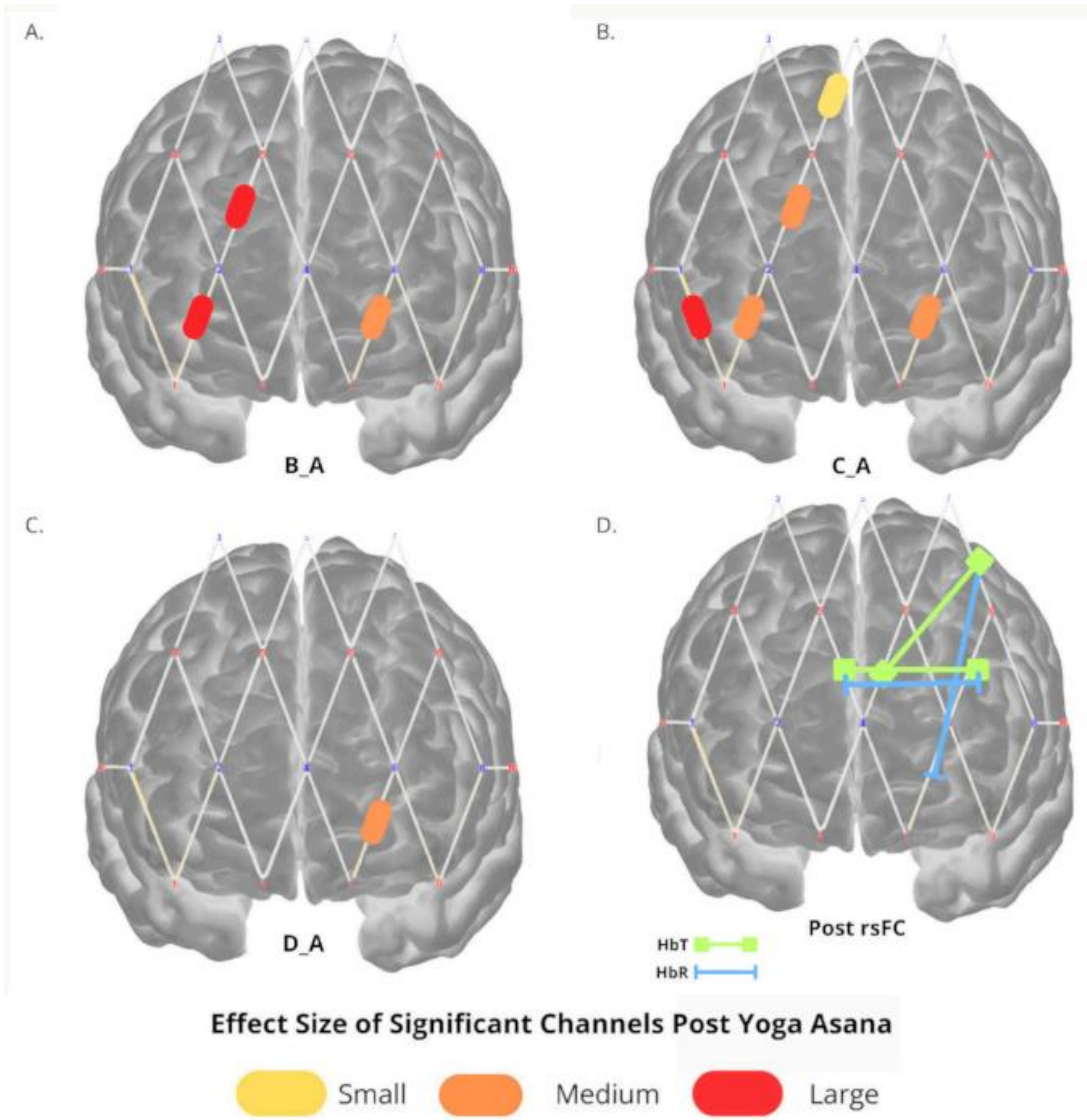

Figure 16. Mean HbO increases by posture and reduced rsFC post-practice. Mean HbO concentration significantly increased in (A) posture B, (B) posture C, and (C) posture D compared to baseline posture A, as revealed by a one-way ANOVA. (D) Brain area where reduced rsFC was observed after yoga asana practice.

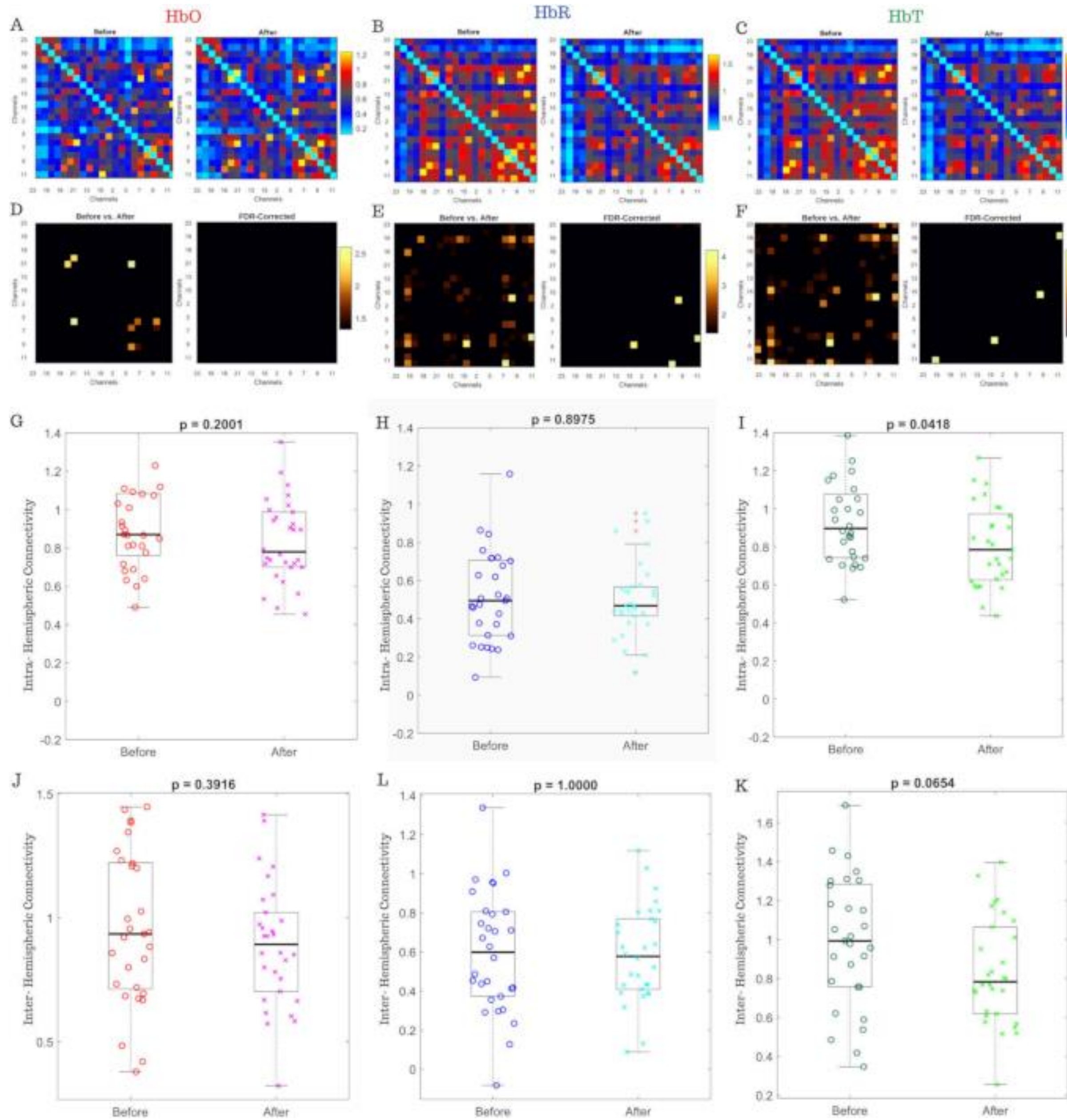

Figure 17. Functional connectivity analysis before and after yoga asana. Functional connectivity: (A-C) Color-coded average functional connectivity matrices (Fisher's z-score) between channels for both groups calculated for HbO, HbR, and HbT, respectively. Warm colors denote positive correlations, and cold colors denote negative correlations. (D-F) Statistical comparison between resting states before and after Yoga Asana. Only statistically significant correlations are shown ($p < 0.05$). (G-I) Group comparison of intrahemispheric connectivity (synchronicity within the same hemisphere) computed for HbO, HbR, and HbT, respectively. (J-K) A statistically significant decrease in intrahemispheric connectivity after Asana practice compared with resting state before was found in HbT measurements, with group comparison of interhemispheric connectivity (synchronicity between hemispheres) showing a trend toward a significant change in HbT.

Table 2.

Participant demographics

Measure	Value
Age (years)	39 (12.3)
Women (% proportion of sample)	20 (76%)
Men (% proportion of sample)	7 (26%)
Total sample size	27
Education (years)	13.18 (3.60)
BMI (kg/m²)	24.45 (4.59)
Years of yoga practice	4.52 (5.71)

Note. Mean values ± standard deviation, unless otherwise indicated.

Discussion

This study utilized fNIRS to assess PFC activity during a structured yoga asana practice, emphasizing key methodological considerations and advancements in real-world neuroimaging. Critical protocol elements included precise fNIRS optode placement, with optimal source-detector spacing (3.0 cm) and proper optode-scalp coupling to ensure accurate signal acquisition. A randomized block design, alternating between active postures (B, C, D) and a baseline posture (A) with support from yoga ropes, minimized participant fatigue and ensured consistent data collection. The use of short separation channels (1.0 cm spacing) reduced superficial hemodynamic interference, improving measurement accuracy. To isolate neural signals and mitigate motion artifacts, common in movement-based studies, the GLM and TCCA filters were employed.

Real-time monitoring of optode positioning and signal quality allowed for immediate adjustments to prevent signal degradation from hair or poor coupling. Despite these precautions, residual motion artifacts remained, underscoring the need for further advancements in signal correction algorithms and hardware. The primary limitation of this method is its sensitivity to motion artifacts, which, despite the TCCA filter and short separation channel regression, still led to data variability.

Alternative approaches, such as adaptive filtering techniques, Kalman filtering, wavelet-based denoising, and machine learning-driven artifact removal, can be used to mitigate these issues, offering robustness against motion-related noise while preserving physiological signals. Additionally, fNIRS's limited penetration depth restricts measurements to cortical regions, excluding direct measurements to deeper brain structures like the DMN. The small sample size and lack of longitudinal data also limit the generalizability of the findings. Expanding the range of postures and including clinical populations would increase the method's applicability.

This study, conducted with 27 participants, highlights the potential of functional near-infrared spectroscopy (fNIRS) to advance research on movement-based interventions such as yoga. By capturing prefrontal cortex (PFC) activity and assessing functional connectivity during active movement, fNIRS enables the investigation of the underlying neural mechanisms associated with the well-documented psychological and physiological benefits of practices like yoga and dance. These benefits are supported by a recent meta-analysis that reviewed over 97 randomized controlled trials involving more than 7,000 participants, demonstrating that physical activity significantly reduces symptoms of depression and anxiety. Among the most effective interventions identified were moderate-intensity activities such as yoga, walking, and dancing [194].

The portability and motion-tolerant design of fNIRS make it particularly well-suited for studying such naturalistic, embodied practices, which are difficult to assess using traditional neuroimaging modalities like fMRI. In contrast to the limitations of static imaging environments required by fMRI and PET, despite their superior spatial resolution, fNIRS offers real-time data acquisition during dynamic physical tasks and enables the evaluation of resting-state functional connectivity (rsFC) in ecologically valid settings [112], [167]. Beyond yoga, this methodological advantage positions fNIRS as a valuable tool in fields such as sports science, physical rehabilitation, and cognitive-motor integration, facilitating a more realistic understanding of brain function in everyday movement contexts. Ultimately, fNIRS supports the development of evidence-based interventions for both clinical and non-clinical populations, offering a critical bridge between laboratory research and real-world application.

Yoga Asana Increases Prefrontal Cortex Activity and Reduces Resting-State Functional Connectivity

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Abstract

Introduction: Various aspects of yoga have been researched for their psychological benefits, yet the neurological mechanisms underlying physical yoga postures (asana) remain inadequately explored due to limitations in prior neuroimaging techniques. The prefrontal cortex (PFC) has been established as an important region of interest concerning psychological health. Therefore, this study aimed to characterize changes in the PFC before, during, and after asana by applying the functional near-infrared spectroscopy (fNIRS) mobile neuroimaging technique. Methods: Twenty-seven healthy adults completed two 6-min, task-independent resting states before and after a 23-min asana routine. With the fNIRS device positioned on the frontal region of the skull, PFC activity was measured during each asana and resting state. The block design involved alternating between three active postures and one control posture. Each active posture was performed for 30 s and repeated 8 times, while the control posture was held during inter-trial intervals lasting 25–30 s. Across the session, this block design resulted in a total of 24 active blocks (8 repetitions of each active posture) and 25 baseline blocks (control posture intervals). Results: All three active asanas significantly increased PFC activity versus baseline, particularly in the right PFC. Furthermore, analysis of short-term changes in resting-state functional connectivity (rsFC) revealed a significant decrease, primarily in the left medial PFC, a key region of the default mode network (DMN), an area known to exhibit heightened activity in individuals suffering from depression and anxiety. Conclusion: This study provides neurological insight into the effects of yoga asana and supports fNIRS for assessing movement-based practices in real-world settings.

Introduction

The clinical diagnosis of depression and anxiety continues to increase worldwide [195]. A recent meta-analysis reviewing exercise in the treatment of depression and anxiety concluded that pharmaceutical and talk therapy interventions are more effective when combined with physical activity [194]. Scores for mood, quality of life, anxiety, and depression have demonstrated to significantly improve more with yoga interventions than with other forms of exercise [19], [60], [196].

Yoga is a discipline originating in India that consists of meditative, breath, physical, and ethical practices. It is recognized as a complementary and alternative medicine with "asana" (physical postures) and "pranayama" (breathing exercises) being the most widely practiced aspects of yoga [197], [198]. According to Yogic teachings, the mind and body are interconnected, and practitioners can improve their mood, prevent, reduce, or alleviate physiological as well as psychological pain and suffering through the practice of "asana" [63], [198], [199].

In yogic teachings, inversions and backbends are emphasized in addressing depression and anxiety. Authorities in the field of yoga therapy assert that these poses enhance the flow of "Prana" to the brain, helping to regulate both hyperactive and hypoactive cerebral activity [198], [199]. "Prana," translated from Sanskrit, means "breath of life or vital energy" and is thought to be primarily derived from circulating oxygen [200].

Scientific literature suggests that brain activity, and consequently the circulation of oxygenated hemoglobin (HbO), may diminish in cases of depression, particularly in the prefrontal cortex (PFC) [201], [202]. The PFC is an important region of interest for other psychological disorders such as anxiety [203], attention deficit disorder [204] and schizophrenia [205]–[207]. It is also implicated in stress levels, emotional response [208]–[210] and overall general psychological well-being [211].

Previous neuroimaging techniques, such as positron emission tomography and functional magnetic resonance imaging (fMRI), have shown that individuals with major depression often display reduced brain activity, particularly around the PFC [201], [212]–[214]. Extensive research supports that the PFC, and more specifically the medial PFC (mPFC), serves as a key substrate of the default mode network (DMN) [215]–[217]. One of the most consistent findings in the study of depression is increased DMN functional connectivity (FC) at rest [218], [219]. Studies suggest that hyperconnectivity in the mPFC is associated with depression, anxiety [203], [220], and related symptoms such as loneliness and social isolation [216]. Human fMRI scans and rodent models indicate that dysregulation of the DMN originates within the PFC and may also precede other structural pathological changes [221], [222].

An expanding body of scientific literature supports the beneficial effects of yoga on depression, anxiety, stress, and overall quality of life. For example, significant decreases in self-reported symptoms of depression, trait anxiety, changes in acute mood, cortisol levels, and decreased levels of negative mood and fatigue were reported in a randomized controlled trial by participants of a yoga course when compared with controls [223]. These findings align with a review of five randomized controlled trials examining various yoga interventions for individuals with mild to severe depression. The review concluded that yoga led to an overall improvement in depressive symptoms without reporting any adverse effects [224].

Furthermore, a review of 20 years of peer-reviewed research on yoga interventions reported that yogic practices support addiction recovery, reduce stress, anxiety, depression, and chronic pain; improve cardiovascular function and sleep patterns; and enhance overall well-being and quality of life [225]. Nonetheless, despite growing scientific interest and clinical demand, the neurological mechanisms underlying asana practice remain largely unexplored, primarily due to the limitations of earlier neuroimaging techniques [196], [226], [227]. Advances in functional near-infrared spectroscopy (fNIRS) now allow for real-time measurement of brain activity during yoga asana movements. This is achieved by analyzing the cerebral hemodynamic response function (HRF), which tracks changes in HbO and HbR as indirect indicators of brain activity. To the best of our knowledge, this is the first controlled experiment that has used neuroimaging technology to document the real-time effects of yoga asana as well as resting-state functional connectivity (rsFC) in the PFC with a sample size larger than one [228].

Methods

Applying the fNIRS mobile neuroimaging technique, this study aimed to characterize changes in the HRF in the PFC before, during, and after a basic yoga asana practice of four specific asanas repeated randomly during 25–30 s each for 23 min with 27 volunteers.

Functional Near-Infrared Spectroscopy

Functional near-infrared spectroscopy (fNIRS) is a portable, non-invasive, non-ionizing neuroimaging technology that takes advantage of the biological tissues being transparent to light in the near-infrared (NIR) spectrum (700–1,300 nm) and enables the measurement of NIR light absorption in HbO, HbR, and total hemoglobin (HbT) [104], [167]. fNIRS indirectly evaluates brain activation by providing the outcome metrics of HbO, HbR, and HbT responses in cortical tissues. Akin to fMRI, these changes are governed by neurovascular coupling, which posits that local blood flow increases in response to elevated neuronal activity [177]. This rise in regional cerebral blood flow elevates the local concentration of HbO and reduces HbR, collectively constituting the HRF [112].

By measuring the HRF, fNIRS has been used to investigate the neural correlations of cognitive and emotional processes [229], [230] as well as physical activity [231], [232]. It is less sensitive to motion artifacts and environmental noise than other imaging techniques [168], [231], [232] and is a viable alternative to fMRI as it allows participants to move freely, making it well-suited to exploring brain activity during physical movements such as yoga asana [228].

Participants

Subjects were recruited via word of mouth as well as Facebook and Instagram, social media platforms. The recruiting period was from February 2023 to May 2023. Demographic details were self-reported by participants and collected by the authors in an interview format. They were recorded in an Excel spreadsheet with each participant anonymously identified with a unique numbered code.

Participants received no monetary compensation and were informed that they could end the experiment at any time. Yoga asana experience varied between 0 and 10 years and the average

age was 39 years old (see Table 1 in online supplementary material; for all online supplementary material, see https://doi.org/10.1159/000545381). All participants were residents of the same country and native speakers of the same language. 76% of participants were women, which reflects the estimated real-world statistics of approximately 75% of yoga practitioners being women [233].

The sample size and statistical considerations were guided by prior research investigating yoga's effects on anxiety and depression, with the expected difference between means estimated to be approximately 0.50 [17], [157], [234]. Using the online calculator developed by Dhand and Khatkar [235], the initial expected proportion was set at 25 participants, with a significance level of p = 0.05. The expected standard deviation was calculated to be approximately 0.433, with a statistical power of 80%. To account for potential attrition, motion artifacts, and technical errors, the final sample size was increased to 30 healthy adults (ages 18–65), inclusive of all genders, biological sexes, and levels of prior yoga asana experience.

fNIRS Data Acquisition

Researchers utilized the portable fNIRS system Brite MKII (Artinis Medical Systems BV, The Netherlands) to measure changes in HbO and HbR before, during, and after yoga asana to assess alterations in PFC activity. The bilateral PFC template used in the experiment was customized and provided by Artinis, along with the fNIRS cap and Oxysoft software for data acquisition and optode-scalp coupling.

In accordance with the predetermined PFC configuration (Figure 18a–c), light sources (S) and detectors (D) were positioned in cap holders to ensure an S-D spacing of 3.0 cm, allowing for precise sampling of cerebral cortex activity. Additionally, two short channels spaced at 1.0 cm on either side of the skull minimized superficial hemodynamic effects, as recommended in prior studies [117], [173], [236].

A 3-D digitizer (Patriot, Polhemus Inc., USA) was used to record the cap's position and generate MNI coordinates for region labeling. A total of 24 channels (22 long channels and 2 short channels) were employed to measure hemoglobin changes across bilateral PFC regions. The setup utilized 8 detectors (D) and 10 sources (S) equipped with dual-wavelength LEDs centered at 757 nm and 843 nm to capture data on both HbO and HbR (Brite MKII, Artinis, the Netherlands).

After placing the cap on the head of the participant, barriers to the fNIRS optode signal were manually adjusted to ensure a clear optode-scalp coupling with minimum interference, as determined by the real-time acquisition software (Oxysoft, Artinis Medical Systems BV, The Netherlands). Probes were securely held in place with a chin strap throughout data collection. Measurement of cerebral oxygenation in the PFC was achieved with a sampling frequency of 25 Hz.

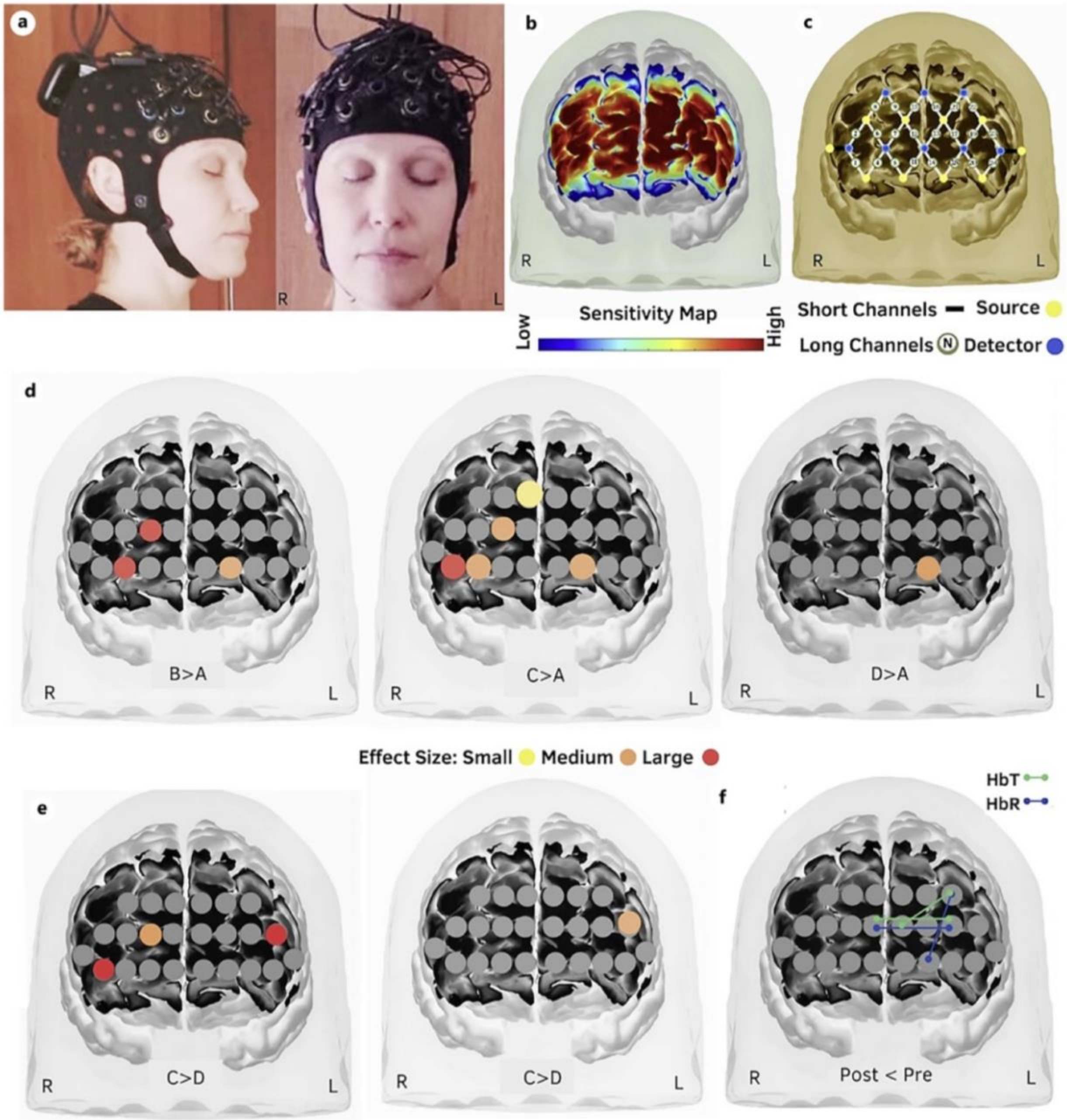

Figure 18. a fNIRS cap with prefrontal cortex configuration held in place with a chin strap. b Sensitivity map for the prefrontal cortex. c Optode placement of the fNIRS probe over the prefrontal cortex. d Significant increases in HbO during yoga asana in comparison to baseline posture A. e Significant increases in HbO during yoga asana between postures. f Regions of decreased rsFC as measured post-yoga asana.

Procedures

The four yoga asanas selected for this study are commonly practiced across various styles of yoga and were chosen for their reputed ability to enhance oxygen delivery to the brain and regulate mood [174], [175], [198], [199], [237]. To optimize data quality while minimizing participant

fatigue, the study focused on three active asanas repeated 8 times each with one baseline posture serving as the inter-task resting period repeated between each active asana. This design leveraged repetition to minimize motion artifacts and enhance data quality. To highlight the physical functionality of asanas, participants performed these three active asanas with the support of yoga ropes anchored to the wall [166], [238]. The selected asanas are as follows: posture A (tadasana): a neutral standing posture, or "mountain pose," served as the inter-task resting period due to its minimal biomechanical demands; posture B (Uttanasana): a forward bend with the torso hanging toward the ground; posture C (Adho Mukha Svanasana): "Downward-facing dog," a full-body stretch and mild inversion involving support from hands and feet; posture D (Urdhva Mukha Svanasana): "Upward-facing dog," a posture involving backward spinal extension, an open chest, and an upward gaze.

After completing the pre-asana 6-min resting state, volunteers were instructed to follow a PowerPoint presentation which demonstrated the photos and names of each posture labeled in the native language with the Sanskrit names written in parentheses while the experimenter said the name of each posture out loud. Each stimulus (postures B, C, and D) was assigned a unique marker and changed automatically every 30 s in random order. The predetermined markers were typed in manually as the task was completed. As shown in Figure 19 and in accordance with previous research, each measurement block lasted between 55–60 s with volunteers realizing the baseline inter-task (rest) measurement of posture A for a period of 25–30 s after each posture of B (30 s), C (30 s), and D (30 s) to ensure that the baseline could be distinguished from the task-dependent stimulus [169], [232], [239], [240]. At the end of each individual session, block markers were reviewed to reduce experimenter error and assure that they correctly coincided with the pre-established PowerPoint timestamps.

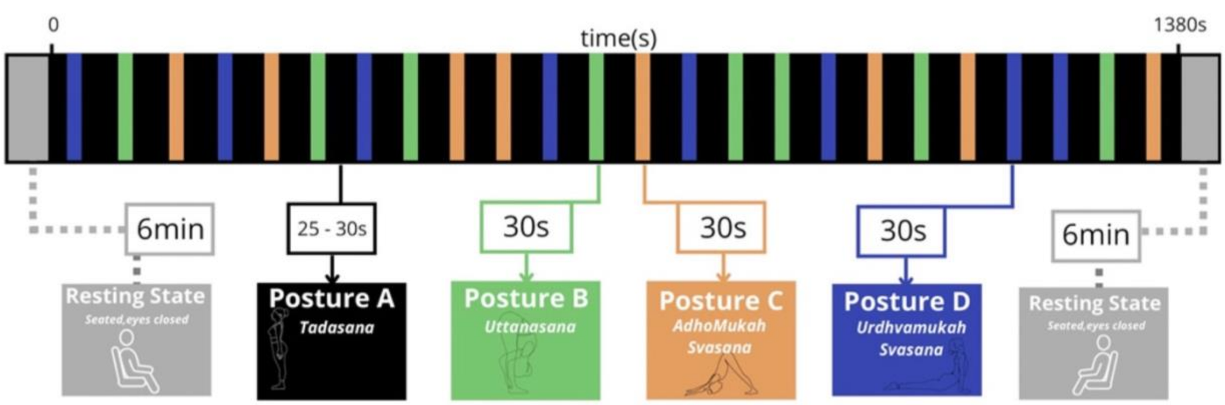

Figure 19. Experimental design: measuring HbO before, during and after yoga asana. Postures B, C, and D repeated 8 times randomly with posture A inter-task (rest) executed between each posture for 25–30 s. In a seated position, resting states were measured before and after the 23 min of yoga asana for 6 min.

Resting-State Functional Connectivity

Before and after completing the 23 min of yoga asana practice, participants were instructed to remain as motionless as possible in a seated position for 6 min, without falling asleep. Participants were asked to close their eyes, remain relaxed, and refrain from concentrating on anything specific. None of the participants reported that they had fallen asleep during the 2 measurements of resting state, though many reported feeling deeply relaxed post-yoga asana.

fNIRS Data Processing and Analysis

To estimate the HRF elicited by yoga asana, the following procedure was implemented: fNIRS raw data were converted to optical density and processed using the open-source HOMER3 toolbox (RRID:SCR_009586). Changes in HbO and HbR concentration were measured using the modified Beer-Lambert law linear algorithm, combined with short-span channel regression, to minimize the influence of superficial vascular activity.

Data were analyzed using MATLAB (Mathworks, Natick, MA, RRID:SCR_001622) [140]. For each participant, block averages were calculated for each channel and condition to ensure consistency. The raw time-series data were first subjected to a quality control procedure, during which readings with extreme optical density fluctuations, low signal-to-noise ratios (SNR), or large source-detector distances were excluded using the hmrR_PruneChannels function (valid range: 1×10^{-7} to 1×10^{7}, SNR threshold = 2, source-detector range = 0.45–45 mm).

Motion artifacts were identified for each channel using the hmrR_MotionArtifactByChannel function. Segments were flagged as containing motion artifacts if signal amplitude exceeded 0.5 (AMPthresh) or the standard deviation increased by more than a factor of 15 (SDthresh) within a 1-s time window (tMotion). Flagged segments, 1 s in length (tMask), were excluded. To reduce the impact of surface and systemic physiological noise on HRF estimates, short-span (SS) regressors were applied to long-span (LS) channels [117], [173].

Using data from both long and short channels, a general linear model (GLM) was applied with a time window spanning 2 s before to 23 s after stimulus onset. The GLM addressed motion artifacts, systemic noise, and isolated brain activity for HRF estimation [119], [121], [184], [185]. Ordinary least squares were used to solve the GLM [241].

Finally, to further mitigate motion artifacts, regularized embedded canonical correlation analysis was applied using participants' resting state (30–210 s) as a regressor [131]. HRFs were then estimated for each channel, condition, and participant. This comprehensive filtering and preprocessing pipeline effectively reduced motion artifacts and physiological noise, improving the SNR and ensuring consistent neural response estimates for precise analysis.

Mean HbO values were used in the analysis of asana as HbO is less susceptible to noise and variability compared to model-derived beta coefficients [190]. While beta coefficients are effective for capturing task-dependent activity, they are highly sensitive to fluctuations in data quality and model assumptions, which can compromise their robustness in tasks involving sustained or localized activity such as yoga asana. In contrast, HbO provides a clearer and more reliable signal of neural activation than HbR or HbT as it is less influenced by noise and variability. This precision makes HbO the preferred metric in functional brain imaging, particularly for movement-related tasks [180]–[182].

The software package Origin(Pro), Version 2018 (OriginLab Corporation, Northampton, MA, USA, RRID:SCR_002815), was used to complete one-way repeated measures ANOVA to assess statistical differences in the mean HbO values of the estimated HRF between each long channel, comparing the baseline posture A to B, C, and D as well as between postures B, C and D. Normal distribution of data was determined by Shapiro–Wilk test. A post hoc pairwise comparison using Bonferroni correction for multiple comparisons with a p-value less than 0.05 was used as the threshold for significance.

Cohen's d (d) was then applied to estimate effect sizes of channels that demonstrated significant differences in HbO response [186], [187]. A complete table of ANOVA results, including p-values and effect sizes for those with $p < 0.05$, is provided in the online supplementary material (see Tables 2, 3).

Resting-State Analysis

FC within (intrahemispheric) and between (interhemispheric) hemispheres was evaluated separately for each participant, based on the statistical dependency between time series reflecting co-activation of brain structures [188], [189]. A 6-min resting-state period was selected for this study, aligning with the commonly accepted range of 5–10 min for such analyses, as sufficient rsFC is typically achieved after 5 min [131], [180]–[182]. The analysis benefited from reduced noise levels during resting-state measurements compared to active asanas, allowing for the assessment of HbO, HbR, and HbT concentrations [121], [140], [190]. Motion artifacts were identified and corrected prior to applying bandpass filtering (0.009–0.08 Hz) to the time series. The filtered signals were then converted into hemoglobin concentrations, isolating frequencies within the FC range (0.009–0.08 Hz) for analysis [122], [140], [191]. FC analysis focused only on time points free from motion artifacts as removing these segments helps preserve the integrity of interhemispheric connectivity [192]. To account for common spontaneous fluctuations across all channels, short separation channel (SSC) signal regression was applied. This involved calculating the average time course across all SSCs, followed by regression of the SSC signal from the measured fNIRS time-series using a Tikhonov regularization method [191].

The resulting residual time-series were then used to construct connectivity matrices, with Pearson correlations computed between every pair of channels (see online supplementary Fig. S1). Intrahemispheric connectivity was assessed by averaging the correlation coefficients between channels within the left and right hemispheres separately. For interhemispheric connectivity, correlations between each channel and its contralateral counterpart were averaged [189]. For statistical analysis of both forms of rsFC, Pearson's r values were transformed into Fisher z-scores before conducting Wilcoxon-Mann-Whitney tests [117].

Multiple comparisons were corrected using the false discovery rate method, and categorical variables were analyzed using the chi-square test [242].

Results

Significant hemodynamic activation ($p < 0.05$) in the PFC was observed during all three postures, with activity increasing in both hemispheres and a more pronounced effect, including more active channels, in the right hemisphere (Figure 18d, e). As illustrated in Figure 18d and detailed in the accompanying narrative, channel-bychannel ANOVA comparisons demonstrated significant increases in HbO across all three yoga postures (B, C, and D). Effect sizes (d) ranged from small to large when compared to the baseline posture A. Postures B and C also showed increased HbO activation in comparisons with posture D (Figure 18e). Detailed tabular results for each channel, along with their corresponding effect sizes (d), and F-test statistics (F) are provided in Tables 2 and 3 of the online supplementary material. No significant correlation was found between PFC activation and years of yoga experience.

Comparing Postures B, C, and D with Baseline Posture A

Compared to baseline posture A, the largest effect sizes ($d = 1.90$ and 2.89) were observed during posture B in the right hemisphere, specifically in the inferior frontal cortex (Frontal_Inf_Tri_R; $d = 1.90$) and the frontal medial cortex (Frontal_Mid_R; $d = 2.89$). The fewest activated channels occurred during posture D, with only one channel showing a medium effect size ($d = 0.57$) in the left Frontal Superior Cortex (Frontal_Sup_L; channel 18), which also exhibited a consistent effect size across all three postures.

While smaller in effect size than posture B, posture C showed the greatest number of activated channels (5), with HbO increases observed in both hemispheres. These included small ($d = 0.43$), medium ($d = 0.74$, 0.57, 0.75), and large ($d = 1.32$) effect sizes in the right inferior frontal cortex, right frontal medial cortex, right superior medial cortex (Frontal_Sup_Mid_R), and left frontal superior cortex. Three channels (4, 7, and 18) showed increased activation in both posture B and C, although with varying effect sizes. In both postures B and C, the right hemisphere showed greater activation and effect sizes compared to the left hemisphere.

Comparing Postures B, C, and D

Significant differences were observed between postures C and D, as well as between postures B and D (online supplementary Fig. S1; online supplementary Table 2). Compared to posture D, posture C showed a greater number of channels in both hemispheres with significant increases in HbO, exhibiting large ($d = 0.84$, 0.81) and medium ($d = 0.55$) effect sizes. Channel 23 in the left hemisphere demonstrated a significant increase in HbO in both postures B and C, with a larger effect size during posture C ($d = 0.81$ vs. $d = 0.74$). No significant differences in HbO response were found between postures B and C in the PFC.

Baseline and In-Between Posture Comparison

The most significant increases in HbO in the PFC between postures and baseline were observed in the right inferior frontal cortex. In three of the five posture comparisons, HbO increases were seen in both hemispheres, while in posture D, activity was confined to the left hemisphere (online supplementary Tables 2, 5). Among the significantly active channels, the only small effect size (d = 0.43) was found in the right superior medial cortex (channel 15) during posture C. Despite this, posture C exhibited the greatest overall activity across channels and regions. The largest HbO increases were observed in the right frontal inferior cortex (d = 1.90) and right frontal medial cortex (d = 2.89) during posture B. While posture D showed fewer active channels compared to postures B and C, it still demonstrated significant HbO increases in the left frontal superior and inferior cortex. Overall, the results indicate that yoga postures B, C, and D primarily affect the frontal inferior cortex, with the greatest activation in the right hemisphere.

Resting-State Functional Connectivity

Significant differences in HbR and HbT were observed between pre- and post-resting-state measurements, but no significant changes were detected in HbO. The largest reduction in rsFC occurred in the left hemisphere (Figure 18f), contrasting with the significant increases in the right hemisphere during yoga asana. The decrease in HbR and HbT connectivity was observed in the left frontal superior medial cortex, left frontal superior cortex, left frontal medial cortex, and right frontal superior cortex.

For a complete illustration of the rsFC matrices, refer to S1 in the online supplementary material. No significant differences were found in HbO or HbR for intrahemispheric connectivity changes. However, a significant decrease in HbT intrahemispheric connectivity was observed after yoga asana. While no significant changes occurred in interhemispheric connectivity, a trend toward a decrease in HbT was noted. Additional details on MNI coordinates, brain regions, and channels are available in Tables 4 and 5 of the online supplementary data section.

Discussion

These findings exhibit that yoga postures B (Uttanasana), C (Adho Mukha Svanasana), and D (Urdhva Mukha Svanasana) significantly influence HbO levels and uniquely affect PFC activity. All three asanas were linked to significant increases in HbO levels in comparison to the neutral standing posture A (tadasana) and support the yogic therapy assertion that backbends and inversions enhance the flow of “Prana,” or in other words, oxygen, to the brain.

Results appear to indicate a compensatory relationship between hemispheres with increased HbO levels in the right PFC during yoga postures corresponding with a reduction in rsFC in the left hemisphere post-asana, aligning with the hypothesis of complementary hemispheric functionality, where the two hemispheres dynamically regulate and balance each other’s activity [243]. Furthermore, as highlighted previously, increased connectivity in the mPFC is associated with psychological conditions such as anxiety and depression [203], [215], [220].

Therefore, the heightened activity in the right hemisphere during asana practice being correlated with reduced rsFC in the left mPFC post-asana offers neurological insight for previously observed positive clinical outcomes, the “silent mind” and the sense of calm reported post-yoga practice by practitioners [19], [60], [158], [194], [196], [244]–[247].

Nonetheless, the generalizability of these findings is constrained by a small sample size, limited posture selection, and the lack of a longitudinal study design. Future research with larger, more diverse populations, a broader selection of asanas, and an exercise comparison group would enhance these findings. Including clinically diagnosed populations and integrating psychological scales with fNIRS measurements would provide deeper understanding into the relationship between brain activity, mood, and the effects of yoga asana. As neuroimaging technology advances, methods capable of measuring deep cortical activity during movement could clarify the connection between yoga asana, the mPFC, and the DMN.

To the best of the authors’ knowledge, this study is the first experiment with a sample size greater than one to investigate how yoga asana affects brain activity, specifically in the PFC. This study offers novel neurological insights into the effects of yoga asana and highlights the utility of fNIRS in evaluating movement-based practices in naturalistic settings, including inverted physical forms and backbends—key components of yoga asana that are not typically examined in other physical activities such as running, walking, or cycling. Furthermore, this study addresses the call to identify neurological markers of yoga, contributing to the development of evidence-based yoga interventions for clinical applications [148].

Neural, Biochemical, Postural, and Subjective Outcomes Following a 30-Day Yoga Program: A Multimodal Mixed-Methods Study

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Abstract

Objective: Building on growing evidence linking yoga with enhanced mental health and well-being, and employing a multimodal design that reflects yoga's integrative epistemology, this exploratory mixed-methods study examined whether 30 sessions of alignment-focused yoga were associated with coordinated neural, biochemical, postural, and experiential changes.

Methods: Thirty-eight adults aged 18 to 35 years were enrolled, of whom 29 completed at least 70% of the 30 yoga sessions and the pre- and post-program assessments. Functional near-infrared spectroscopy (fNIRS) was used to examine prefrontal cortex (PFC) activation during the Breath-Holding Task and Affective Image Task, as well as functional connectivity at rest (rsFC). Fasting biochemical markers, baropodometric posture, and neurological measures were assessed within 1 to 5 days before and after the program. Likert-scale questionnaires were administered on days 15 and 30, and semi-structured interviews were conducted with 15 participants within 7 days after completion.

Results: After the program, negative images elicited the broadest increase in PFC activity, spanning 10 bilateral channels, while Network-Based Statistics showed greater resting-state connectivity within a right inferior frontal network. Mediolateral postural misalignment decreased from a median of 2 to 0 ($n = 27$, $p = 0.003$). By day 30, 85.7% to 92.9% reported improved body awareness, sleep, energy, and mental well-being, while 67.9% reported improved interpersonal relationships. Participants also reported reduced pain across all assessed body regions. Semi-structured interviews provided convergent accounts of improvements in emotional regulation, sleep, concentration, physical comfort, and interpersonal awareness. Among six biochemical markers assessed, only total cholesterol ($n = 26$) and oxytocin ($n = 20$) changed significantly.

Conclusion: Participation in 30 yoga sessions was associated with significant changes in posture and breath-related neural activity, together with affective, biochemical, and subjective outcomes. Although exploratory, the convergence of these findings suggests that changes arising through the coordinated practice of alignment, breath, movement, and attention may be related to broader shifts in emotional processing and perceived well-being. This multidimensional pattern highlights the

value of mixed-methods approaches for studying yoga and other embodied interventions without reducing their effects to a single variable.

1. Introduction

Yoga is an integrative psychophysiological discipline originating in India that combines physical postures (*āsana*), breath regulation (*prāṇāyāma*), attentional and meditative practices (*pratyāhāra*, *dhāraṇā*, and *dhyāna*) within the ethical framework of the *yamas* and *niyamas* [248]. Rather than separating mind and body, yoga conceptualizes posture, respiration, interoception, and cognition as dynamically interrelated [248], [249]. Modern-day embodiment research similarly demonstrates that posture and interoceptive awareness influence mood, cognition, and emotional processing [27], [28], potentially through autonomic, endocrine, and cortical mechanisms [9], [10], [20], [21], [60].

Amid rising rates of depression and declining psychological well-being, accelerated by the COVID-19 pandemic [250], yoga has gained attention as an accessible adjunct to conventional mental health care. Evidence indicates benefits for depression, anxiety, stress, trauma-related distress, psychological well-being, and quality of life [17], [19], [251], [252]. A network meta-analysis of 218 controlled trials involving approximately 14,000 participants identified yoga as a viable core treatment for depression, with effects comparable to established pharmacological and psychotherapeutic approaches and favorable tolerability [19].

Nonetheless, despite growing evidence of benefit, yoga research often examines isolated outcomes that may not fully reflect its integrated physical, psychological, and contemplative framework [253]. Addressing this gap requires investigation of the interacting mechanisms through which yoga may support emotional regulation, psychological resilience, and well-being.

Multimodal methods may better capture this complexity. Responding to calls for more integrative, phenomenologically informed approaches in neuroscience and mind-body research [14], [156], as well as greater representation of diverse populations [254]–[256], this study examined a 30-day yoga program in a Latino cohort of native Spanish speakers. Neural, biochemical, and postural changes were assessed before and after the program using functional near-infrared spectroscopy, serum and plasma assays, and baropodometry, while subjective experiences were examined through questionnaires and semi-structured interviews.

2. Methods

2.1. Participants

An a priori power analysis ($\alpha = 0.05$, power = 0.80; medium effect size, Cohen's d = 0.50 to 0.64), drawing on fNIRS yoga and neurofeedback intervention studies [21], [257] and yoga intervention meta-analyses [17], [258], indicated a recommended sample of 23 to 34 participants. To account for anticipated attrition, motion artifacts, and technical data loss, thirty-eight adults (ages 18 to 35; mean = 30.45 years, SD = 3.38 years) were recruited via social media, university announcements, classroom visits, and public presentations. Twenty-nine participants met the minimum attendance threshold (70% of sessions) and completed all fNIRS assessments before and after the program. Participants voluntarily elected to enroll in the 30-day yoga program and no withdrawals were attributable to adverse events. Demographic characteristics of the analytic sample are summarized in Table 1, and complete participant flow is presented in Fig. 20. All quantitative measures were obtained using identical protocols at both time points.

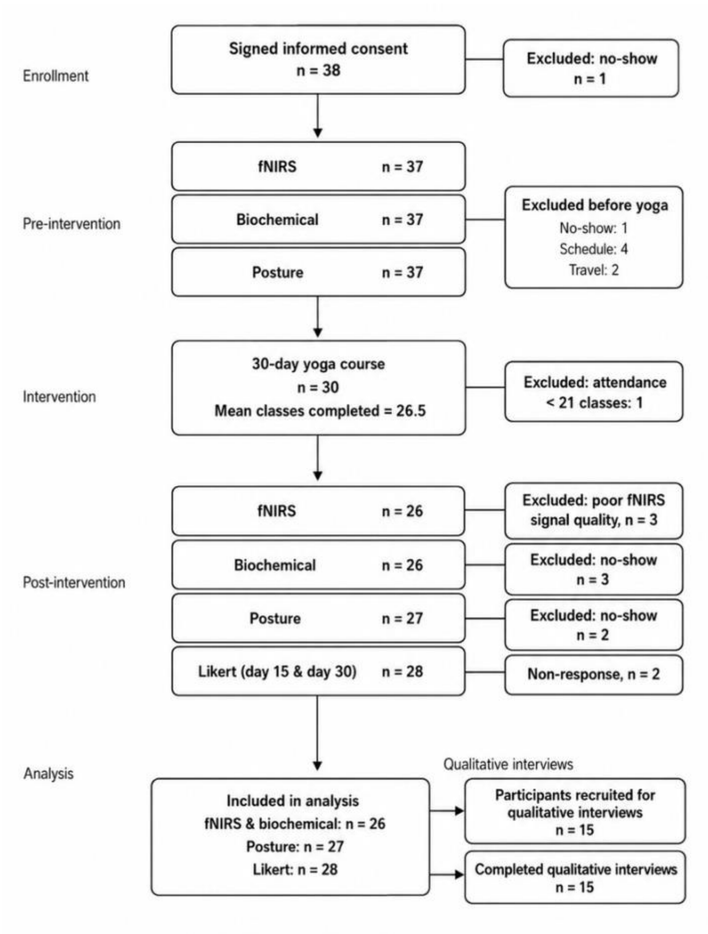

Figure 20. Participant flow through the study, including enrollment, assessment before the program, the program, assessment after the program, and analysis.

Thirty-eight adults aged 18 to 35 years were recruited from a public university and the study was approved by the institution's research ethics committee; identifying university, committee and approval details have been withheld for double-blind peer review. All participants provided written informed consent in accordance with the Declaration of Helsinki.

Exclusion criteria included self-reported neurological or physiological conditions contraindicating yoga practice, more than one year of prior yoga experience, or concurrent enrollment in an exercise program during the study period. Women accounted for 72.4% of the analytic sample, consistent with participation patterns previously reported in the yoga research literature [233].

Table 3. Demographic characteristics of participants who completed the 30-day yoga program (n = 29).

Characteristic	Mean (SD)	n	%
Age (years)	30.45 (3.38)	29	
BMI (kg/m²)	27.36 (6.68)	29	
Women		21	72.4
Men		8	27.6
Education (years)	18.48 (1.74)	29	
Bachelor's degree (16 years)		5	17.2
Master's degree (18 years)		16	55.2
Doctorate (21 years)		8	27.6

Note. Values are presented as mean (SD) unless otherwise indicated. Percentages are column percentages. Education levels were standardized to years of formal schooling as follows: bachelor's degree = 16 years, master's degree = 18 years, and doctorate = 21 years. BMI, body mass index; SD, standard deviation. SD values are sample standard deviations (n − 1).

2.2. 30-Day Yoga Program

The program consisted of 30 in-person, instructor-led sessions held on consecutive weekdays, excluding holidays, from 16:00 to 17:15 on the university campus, totaling 37.5 hours. Participants confirmed that they did not participate in any other exercise program during the program. Attendance was recorded, and completion of at least 21 sessions (70%) was required for inclusion in the post-program fNIRS, biochemical, and postural analyses consistent with comparable yoga research [259]. The anonymous questionnaires were available to all 30 participants who began the program; 28 submitted responses. Because responses were anonymous, questionnaire respondents could not be linked to individual attendance records.

Each session followed a standardized sequence integrating *āsana*, *prāṇāyāma*, *dhāraṇā*, and *dhyāna*, with emphasis on skeletal alignment and interoceptive awareness. Chairs, belts, walls, and massage balls were used for support and to refine somatic and postural awareness. Illustrated slides provided consistent posture, alignment, and breathing instructions. The full sequence is presented in Supplementary Table 1. All sessions were delivered in Spanish by a single instructor holding 200-hour and 500-hour Yoga Alliance certifications, as well as certification from the International Association of Yoga Therapists.

2.3. Functional Near-Infrared Spectroscopy (fNIRS)

Functional near-infrared spectroscopy (fNIRS) noninvasively estimates cortical activity from changes in oxygenated (HbO) and deoxygenated hemoglobin (HbR) arising through neurovascular coupling [104], [112]. Its portability and relative tolerance of movement make it suitable for naturalistic, movement-based research [112].

2.3.1. Prefrontal Cortex as Region of Interest

The prefrontal cortex (PFC) was selected because of its central roles in emotion regulation and executive control and documented alterations in anxiety and depression [201], [203], [208]. The bilateral optode configuration is shown in Figure 21; channel locations and MNI coordinates are provided in Supplementary Table 2.

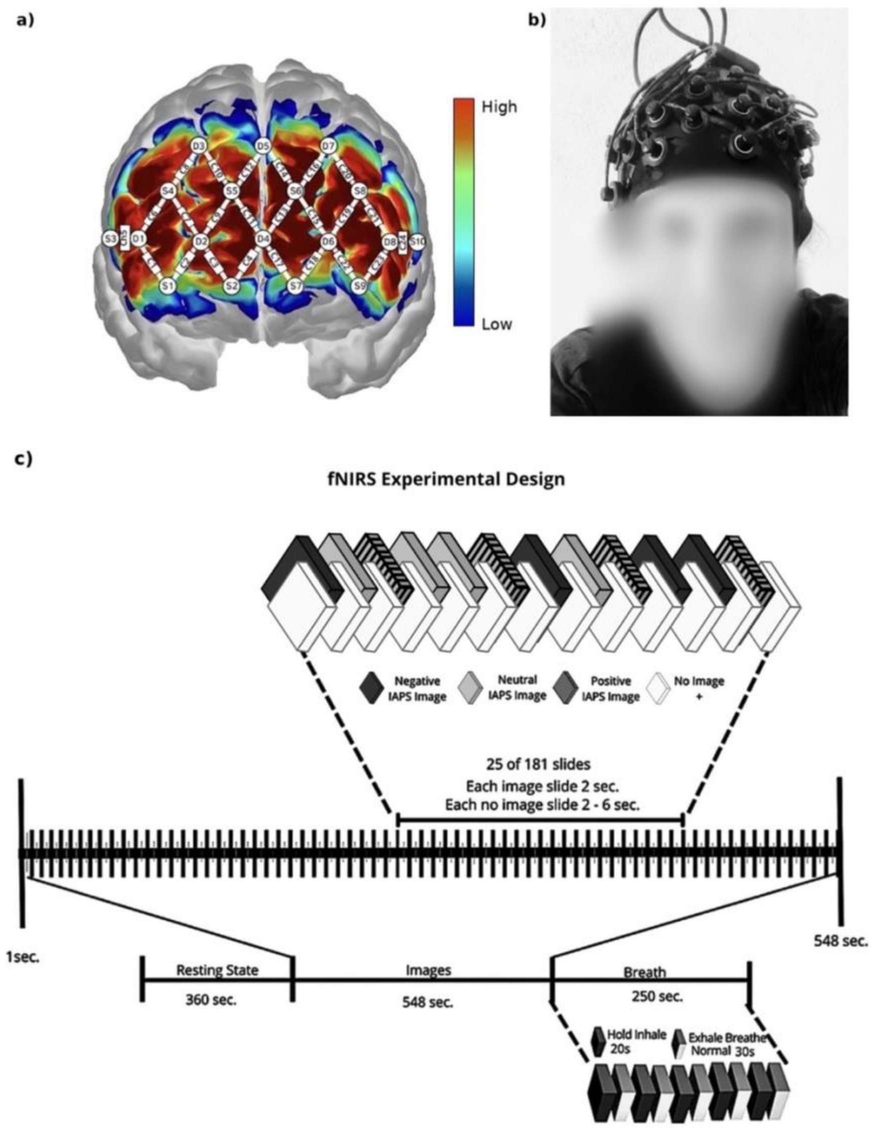

Figure 21. fNIRS configuration and protocol. (a) Prefrontal sensitivity map and optode array; colors indicate sensitivity. (b) Cap placement with identity obscured. (c) Resting-state, affective-image, and breath-hold sequence. S, source; D, detector; IAPS, International Affective Picture System.

2.3.2. fNIRS Data Acquisition

Data were acquired with a Brite MKII fNIRS system (Artinis Medical Systems BV, The Netherlands) using 22 long-separation (3.0 cm) and two short-separation (1.0 cm) channels at 757 and 843 nm (25 Hz). The cap was aligned to Cz, signal quality was monitored in OxySoft, and optical density was converted to HbO, HbR, and total hemoglobin using the modified Beer-Lambert law [111]. Full acquisition and positioning procedures are provided in the Supplementary Methods under "fNIRS acquisition and experimental protocol."

2.3.3. fNIRS Experimental Protocol

At both assessments, participants completed a 6 min resting-state recording with eyes closed, an IAPS Affective Image Task and a Breath-Holding Task in a standardized, computer-guided sequence (Figure 21c).

2.3.3.1. Resting-State Functional Connectivity

Resting-state functional connectivity (rsFC) was assessed during 6 min of seated, eyes-closed rest, consistent with evidence that spontaneous low-frequency activity reflects intrinsic network organization and recordings of approximately 5 minutes provide reproducible fNIRS connectivity estimates [260]–[262].

2.3.3.2. PFC Activation during Affective Image Task

Affective processing was assessed with the International Affective Picture System (IAPS) [263], which is established in fNIRS emotion research [264], [265]. Participants viewed 30 positive, 30 negative, and 30 neutral images for 2 s each, separated by jittered 2 to 6 s intervals; nonoverlapping image sets used before and after the program limited habituation. Stimulus lists and ratings are provided in Supplementary Table 3.

2.3.3.3. PFC Activation during Breath-Holding Task

Cerebrovascular reactivity (CVR) was assessed using a validated endogenous CO_2 challenge in which participants completed five 20-s breath holds separated by 25 to 30 s of normal breathing [266], [267]. Visual cues standardized inhalation, retention, and exhalation.

2.3.4. fNIRS Data Preprocessing

Data were preprocessed in HOMER3 [140] using MATLAB R2023b. After quality control, 26 of 29 datasets were retained; three were excluded because of excessive motion or poor optode-scalp coupling. Channels were pruned for signal quality; motion artifacts were detected and corrected using spline interpolation and Savitzky-Golay filtering [126], [192], task data were bandpass filtered, and hemodynamic responses were estimated using a general linear model with short-separation regression.

2.3.5. fNIRS Stimulus Data Analysis

HbO was the primary activation measure because of its sensitivity and stability [190]; HbR was also analyzed to provide complementary information and improve interpretability [145].

Breath-holding responses were quantified during retention (4 to 10 s) and post-release recovery (25 to 31 s), with peak HbO as the primary outcome [268]. Affective Image Task responses were quantified from peak HbO and HbR values 1.5 to 4.5 s after stimulus onset [269]. Group-level averages and paired pre- versus post-program comparisons were generated in HOMER3.

Epoch and baseline definitions, preprocessing thresholds, parameters, and analysis commands are detailed in the Supplementary Methods under "fNIRS preprocessing and task-response analysis." Complete analysis scripts and supporting data are available in Zenodo [146].

2.4. Statistical Analysis

Analyses were conducted in MATLAB R2023b. For the Breath-Holding Task, normality of pre- to post-program difference scores for HbO and HbR was assessed channel by channel using the Shapiro–Wilk test. Channels satisfying normality assumptions were analyzed with paired-samples t tests; those violating normality were analyzed with Wilcoxon signed-rank tests. For the Affective Image Task, peak-window HbO and HbR responses were analyzed using a two-way repeated-measures ANOVA with within-subject factors of Time (pre, post) and Valence (positive, negative, neutral), separately for each channel and chromophore. False-discovery-rate correction was applied to channel-wise comparisons; significance was set at $p < .05$, and paired standardized effect sizes were calculated as Cohen's *d* for paired observations [270].

2.4.1. Resting-State Functional Connectivity Statistics and Analysis

Resting-state connectivity was estimated from motion-corrected, short-separation-regressed HbO, HbR, and HbT time series bandpass filtered at 0.009 to 0.08 Hz [191], [192], [261], [262], [271]. Pearson correlation coefficients were Fisher z-transformed [117]. Intrahemispheric, interhemispheric, and connection-level pre- to post-program differences were evaluated using paired tests selected according to distributional assumptions, with false discovery rate correction [242], [262]. Network-Based Statistics used a t statistic to identify connected components while controlling the family-wise error rate [137]. Full processing and regularization parameters are provided in the Supplementary Methods under "Statistical and resting-state connectivity analyses."

2.5. Biochemical Analysis

Oxytocin, cortisol, cholesterol, triglycerides, uric acid, and prolactin were assessed. Fasting morning samples were collected at 1 to 5 days pre- and post-program [272], then processed immediately or stored at −20 or −80 °C. Detailed sample handling is provided in the Supplementary Methods under "Biochemical sampling and assays."

2.5.1. Oxytocin and Cortisol

Plasma oxytocin and cortisol were quantified by competitive ELISA (Fine Biotech Co., Wuhan, China) and read at 450 nm on a Synergy H1 microplate reader. Concentrations are reported in pg/mL and ng/mL, respectively. Complete biochemical data were available for 26 participants; oxytocin analysis included 20 usable paired samples. Full assay procedures are provided in the Supplementary Methods under "Biochemical sampling and assays."

2.5.2. Total Cholesterol, Triglycerides, Uric Acid, and Prolactin

Total cholesterol, triglycerides, and uric acid were measured from fasting serum using standard automated enzymatic methods, and prolactin by immunoassay, under identical preanalytical conditions at both time points. Method details are provided in the Supplementary Methods under "Biochemical sampling and assays." Pre- to post-program differences were assessed with paired t tests for total cholesterol, uric acid, and cortisol and two-sided Wilcoxon signed-rank tests for oxytocin, prolactin, and triglycerides.

2.6. Posture

Posture was assessed by measuring mediolateral center-of-pressure displacement using a FreeMed baropodometric platform and FreeStep software (version 1.0.3) during a 10-second modified Romberg stance with eyes open [273]. One trial was obtained at each assessment, and differences between assessments were tested with the Wilcoxon signed-rank test. Full acquisition settings are provided in the Supplementary Methods under "Postural assessment."

2.7. Self-Report Measures and Subjective Experience

2.7.1. Likert Scales

Participants completed anonymous five-point Likert questionnaires on Day 15 and within 5 days of program completion, with a "not applicable" option. Items were adapted from a national yoga and well-being survey [9], [160], translated, and bilingually verified. Two exploratory menstrual-symptom items were added at Day 30 in response to unsolicited participant reports [274]. Responses (n = 28) were analyzed at item and domain levels across physical and mental well-being, energy, sleep, social relationships, quality of life and body awareness. Complete items and categories are provided in Supplementary Tables 4 and 5.

Because questionnaire responses were anonymous and could not be linked across time points, Day 15 and Day 30 distributions were summarized descriptively rather than analyzed as paired observations. Response percentages were calculated using the number of respondents completing each questionnaire (n = 28).

2.7.2. Qualitative Interviews

Fifteen eligible participants were randomly selected for voluntary, uncompensated Zoom interviews, which were recorded, deidentified, and transcribed verbatim. The interview guide drew on prior qualitative yoga research [275] and examined practice experiences, emotion regulation, sleep and health behaviors, daily integration, and interpersonal change. Interviews were analyzed inductively using Braun and Clarke's six-phase thematic framework [276]. A second researcher independently coded 20% of transcripts and discrepancies were resolved by consensus.

Table 4. Summary of study measures and analysis procedures.

Measure/instrument	Analysis procedure
Resting-state fNIRS Six-minute eyes-closed resting-state recording used to assess prefrontal functional connectivity.	Pre- to post-program changes in intrahemispheric and interhemispheric functional connectivity were evaluated using paired tests selected according to distributional assumptions, FDR correction, and NBS.
Affective Image Task – IAPS/fNIRS Participants viewed positive, negative, and neutral IAPS images to assess prefrontal responses to affective stimuli.	Pre- to post-program HbO and HbR responses were analyzed using a two-way repeated-measures ANOVA; channel-wise comparisons were evaluated with FDR correction.
Breath-Holding Task – fNIRS Five 20-s breath-hold blocks were used to assess cortical hemodynamic responsiveness and CVR.	Pre- to post-program HbO and HbR responses were analyzed using channel-wise paired t tests or Wilcoxon signed-rank tests according to normality, with FDR correction.
Biochemical measures Fasting blood samples were collected before and after the program. Measures included cortisol, oxytocin, total cholesterol, triglycerides, uric acid, and prolactin.	Pre- to post-program changes were evaluated using paired t tests or Wilcoxon signed-rank tests according to distributional assumptions.
Posture – FreeMed posturography Postural organization was assessed using a FreeMed baropodometric platform. Mediolateral center-of-pressure misalignment was the primary outcome.	The pre- to post-program difference was evaluated using a two-sided Wilcoxon signed-rank test.
Self-report questionnaires – SurveyMonkey Participants completed anonymous Likert-scale questionnaires at Day 15 and Day 30 assessing perceived physical, emotional, cognitive, social, and quality-of-life changes.	Because responses could not be linked across time points, Day 15 and Day 30 distributions were summarized descriptively at the item and domain levels; no paired inferential testing was performed.
Qualitative interviews Semi-structured Zoom interviews were conducted with 15 participants to contextualize experiences of the program.	Transcripts were analyzed using Braun and Clarke's six-phase framework.

3. Results

3.1. Breath-Holding Task

Following the program, oxygenated hemoglobin (HbO) decreased during breath retention in the right triangular part of the inferior frontal gyrus (IFGtri), left middle frontal gyrus (MFG), and left IFGtri, with medium-to-large effects. During post-release recovery, HbO increased in the left MFG, left superior frontal gyrus (SFG), and left IFGtri, with large effects, whereas deoxygenated hemoglobin (HbR) decreased in the right MFG, with a medium effect. Channel-level statistics are presented in Table 5; spatial distributions and response profiles are shown in Figure 22.

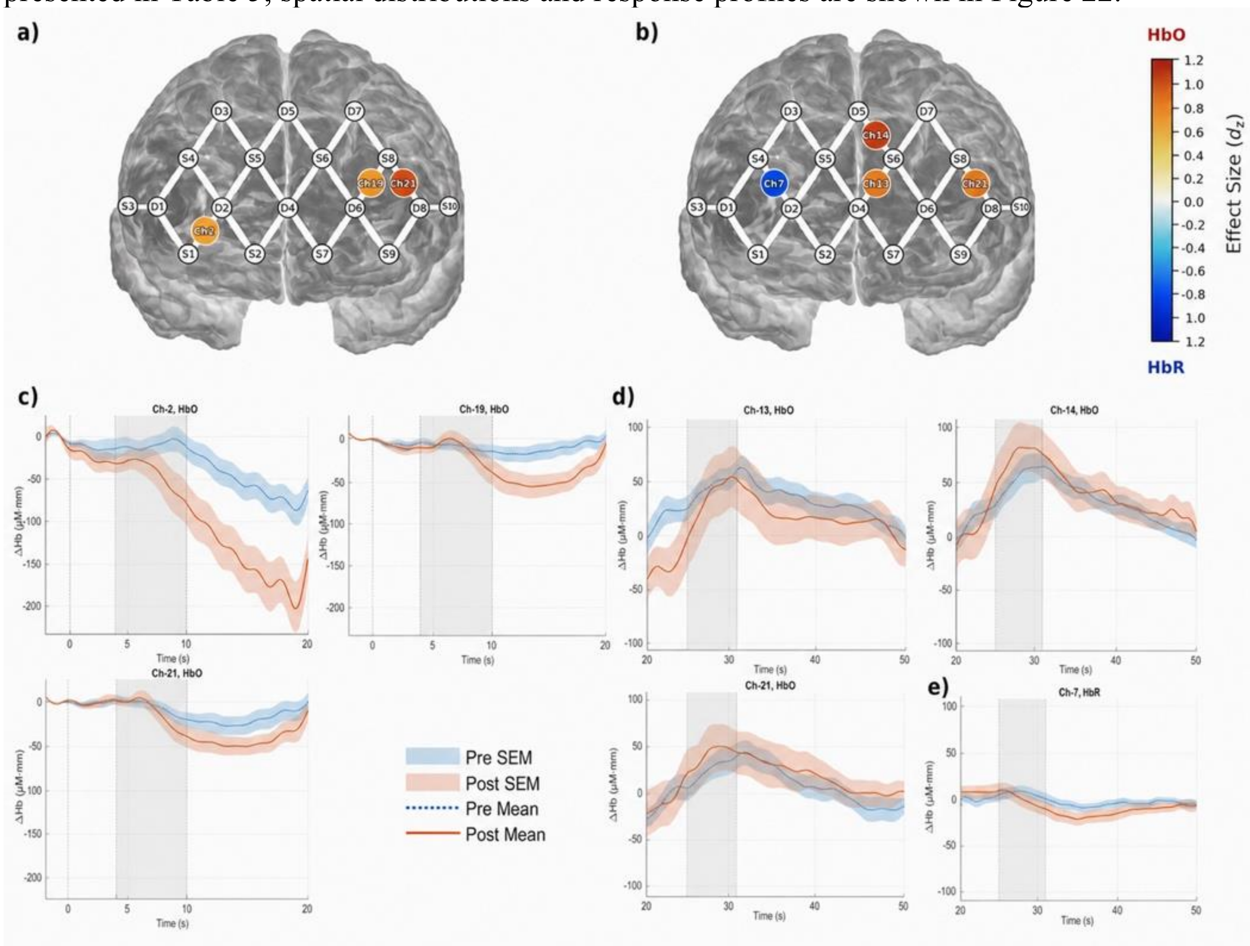

Figure 22. Breath-holding task results. (a) Significant HbO decreases during breath retention; (b) significant HbO increases and HbR decrease during post-release recovery; (c–e) corresponding hemodynamic response profiles. Blue and orange indicate pre- and post-program means, respectively; shaded areas indicate SEM; gray bands indicate the analysis windows.

Table 5. Significant pre- to post-program changes in HbO and HbR during breath retention (4–10 s after onset) and post-release recovery (25–31 s after onset) (n = 26).

Ch	Hb/direction	Epoch (s)	MNI (X, Y, Z)	Brain region	p value	Cohen's d	95% CI for d
2	HbO↓	4–10	48, 41, 14	IFGtri, R	0.0494	0.64	0.20–1.08
19	HbO↓	4–10	−28, 38, 20	MFG, L	0.0495	0.68	0.23–1.12
21	HbO↓	4–10	−36, 31, 25	IFGtri, L	0.00283	1.00	0.50–1.49
13	HbO↑	25–31	1, 51, 22	MFG, L	0.00607	0.87	0.39–1.34
14	HbO↑	25–31	−3, 44, 28	SFG, L	0.000608	1.14	0.62–1.65
21	HbO↑	25–31	−36, 31, 25	IFGtri, L	0.0337	0.83	0.37–1.30
7	HbR↓	25–31	29, 35, 27	MFG, R	0.0282	0.79	0.33–1.26

Note. The 4–10 s epoch represents active breath retention, and the 25–31 s epoch represents post-release recovery. Exact p values, paired-samples Cohen's d, 95% confidence intervals, and FDR-corrected results are reported. MNI coordinates are given in Montreal Neurological Institute space. ↑, increase; ↓, decrease; Ch, channel; CI, confidence interval; L, left; R, right.

3.2. Affective Image Task

The affective image task produced condition-specific increases in prefrontal HbO and HbR. Spatial distributions are summarized in Figure 23, channel-level statistics in Tables 6a–6c, and representative response profiles in Figure 24 and Figure 25.

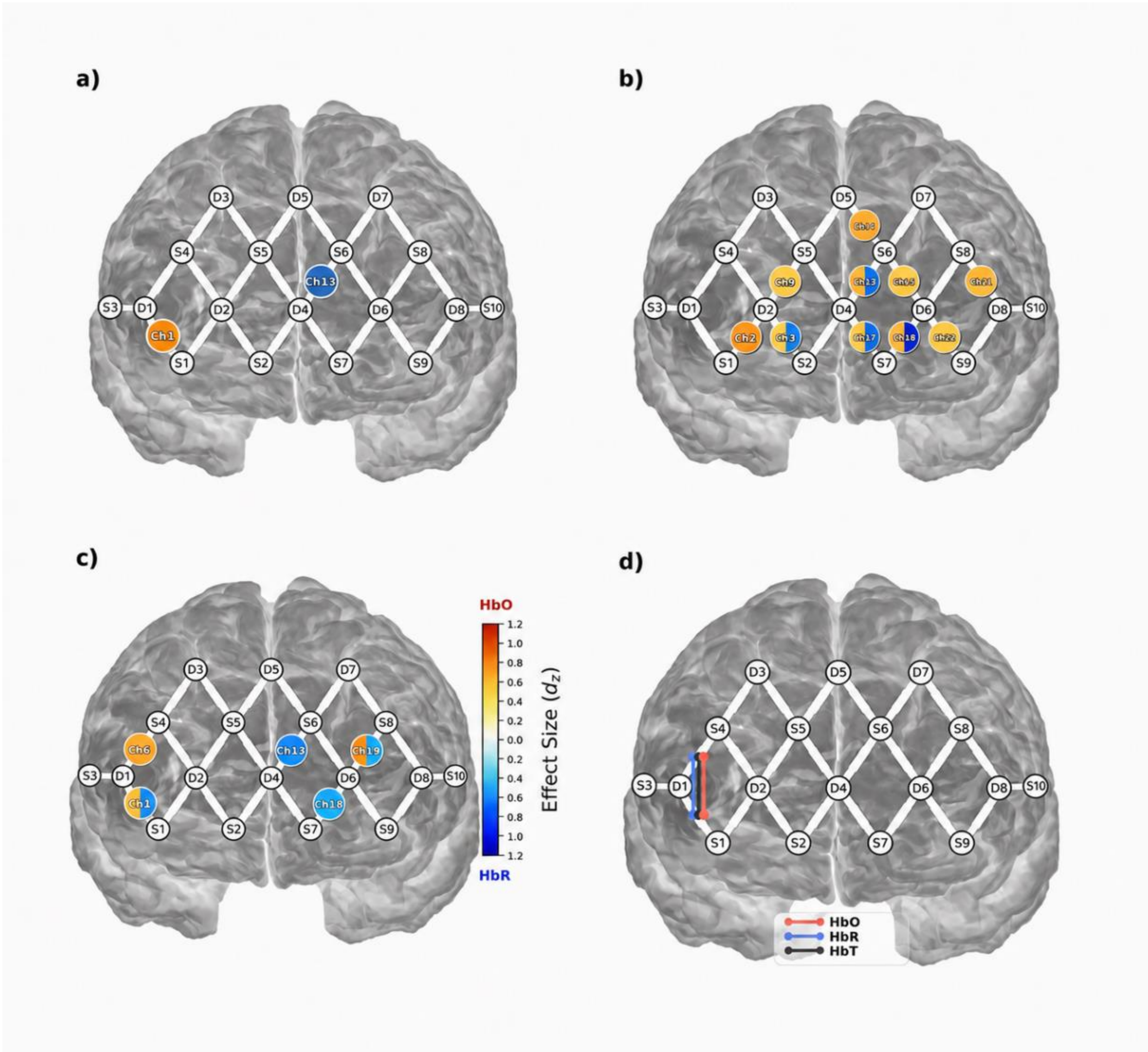

Figure 23. Prefrontal changes during (a) neutral, (b) negative, and (c) positive image conditions, and (d) resting-state connectivity in the right IFG. Warm and blue markers indicate HbO and HbR effects, respectively; line colors in panel (d) indicate HbO, HbR, and total hemoglobin (HbT).

3.2.1. Neutral and Positive Conditions

Neutral images increased HbO in the right IFGtri and HbR in the left MFG (Table 6a; Figures 23a and 24a). Positive images increased HbO in three bilateral prefrontal channels and HbR in four bilateral channels (Table 6c; Figures 23c and 24b–c).

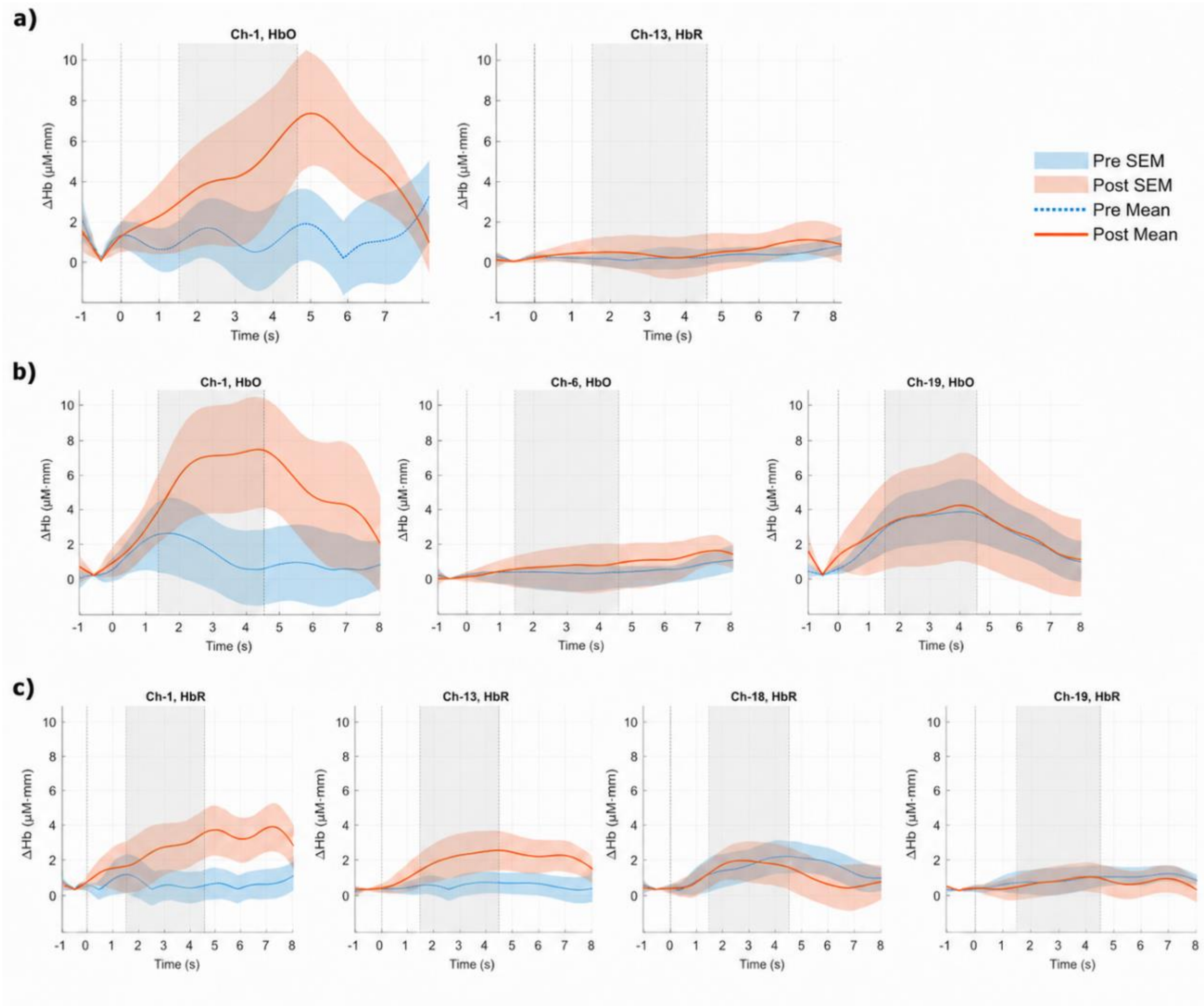

Figure 24. Hemodynamic response profiles for (a) neutral and (b–c) positive image conditions. Mean ± SEM ΔHb time courses (μM·mm) are shown before (blue) and after (orange) the program. Dashed vertical lines indicate stimulus onset, and gray bands indicate the 1.5–4.5 s analysis window.

3.2.2. Negative Condition

Negative images elicited the broadest response, with HbO increases across 10 bilateral prefrontal channels and HbR increases in four overlapping channels (Table 6b; Figures 23b and 25).

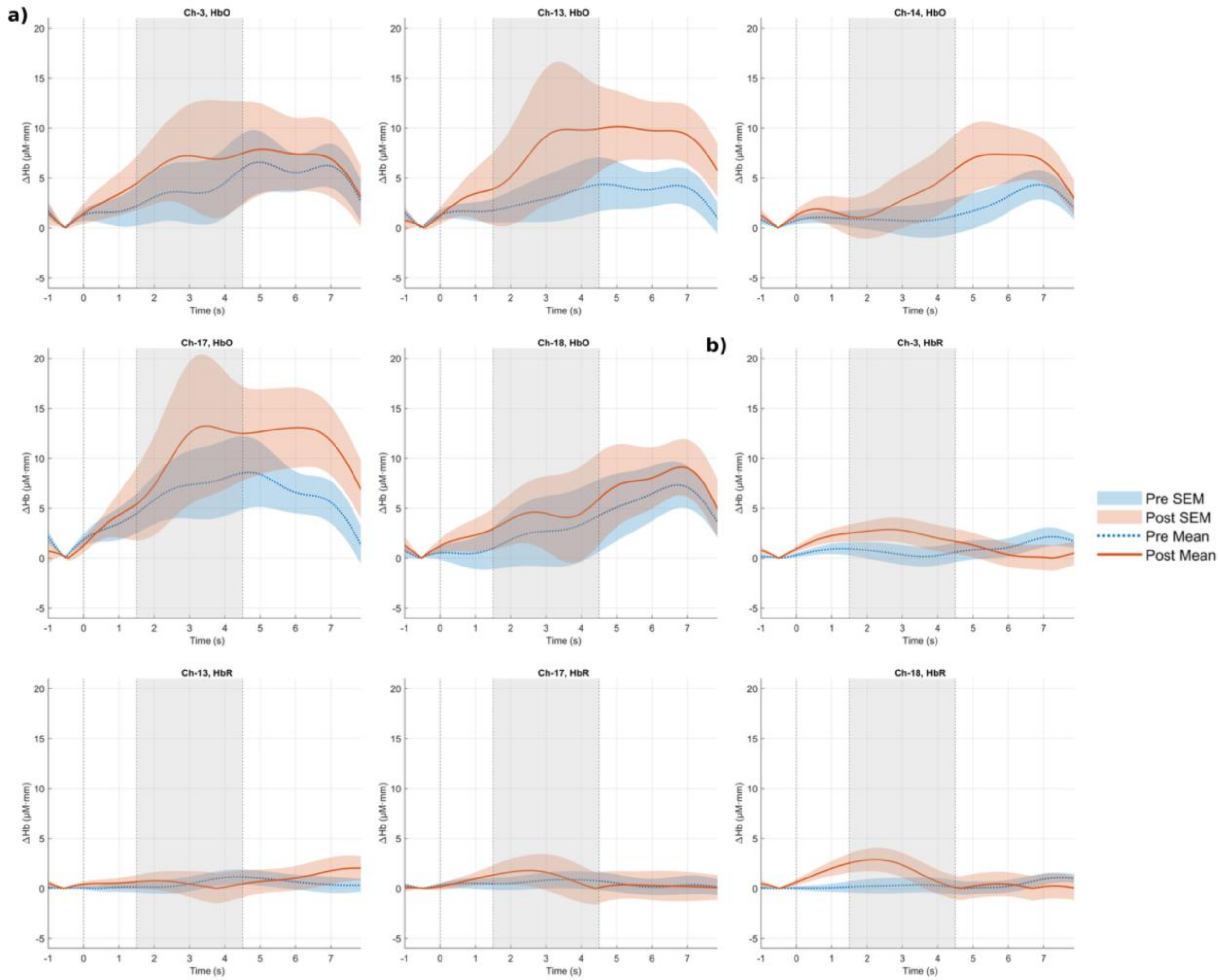

Figure 25. Representative hemodynamic response profiles for the negative image condition. Mean ± SEM ΔHb time courses (μM·mm) are shown for (a) HbO and (b) HbR before (blue) and after (orange) the program. Dashed vertical lines indicate stimulus onset, and gray bands indicate the 1.5–4.5 s analysis window. All significant channels are listed in Table 6b.

Table 6a. Significant pre- to post-program increases in HbO and HbR during the neutral image condition (n = 26).

Channel	Hb type	MNI (X, Y, Z)	Brain region	p value	Cohen's d	95% CI for d
1	HbO	63, 24, 17	IFGtri, R	0.000545896	0.65	0.20–1.09
13	HbR	1, 51, 22	MFG, L	0.000192452	0.65	0.21–1.10

Table 6b. Significant pre- to post-program increases in HbO and HbR during the negative image condition (n = 26).

Channel	Hb type	MNI (X, Y, Z)	Brain region	p value	Cohen's d	95% CI for d
2	HbO	48, 41, 14	IFGtri, R	0.003794861	0.72	0.26–1.17
3	HbO	20, 56, 14	SFGmed, R	0.01351414	0.44	0.01–0.86
9	HbO	29, 45, 27	MFG, R	0.002321302	0.47	0.04–0.90
13	HbO	1, 51, 22	MFG, L	0.03266655	0.64	0.20–1.08
14	HbO	−3, 44, 28	SFG, L	2.67×10^{-5}	0.64	0.20–1.09
15	HbO	−19, 46, 19	MFG, L	0.034831214	0.46	0.03–0.88
17	HbO	−2, 55, 13	SFGmed, L	0.049694201	0.48	0.05–0.90
18	HbO	−21, 50, 10	SFGmed, L	0.000366548	0.58	0.14–1.01
21	HbO	−36, 31, 25	IFGtri, L	0.004806065	0.55	0.12–0.98
22	HbO	−41, 44, 10	IFGtri, L	0.01079133	0.48	0.06–0.91
3	HbR	20, 56, 14	SFGmed, R	0.031479306	0.63	0.19–1.07
13	HbR	1, 51, 22	MFG, L	0.002440693	0.68	0.23–1.13
17	HbR	−2, 55, 13	SFGmed, L	0.000289653	0.70	0.25–1.16
18	HbR	−21, 50, 10	SFGmed, L	7.66×10^{-7}	0.92	0.44–1.40

Table 6c. Significant pre- to post-program increases in HbO and HbR during the positive image condition (n = 26).

Channel	Hb type	MNI (X, Y, Z)	Brain region	p value	Cohen's d	95% CI for d
1	HbO	63, 24, 17	IFGtri, R	0.038996319	0.59	0.15–1.03
6	HbO	44, 26, 28	IFGtri, R	0.04663184	0.62	0.18–1.06
19	HbO	−28, 38, 20	MFG, L	0.006714799	0.84	0.37–1.31
1	HbR	63, 24, 17	IFGtri, R	0.007336049	0.57	0.13–1.00
13	HbR	1, 51, 22	MFG, L	0.003073776	0.60	0.16–1.04
18	HbR	−21, 50, 10	SFGmed, L	0.005958626	0.51	0.08–0.94
19	HbR	−28, 38, 20	MFG, L	0.029610575	0.47	0.05–0.90

Note. Exact p values, paired-samples Cohen's d, 95% confidence intervals, and FDR-corrected results are reported. MNI coordinates are given in Montreal Neurological Institute space. CI, confidence interval; IFGtri, triangular part of the inferior frontal gyrus; L, left; MFG, middle frontal gyrus; R, right; SFG, superior frontal gyrus; SFGmed, medial superior frontal gyrus.

3.3. Resting-State Functional Connectivity

No individual connection survived FDR correction. Network-Based Statistics identified a significant right IFG component linking channels S1D1 and S4D1, with greater post-program connectivity for HbO, HbR, and HbT (all $p < 0.001$; effect size = 0.23–0.25; Figure 23d; Table 7).

Table 7. Significant post-program increase in resting-state functional connectivity within the right inferior frontal network (n = 26).

Chromophore	Connection	p value	t statistic	Effect size (t/√n)
HbO	S1D1–S4D1	<0.001	1.22	0.24
HbR	S1D1–S4D1	<0.001	1.26	0.25
HbT	S1D1–S4D1	<0.001	1.17	0.23

Note. Permutation p values are reported as $p < 0.001$. Effect size was calculated as $t/\sqrt{n}$. D, detector; HbT, total hemoglobin; NBS, Network-Based Statistics; S, source.

3.4. Biochemical Results

Total cholesterol ($t = 2.66$, $p = 0.013$) and plasma oxytocin ($W = 199$, $p < 0.001$) decreased significantly after the program. Cortisol, prolactin, triglycerides, and uric acid did not change significantly (Table 8; Figure 26a).

Table 8. Biochemical markers before and after the 30-day yoga program.

Measure	Pre-program	Post-program	n	Test statistic	p value
Oxytocin* (pg/mL)	523.8 (423.5–578.9)	343.8 (286.4–394.1)	20	W = 199	<0.001
Total cholesterol* (mg/dL)	184.8 ± 33.42	174.6 ± 30.80	26	t = 2.66	0.013
Prolactin (ng/mL)	15.05 (12.00–21.89)	17.05 (11.05–29.12)	26	W = 125	0.200
Uric acid (mg/dL)	5.775 ± 1.417	5.292 ± 1.071	26	t = 1.24	0.227
Triglycerides (mg/dL)	120.0 (75.2–214.5)	110.5 (80.2–173.5)	26	W = 193	0.657
Cortisol (ng/mL)	125.8 ± 34.26	136.7 ± 58.93	26	t = −1.19	0.247

Note. Values are mean ± SD for normally distributed variables and median (Q1–Q3) otherwise. Paired t tests or two-sided Wilcoxon signed-rank tests were used as appropriate. n = 20 for oxytocin and n = 26 for all other markers. * Significant pre- to post-program difference ($p < 0.05$). Q1–Q3, first to third quartiles; W, Wilcoxon signed-rank statistic.

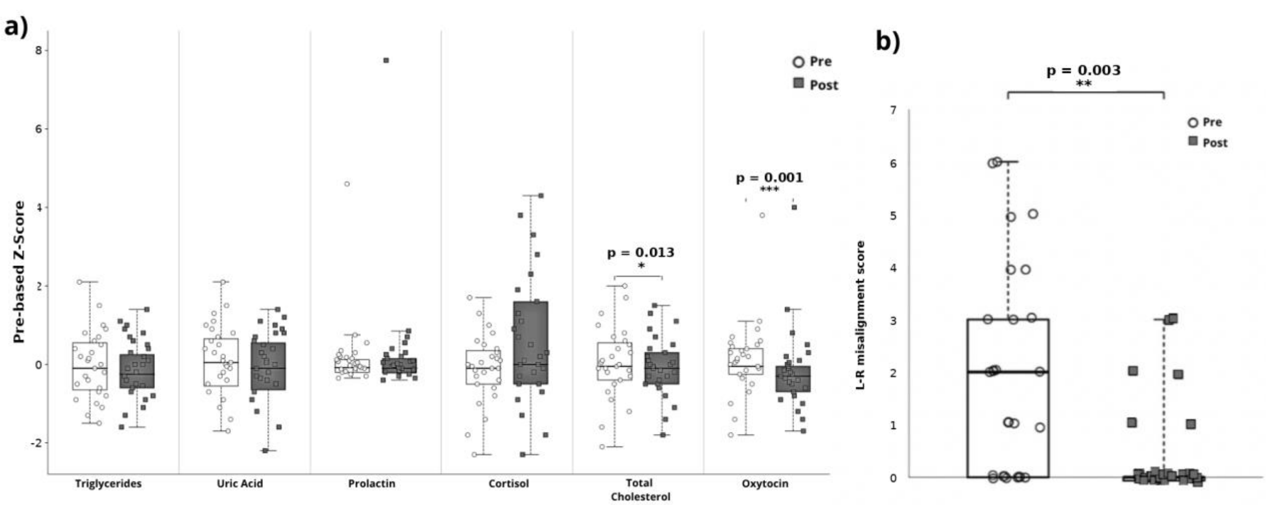

Figure 26. Biochemical and postural outcomes before and after the program. (a) Biochemical markers expressed as z scores standardized to the baseline distribution; total cholesterol and oxytocin decreased significantly. (b) Individual left–right mediolateral misalignment scores before and after the program (n = 27); misalignment decreased significantly (Wilcoxon signed-rank test, $p = 0.003$).

3.5. Postural Results

Among 27 participants with paired postural data, median mediolateral center-of-pressure misalignment decreased from 2 (IQR, 0–3) before the program to 0 (IQR, 0–0) afterward ($p = 0.003$; Table 9; Figure 26b). Detailed FreeMed output is provided in Supplementary Figure 2.

Table 9. Left–right mediolateral center-of-pressure misalignment before and after the 30-day yoga program (n = 27).

Parameter	Pre-program	Post-program	p value
Mean ± SD	1.96 ± 2.14	0.44 ± 0.97	
Median (IQR)	2 (0–3)	0 (0–0)	
Range (min–max)	0–6	0–3	
95% CI for the mean	1.12–2.81	0.06–0.83	
Shapiro–Wilk W (p)	0.821 (0.0002)*	0.831 (<0.0001)*	
Pre- versus post-program comparison			0.003†

Note. Values are mean ± SD, median (IQR), range, or 95% CI, as indicated. Normality was assessed with the Shapiro–Wilk test; the pre- to post-program comparison used a two-sided Wilcoxon signed-rank test (S = −114.00). * Significant departure from normality ($p < 0.05$). † Significant pre- to post-program difference ($p < 0.05$).

3.6. Participants' Perceptions of the Yoga Program: Likert Scale Results

Responses among the 28 respondents were predominantly positive (see Figure 27). The proportion of responses endorsing improvement was generally higher at Day 30 than at Day 15. Body awareness, physical well-being, energy, and sleep showed the highest ratings, whereas ratings for social relationships were more moderate. Respondents reported reduced pain across all assessed regions, especially the back and neck, and most respondents completing the menstruation-related items reported perceived improvement (Tables 10 and 11). Item-level distributions and anonymized data are provided in the Zenodo repository.

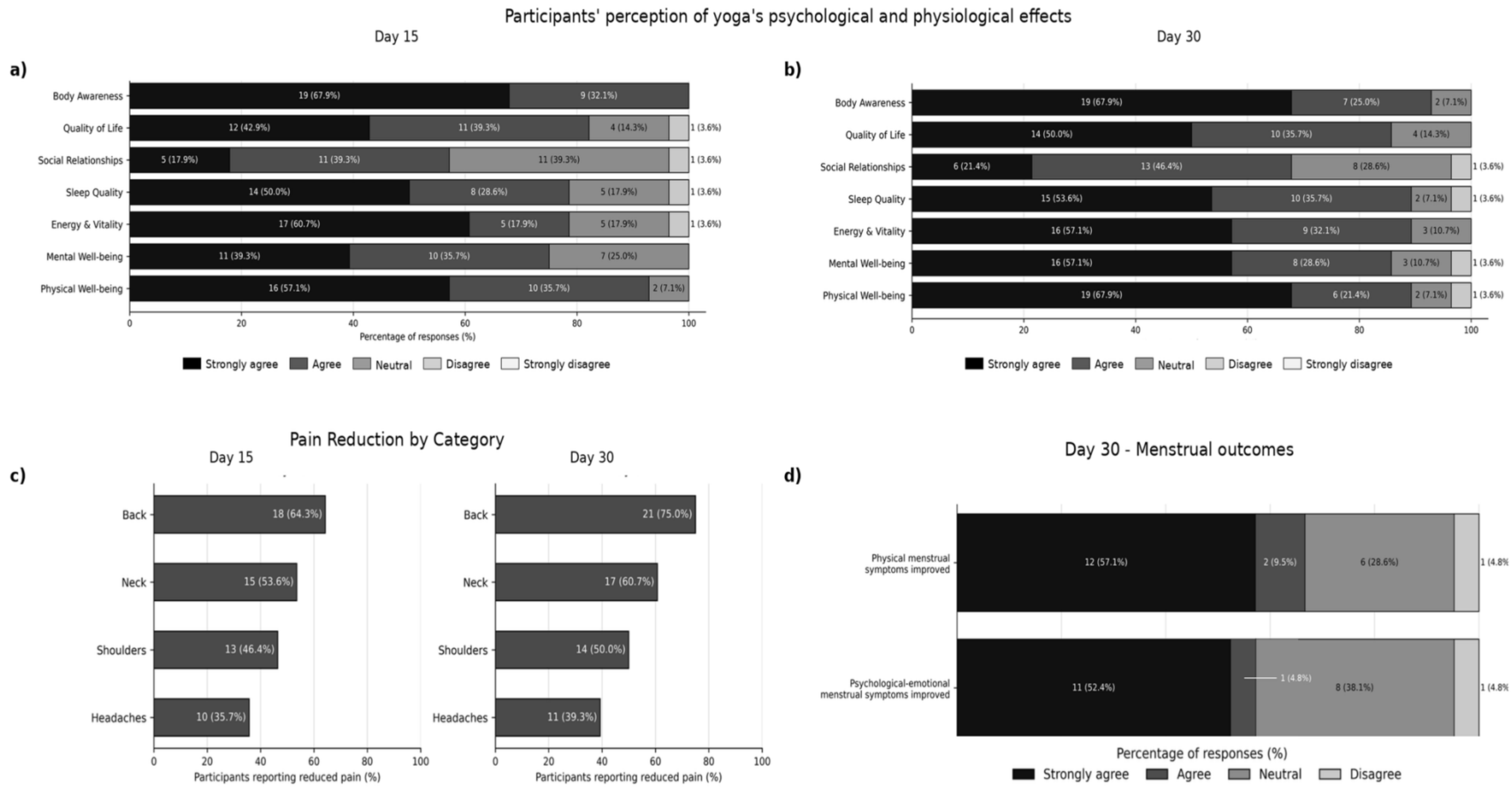

Figure 27. Self-reported outcomes during the 30-day yoga program. (a) Domain-level Likert response distributions on Day 15. (b) Domain-level Likert response distributions on Day 30. (c) Percentage of participants reporting reduced pain by body area on Days 15 and 30. (d) Likert response distributions for perceived improvements in menstruation-related physical and psychological/emotional symptoms on Day 30.

Table 10. Agreement with yoga-related outcomes by domain at Day 15 and Day 30 (n = 28).

Domain	Day 15 agreement, n/N (%)	Day 30 agreement, n/N (%)	Difference (percentage points)
Body Awareness	28/28 (100.0)	26/28 (92.9)	-7.1
Quality of Life	24/28 (85.7)	24/28 (85.7)	0.0
Social Relationships	16/28 (57.1)	19/28 (67.9)	+10.7
Sleep Quality	22/28 (78.6)	25/28 (89.3)	+10.7
Energy & Vitality	23/28 (82.1)	25/28 (89.3)	+7.1
Mental Well-being	20/28 (71.4)	24/28 (85.7)	+14.3
Physical Well-being	26/28 (92.9)	25/28 (89.3)	-3.6

Note. Agreement was defined as the combined proportion of strongly agree and agree responses.

Table 11. Additional self-reported outcomes during the 30-day yoga program: pain reduction and menstruation-related improvement

Outcome category	Outcome	Day 15, n/N (%)	Day 30, n/N (%)	Difference (percentage points)
Pain reduction	Back	18/28 (64.3)	21/28 (75.0)	+10.7
Pain reduction	Neck	15/28 (53.6)	17/28 (60.7)	+7.1
Pain reduction	Shoulders	13/28 (46.4)	14/28 (50.0)	+3.6
Pain reduction	Headaches	10/28 (35.7)	11/28 (39.3)	+3.6
Menstruation-related improvement	Physical menstrual symptoms improved	—	14/21 (66.7)	—
Menstruation-related improvement	Psychological/emotional menstrual symptoms improved	—	12/21 (57.1)	—

Note. Pain-reduction outcomes are based on all respondents at Day 15 and Day 30 (n = 28). Because questionnaires were anonymous, responses could not be paired; differences represent the Day 30 aggregate percentage minus the Day 15 aggregate percentage. Menstruation-related outcomes were assessed at Day 30 only among respondents for whom the items were applicable (n = 21); 'not applicable' responses were excluded from the denominator. Em dashes indicate that an item was not assessed at that time point or that a difference was not calculated. Percentages are rounded to one decimal place.

3.6.1. Open-Ended Written Responses

Open-ended responses converged on emotional regulation, embodied awareness, energy and daily functioning, psychological benefit, and the supportive instructional environment, with benefits perceived as strengthening over time (Supplementary Table 10).

3.7. Qualitative Interview Results

Interviews (n = 15) yielded six themes: emotional and psychological benefits, physical health, social and interpersonal effects, cognition, lifestyle change, and sleep. These themes closely paralleled the questionnaire findings. Emotional regulation was most prominent; participants described greater present-moment awareness and an ability to pause before reacting. As one participant explained, “Yoga taught me to take a moment of pause before reacting.”

Participants also reported increased energy and flexibility; improved posture, sleep, and concentration; pain relief, including one participant’s reported reduction in fibromyalgia-related symptoms; healthier behaviors; greater empathy and a stronger sense of community; and reduced interpersonal conflict. Illustrative comments included, “Since I started practicing yoga, I have slept much better” and “I try to understand people more and avoid heated discussions.” Several participants reported forming new friendships that they intended to maintain and expressed an intention to continue practicing; instructor quality and the learning environment were frequently identified as supporting engagement and perceived safety. Expanded qualitative findings are provided in the Supplementary Results under “Expanded qualitative findings.”

4. Discussion

Using a mixed-methods framework suited to yoga’s integrated psychophysical model [277], this study identified convergent neural, biochemical, postural, and subjective changes after 30 sessions. The program was associated with altered PFC responses during the Breath-Holding Task and Affective Image Task, increased right IFG resting-state connectivity, reduced cholesterol and oxytocin, improved mediolateral alignment, and participant-reported gains in sleep, physical and emotional well-being, pain, social connection, and self-awareness. These multidomain findings are summarized in Figure 28.

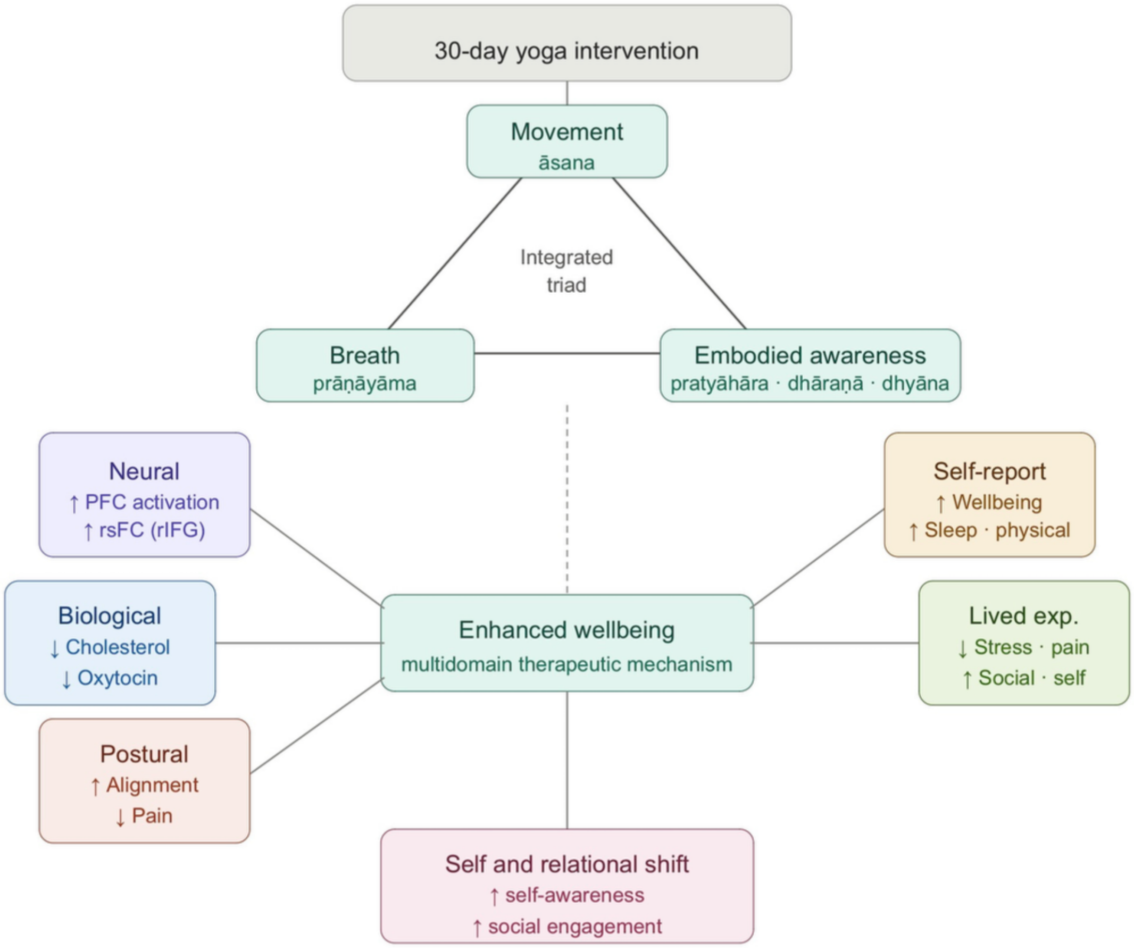

Figure 28. Proposed multidomain effects of a 30-day yoga program. Movement (*āsana*), breath (*prāṇāyāma*), and embodied awareness (*pratyāhāra*, *dhāraṇā*, *dhyāna*) are shown as an integrated triad converging on enhanced well-being. Associated changes were observed across neural, biological, postural, self-report, and lived-experience domains, including prefrontal activation and connectivity, posture, cholesterol, oxytocin, pain, sleep, self-awareness, and social connectedness.

4.1. Breath

Breath holding produced the expected cerebrovascular pattern, with a larger post-program HbO decline during retention and rebound after release [278]. Controlled breathing can increase heart rate variability, modulate cortisol and inflammatory signaling, and promote more efficient autonomic recovery [279]. Accordingly, the stronger post-release HbO rebound may reflect improved cerebrovascular reactivity and autonomic recovery. Because the affected PFC regions support cognitive control, interoception, and emotion regulation and are altered in anxiety and depression [96], [201], [203], [208], [266], [280], these changes may provide a neurophysiological correlate of participants' reported improvements in well-being and social functioning.

4.2. Affective Image Task

The affective task showed the broadest PFC response to negative images, consistent with preferential processing of emotionally salient negative stimuli [281]. Seven of the 10 significant HbO channels were left-lateralized, consistent with valence-lateralization models [203], [282] and, more tentatively, with the account of narrower, categorical processing in the left hemisphere for stimuli eliciting disgust and anger [79]–[82]. The limited neutral response suggests that affective salience, rather than visual stimulation alone, contributed to the pattern.

Right IFGtri activation appeared for neutral and positive but not negative images, possibly reflecting differential hemispheric recruitment during negative processing [80], [81], [203], [282].

The overlapping HbO and HbR effects provide stronger evidence of regionally specific neurovascular engagement than changes in either chromophore alone. In the negative condition, all four channels showing significant HbR changes also exhibited significant HbO effects, while Channels 1 and 19 showed the same convergence in the positive condition. Because coordinated changes in both chromophores are more consistent with a localized hemodynamic response and help distinguish cortical activation from systemic physiological noise [145], this pattern strengthens the interpretation that the observed response reflects localized cortical engagement rather than a purely autonomic artifact [279]. Given the roles of the PFC in emotion regulation, social cognition, mentalizing, and inhibitory control [283], [284], these neurovascular changes may be related to participants' reported increases in empathy, social connectedness, and ability to pause before reacting.

4.3. Functional Connectivity

Although no individual connection survived FDR correction, network-based statistics identified increased connectivity within the right inferior frontal gyrus (rIFG). This contrasts with the acute effects observed after a single 23-minute yoga session using the same device in a comparable population [20], suggesting that the connectivity changes observed 48 hours to 5 days after the final session may reflect delayed or more sustained effects rather than immediate network responses. The rIFG supports inhibitory control [285], [286], while right-hemisphere networks more broadly contribute to interoception and affective empathy [79]–[82], [287]–[289]. This pattern cautiously aligns with participants' reports of greater body awareness, pausing before reacting, and improved relationships.

4.4. Biochemical

The reduction in cholesterol is consistent with reported yoga-related improvements in lipid metabolism and cardiovascular health [290]. Participants also reported improved menstrual symptoms, aligning with evidence for stretching and yoga in dysmenorrhea and quality of life [291], [292]. These findings support further study of yoga as an accessible nonpharmacological approach to menstrual health. Oxytocin also decreased, but this exploratory result requires caution because peripheral concentrations vary with social context, menstrual-cycle phase, and contraceptive use [293]–[296].

4.5. Posture

Improved mediolateral alignment may represent both neuromuscular adaptation and a contributor to psychological well-being. Upright posture has been associated with positive affect, self-efficacy, and reduced depressive rumination [27], [297], while postural correction may reduce mechanical load and improve musculoskeletal function [298]. Previously reported associations among proprioceptive awareness, interoception, and posture [157], [299] also align with participants' reports and the right-lateralized neural findings. Postural change may therefore be one pathway through which yoga influences embodied well-being [27], [28], [300].

4.6. Subjective Measures

Participants reported improvements in physical health, sleep, stress regulation, pain, energy, emotional well-being, social connection, and self-awareness, consistent with prior yoga research [159], [164]. Reports of better emotional coping and bodily awareness align with proposed interoceptive mechanisms of yoga [9], [301], [302]. Improved empathy, communication, and social connection also suggest that relational context may contribute to community-based yoga outcomes [303]–[305]. Together, these accounts indicate that participants experienced yoga as more than physical exercise, encompassing self-perception, emotion regulation, and relational engagement. Their convergence with objective measures supports an integrated, though noncausal, interpretation of embodied change.

5. Conclusions

This exploratory mixed-methods study examined yoga as a coordinated embodied practice rather than as a set of isolated components. Following 30 sessions, changes in prefrontal activity and connectivity, postural alignment, selected biochemical markers, and participants' reported physical, emotional, and interpersonal functioning formed a multidimensional pattern spanning neural, postural, and experiential domains.

These findings are consistent with evidence that embodied practices such as yoga may support mood and stress regulation and psychosocial functioning through body awareness and interoception [19], [300], [306], [307]. They also reinforce calls to incorporate physical and embodied interventions into mental health care [19], [147]–[150] and to use mixed-methods approaches that connect neurophysiological data with first-person evidence [14], [153].

The present design was intended to identify coordinated patterns rather than establish efficacy. Future studies could strengthen causal inference through appropriate comparators, independent instructors, and the incorporation of diaries, experience sampling, or longitudinal qualitative methods to capture contextual and within-participant change [308]–[311]. Further research should also expand neuroimaging coverage, standardize endocrine sampling according to menstrual-cycle phase and contraceptive use, and include morning and evening cortisol measurements to characterize diurnal rhythm [55], [312], [313].

Together, the neural, postural, biochemical, and experiential findings support the rationale outlined in the Introduction for considering yoga as an accessible adjunct to conventional mental health care. The results align with prior evidence of benefits for depression, anxiety, stress, trauma-related distress, psychological well-being, and quality of life [17], [19], [251], [252], as well as research suggesting that yoga may support more attuned intrapersonal and interpersonal functioning through embodied processes in which movement, breath, and bodily awareness influence brain function and perception [21], [69], [314], [315]. The observed improvement in postural alignment is particularly relevant to this framework, as bodily change may represent both a marker of adaptation and one pathway through which broader neurological and psychological changes emerge. These findings may be especially meaningful amid growing concerns about social disconnection and loneliness [316], [317], their intensification following the COVID-19 pandemic [250], [318], the persistent global decline in psychological well-being [319], [320], and the concurrent rise in depression and anxiety [321].

Discussion

"The individual mind is not confined within the head, but extends throughout the living body."
— Thomas Fuchs

"Different from and within the self made of food is the self made of vital breath. Different from and within the self made of vital breath is the self made of mind. Different from and within the self made of mind is the self made of discernment. Different from and within the self made of discernment is the self made of bliss."
—Taittirīya Upaniṣad, 2.2–2.5

Erwin Schrödinger described human inquiry as a "longing for unified, all-embracing knowledge" and a need to synthesize what is known into a whole. Responding to that challenge, this thesis examines yoga as an embodied, multidimensional regulatory practice through three linked studies that progress from methodological feasibility to acute cortical effects and longitudinal changes across neural, biochemical, postural, and experiential domains.

Hypothesis 1: Methodological Feasibility of fNIRS During Yoga *Āsana*

H1 was supported. Article 1, *Resting-State Connectivity and Neuroimaging of Prefrontal Cortex Activity During a Block-Design Yoga Asana Practice Using fNIRS*, demonstrated that functional near-infrared spectroscopy can detect and analyze cortical hemodynamic changes during movement-based yoga *āsana* when appropriate signal filtering, motion-artifact correction, and statistical procedures are applied. The protocol recorded changes in oxygenated and deoxygenated hemoglobin during physically demanding postures, including inversions and backbends, thereby establishing fNIRS as a feasible method for investigating embodied practices that are difficult to examine using movement-restrictive neuroimaging methods.

Hypothesis 2: Acute Effects of Yoga *Āsana* on Prefrontal Cortical Activity

H2 was supported. Article 2, *Yoga Asana Increases Prefrontal Cortex Activity and Reduces Resting-State Functional Connectivity*, found that all three active yoga postures produced significant increases in prefrontal cortical activity relative to the control posture, with the strongest effects observed in the right prefrontal cortex. Following the 23-minute *āsana* sequence, resting-state functional connectivity decreased primarily within the left medial prefrontal cortex. These findings demonstrate an immediate association between bodily form and cortical hemodynamic activity during and following *āsana* practice, although they do not establish a causal pathway linking a particular posture to a specific psychological outcome.

Hypothesis 3: Longitudinal and Multidimensional Effects of Sustained Yoga Practice

H3 was broadly supported, with qualification. Following the 30-day program, Article 3, *Neural, Biochemical, Postural, and Subjective Outcomes Following a 30-Day Yoga Program: A Multimodal Mixed-Methods Study*, identified condition-specific changes in oxygenated hemoglobin (HbO) and deoxygenated hemoglobin (HbR) during breath-related and affective-image tasks; altered connectivity within a right inferior frontal resting-state network across HbO, HbR, and total hemoglobin (HbT); decreases in total cholesterol and oxytocin; improved mediolateral postural alignment; and reported improvements in body awareness, pain, sleep, psychological well-being, and interpersonal relationships. Cortisol, prolactin, triglycerides, and uric acid did not change significantly.

The convergence of significant findings across several domains, rather than change in a single measured variable, supports the use of a multimodal psychophysiological framework for examining the potentially interconnected effects of sustained yoga practice. This convergence does not, however, establish a unified causal mechanism or demonstrate that yoga alone produced the observed changes.

The Five *Kośas* and Eight Limbs as an Embodied Interpretive Synthesis

The integration of yogic philosophy within this discussion is intended to preserve the intellectual and cultural context from which yoga emerged rather than reducing a complex, millennia-old tradition to categories derived exclusively from contemporary Western science. Interpreting yoga only through neurobiological or psychological paradigms risks reproducing a form of epistemic appropriation in which traditional knowledge is considered meaningful only after it has been translated into—and validated by—Western conceptual frameworks. The *kośas*, *guṇas*, *māyā*, and *aṣṭāṅga* are therefore engaged as historically and culturally situated philosophical accounts of embodied experience, perception, action, and self-regulation. They were not measured as empirical variables and are not proposed as direct equivalents to neurobiological models. Instead, they provide a complementary interpretive framework through which the empirical findings may be considered without collapsing either system of knowledge into the other. Throughout this synthesis, conclusions supported directly by the data are distinguished from broader interpretations informed by previous scientific literature and yogic philosophy.

Taken together, the studies support an embodied account of yoga in which posture, breath, attention, action, and lived experience participate in cognition and self-regulation rather than operating upon a mind conceived as separate from the body. As Merleau-Ponty states, “the body is our general medium for having a world” [322, p. 146]. McGilchrist extends this critique of

Cartesian separation by arguing that knowledge becomes distorted when lived reality is reduced to isolated and abstract components [79], [82]. Within his account of hemispheric specialization, the left hemisphere tends to narrow, categorize, and manipulate experience, whereas the right hemisphere is more attuned to context, relationship, novelty, and the apprehension of the whole [79], [81], [82].

Yoga's traditional frameworks offer a complementary account of this embodied and relational organization. The five *kośas* describe interdependent dimensions of human experience, while the eight limbs identify disciplines through which these dimensions may be engaged and integrated. *Āsana* addresses posture and movement; *prāṇāyāma*, breath and physiological regulation; *pratyāhāra*, sensory and interoceptive regulation; *dhāraṇā* and *dhyāna*, focused attention and sustained awareness; *yama* and *niyama*, the ethical and relational foundations of practice; and *samādhi*, their most integrative expression through personal agency.

Long before the development of neuroimaging, biochemical assays, and standardized psychometric instruments, yogic practitioners examined human transformation through sustained practice, disciplined self-observation, and the observation of others. Their experiences were organized through the philosophical concepts and cultural language available to them. Contemporary scientific measurement neither validates these traditional categories as empirical constructs nor renders them obsolete. Rather, it introduces additional levels of description through which phenomena historically recognized through first-person and relational observation may be examined in neural, physiological, postural, psychological, and behavioral terms.

A mixed-methods approach is particularly well suited to this dialogue. Quantitative measures identify patterns, magnitudes, and group-level differences, while interviews and first-person accounts clarify how changes are experienced, interpreted, and incorporated into participants' lives. Measurement establishes change within specific domains; lived accounts provide its context and meaning. Their integration avoids reducing transformation either to numerical variables alone or to subjective description without physiological context.

The *kośas* provide an interpretive structure for examining this convergence of evidence. They are not presented as variables directly operationalized or tested in the studies, nor is a one-to-one correspondence assumed between traditional categories and contemporary measurements. Instead, each *kośa* identifies a dimension of human experience to which particular methods and findings may be meaningfully related. Annamaya *Kośa* provides a lens for interpreting postural and bodily findings; Prāṇamaya *Kośa*, changes associated with breath, physiological regulation, and biochemical processes; Manomaya *Kośa*, emotional, cognitive, and subjective experience; Vijñānamaya *Kośa*, prefrontal function, awareness, discernment, and self-regulation; and Ānandamaya *Kośa*, broader experiences of well-being, coherence, and integration. The following sections examine each *kośa* in turn, relating these interpretive dimensions to the measurements and findings reported across the three studies.

Annamaya *Kośa* - Structural and Biomechanical Regulation

Alignment-based *āsana* may influence posture, spinal organization, and respiratory mechanics. Over the 30-day intervention, significant improvements in physical alignment were observed alongside decreased cholesterol levels. Because the study lacked a control group, these changes cannot be attributed to yoga alone; however, their co-occurrence may reflect broader structural and metabolic adaptation and warrants controlled replication. Improved postural organization may support thoracic mobility and respiratory efficiency [323], [324], while respiratory patterns are associated with autonomic regulation through vagal mechanisms and heart-rate variability [325], [326]. Embodied cognition research further suggests that posture is associated with affective processing and memory recall [327], [328]. Taken together, these findings are consistent with the possibility that structural changes at this layer may contribute to broader neural, autonomic, and emotional regulation.

Prāṇamaya *Kośa* - Vital Energy and the Breath Body

Acutely, the 23-minute *āsana* protocol was associated with increased oxygenated hemoglobin (HbO) in the prefrontal cortex (PFC), with inversions producing greater hemodynamic responses than backbends and both exceeding Tadasana. These findings suggest posture-related differences in cortical oxygenation during *āsana* practice. Longitudinally, post-intervention responses showed a more differentiated HbO pattern across the breath-holding and recovery phases, rather than a simple overall elevation in PFC oxygenation. This pattern may reflect changes in the temporal regulation of cerebrovascular responses following 30 days of practice, although the absence of a control group limits causal interpretation. Qualitative interviews provided a complementary experiential perspective, with participants reporting greater awareness of breathing and bodily sensation. The convergence of these findings suggests that changes in breath-related hemodynamic responses were accompanied by increased interoceptive awareness, without implying that one directly caused the other. These observations are consistent with research showing that respiratory modulation and hypercapnic challenges alter cerebral blood flow measurable through NIRS [329], [330], and that repeated physical training may modify prefrontal hemodynamic responses over time [331], [332].

Manomaya *Kośa* - State-Dependent Emotional Appraisal

Manomaya *Kośa* corresponds to the cortical appraisal of embodied affect — the layer at which physiological states become interpreted as emotion [95], [333]. Acutely, the 23-minute protocol elicited predominantly right-hemispheric activation during movement, while longitudinally, participants showed increased left PFC activation in response to emotionally salient negative stimuli, which may be consistent with altered affective appraisal. Frontal asymmetry research associates left PFC activity with the evaluation of aversive material [334], [335], suggesting heightened emotional responsiveness rather than suppression. In participants' reports, greater empathy alongside an improved capacity to pause before responding was shared. This dissociation between affective sensitivity and behavioral reactivity is consistent with models in which PFC engagement supports the elaboration of emotional experience without automatized discharge [336], [337], and foreshadows the inhibitory reorganization indexed at the Vijñānamaya layer.

Vijñānamaya *Kośa* - Trait-Level Regulatory Reorganization and Discernment

In classical yoga philosophy, Vijñānamaya *Kośa* is associated with wisdom, intuition, and discernment—the capacity to perceive clearly, distinguish relevant information from background noise, and respond through awareness rather than automatic reactivity. In this thesis, this concept is used as an interpretive lens rather than as an empirical variable directly measured by the research protocols. Resting-state functional connectivity (rsFC), which indexes patterns of temporal association among cortical hemodynamic signals in the absence of an explicit task, provides one neurophysiological perspective from which changes in intrinsic network organization may be examined [260], [338].

Acutely, reduced resting-state functional connectivity within the left medial prefrontal cortex following the 23-minute *āsana* session may reflect a temporary alteration in intrinsic network organization, potentially involving reduced analytic or evaluative processing. This interpretation remains provisional and should not be understood as a direct measure of discernment or as evidence of hemispheric causation. Longitudinally, altered intrinsic coupling involving the right inferior frontal gyrus (rIFG), a region associated with inhibitory control and response regulation [339], [340], is consistent with changes in regulatory network organization following sustained practice.

Because rsFC reflects statistical covariation rather than direct causal communication between brain regions, these findings cannot establish enhanced inhibitory behavior or a specific regulatory mechanism. Nevertheless, altered rIFG connectivity may indicate greater regulatory flexibility, a changed readiness to modulate automatic responses. In this sense, the findings resonate with the yogic concept of discernment and may represent a possible neurophysiological correlate of this flexibility, consistent with broader accounts linking interoceptive integration, predictive processing, and emotion regulation [341]–[344].

This change in network organization was accompanied by a post-intervention decrease in oxytocin. Although this finding may initially appear counterintuitive, oxytocin is not uniformly associated with prosocial behavior; depending on context, it has also been linked to in-group bias, conformity, and stress-related patterns of social affiliation [345]–[348]. The decrease may therefore point to altered social-affiliative regulation or reduced reactivity, particularly in a cohort whose social and neuroendocrine responses may have been shaped by prolonged pandemic-related isolation [349], [350]. This interpretation remains speculative, however, and cannot be confirmed by the present uncontrolled design; future controlled studies are needed to determine whether the change reflects a meaningful shift in social-affiliative regulation or other physiological processes [294].

Importantly, the neural and biochemical findings converged with participants' subjective reports. Participants described reductions in reactivity, including decreased cigarette use and less escalation during interpersonal conflict, which they experienced not as effortful suppression but as a diminished sense of compulsion. More than half reported improvements in social relationships, alongside reduced anger, a greater capacity to pause before responding, and increased relational awareness.

Within the interpretive framework of this thesis, Vijñānamaya *Kośa* provides a philosophical context for understanding participants' descriptions of pausing, perceiving more clearly, and responding with less compulsion as expressions of discernment or wisdom.

Ānandamaya *Kośa* - Emergent Regulatory Freedom

The findings considered across the four preceding *kośas* suggest a potentially reciprocal and bidirectional pattern of change rather than a linear causal sequence. Changes were observed across postural, respiratory, neural, emotional, and behavioral domains; however, the present study design cannot determine whether changes within any one domain produced those observed in another. The findings of this thesis, together with previous research on *prāṇāyāma*, *āsana*, and meditation, identify autonomic and sympathoadrenal regulation as possible pathways through which stress responses may be modulated [279], [351], [352]. These pathways provide a coherent integrative framework for interpreting the co-occurrence of changes across domains, suggesting a shared regulatory substrate rather than isolated or sequential effects; however, they remain inferential and cannot be construed as demonstrated causal mechanisms within the scope of the present study.

Within this integrative interpretation, *Ānandamaya Kośa* is understood not simply as a state of transient pleasure or bliss, but as a condition of greater regulatory freedom in which strengthened inhibitory regulation, enhanced interoceptive awareness, and improved sensitivity to context may support a more embodied sense of agency. This capacity may be understood as an internal locus of control expressed not only as a cognitive belief, but also through greater flexibility in coping, responding, and adapting to changing circumstances [353], [354]. Neurovisceral integration provides a contemporary scientific framework for interpreting this possibility, proposing that coordinated interactions among autonomic, prefrontal, and affective systems contribute to adaptive flexibility [355], [356]. Interoceptive awareness may further support self-agency and emotion regulation by connecting bodily states with conscious appraisal and behavioral choice [343], [344]. From the yogic interpretive perspective employed in this thesis, bliss may therefore contextualize an integrated condition characterized by reduced automatic reactivity, increased agency, and greater behavioral adaptability, without implying a direct correspondence with specific neurobiological mechanisms.

Conclusion

Reciprocal Regulation and *Āsana* as Self-Education

The findings are consistent with a reciprocal model of regulation in which posture, respiration, autonomic activity, cortical processing, affective appraisal, and behavior interact through dynamic feedback rather than a linear causal sequence. The concurrent changes observed in posture, sleep, pain, perceived well-being, and neurophysiological activity support this interpretation, although the present studies cannot determine the direction or causal order of these relationships.

This model is compatible with classical accounts of the *kośas* and eight limbs as interdependent dimensions of practice. Although the intervention primarily emphasized *āsana*, postural practice also engaged respiration, interoceptive awareness, attentional control, and affective regulation. *Āsana* may therefore be understood not as an isolated physical technique, but as a point of convergence through which multiple limbs and kośic dimensions are simultaneously engaged.

Repeated attention to posture, breath, and bodily sensation may also allow *āsana* to function as a form of structured self-education. Through this process, practitioners may become more capable of recognizing internal signals, interrupting habitual reactions, and selecting more adaptive responses. Participants' reports of reduced impulsivity and compulsion, together with greater relational awareness, are consistent with this possibility.

These interpretations are specific to the *āsana* sequences, intervention duration, measurement conditions, and participant samples examined across the three studies, and should therefore be understood as context-bound rather than representative of yoga practice more broadly. Further research is needed before extending these findings to other forms of practice or populations.

Clinical and Public Health Implications

Evidence from systematic reviews and meta-analyses associates physical activity with improvements in depression, anxiety, and emotional regulation, supporting further investigation of accessible embodied practices such as yoga, walking, and dance within broader models of care [147]–[149], [307], [357], [358]. The present findings, however, were derived primarily from healthy adults and should not be interpreted as evidence of clinical efficacy. They instead support controlled investigation of yoga as a possible adjunct to, rather than a replacement for, established mental health care.

Because yoga simultaneously engages bodily, physiological, attentional, emotional, and relational processes, its study requires methods capable of preserving this complexity. In the present research, questionnaires and semi-structured interviews provided experiential context for neurophysiological, biochemical, and postural findings, particularly in domains such as meaning, agency, and relational change that cannot be fully represented by isolated measures [14], [359]–[361]. Mixed methods therefore offer a means of examining convergence across domains without reducing transformation either to numerical variables alone or to subjective accounts without physiological context.

Methodological Limitations

Several limitations should be considered when interpreting these findings. The predominantly healthy, self-selected sample may not be representative of broader populations and limits the generalizability of the results, particularly to individuals with clinical conditions. In addition, the longitudinal study was designed to examine changes occurring alongside participation in the yoga program rather than to establish intervention-specific effects. Without a control group, the observed changes cannot be distinguished from the potential influences of expectancy, repeated testing, social participation, instructor contact, concurrent lifestyle changes, general physical activity, motor learning, or sustained attentional engagement.

The principal outcomes were also assessed immediately following the 30-day program. Although this design permitted the examination of pre–post changes, it does not establish whether the observed effects persisted beyond the intervention period. Future studies should incorporate randomized active-control conditions, more diverse and clinically relevant samples, and longer-term follow-up assessments to clarify the specificity, generalizability, and durability of the findings.

fNIRS measurement was limited to superficial prefrontal cortex and could not assess subcortical or broader autonomic, interoceptive, emotional, and motor networks. Because fNIRS measures hemodynamic rather than direct neuronal activity, signals may also reflect respiration, cardiovascular activity, or scalp circulation, an important concern in yoga research. Future studies should extend physiological monitoring beyond SSC to include spatially resolved near-infrared spectroscopy (SPA-fNIRS), as well as complementary neuroimaging or autonomic measures.

Technical exclusions, incomplete assessments, and variable data quality produced different sample sizes across tasks, reducing statistical power and cross-domain comparability. Larger pre-registered studies should define task-specific sample sizes, outcomes, exclusion criteria, and missing-data procedures in advance. Importantly, future studies should systematically record participants' skin color and hair characteristics, as these factors may account for signal quality variability in fNIRS data [362].

Expectancy and reporting bias are also possible because participants knew they were receiving yoga instruction and the instructor served as researcher. Future studies should use blinded assessors, independent interviewers and analysts, treatment-fidelity procedures, reflexive documentation, and direct expectancy measures.

Finally, the qualitative findings indicating perceived increases in agency and behavioral flexibility could not be validated with a Rotter's LOC scale. Due to the cultural context of the sample population, existing measures may inadequately capture relational, communal, spiritual, and contextual forms of agency in Latino populations, including *familismo* and *fatalismo* [363], [364]. Future research should develop culturally responsive measures of agency.

Future Directions

Future prospective studies should integrate neural, autonomic, biochemical, postural, psychometric, behavioral, and qualitative measures while addressing the design limitations identified above. Interviews, ecological momentary assessment, participant diaries, behavioral tasks, and culturally validated questionnaires could be combined with fNIRS, heart-rate variability, respiratory monitoring, biomarkers, and postural assessment. Convergent and sequential designs could then examine whether physiological changes correspond with reported changes in interoception, reactivity, agency, and relationships, as well as whether experiential or biological changes emerge first.

Research on agency should prioritize the development or validation of culturally responsive measures capable of distinguishing individual, relational, spiritual, and contextual forms of control. More broadly, larger and more diverse samples, active comparison groups, preregistration, and longer follow-up periods are needed to evaluate the durability, sequence, mechanisms, and clinical relevance of the observed findings.

Taken together, the studies do not establish a unified mechanism or clinical effect. They nevertheless demonstrate the value of treating neurobiological measures and lived experience as complementary forms of evidence. Such integration may provide a more complete account of how embodiment practices such as yoga influences regulation across body, brain, behavior, and subjective experience.

Summary

It seems plain and self-evident, yet it needs to be said: the isolated knowledge obtained by a group of specialists in a narrow field has in itself no value whatsoever, but only in its synthesis with all the rest of knowledge and only inasmuch as it really contributes in this synthesis toward answering the demand, "Who are we?"

Erwin Schrödinger, Science and Humanism, Physics In Our Time

Across three linked studies, this thesis established the feasibility of fNIRS during movement-based yoga *āsana*, identified immediate posture-related changes in prefrontal cortical activity and resting-state functional connectivity, and documented longitudinal changes across neural, biochemical, postural, and experiential domains. The longitudinal findings remain preliminary because the intervention lacked a control group, and they indicate multidimensional adaptation rather than proof that yoga alone caused the observed changes.

The principal contribution is a methodological and interpretive framework that connects acute and longitudinal findings without reducing yoga to a single mechanism. Within this framework, the five *kośas* serve as conceptual lenses for layered dimensions of embodied experience, while the eight limbs describe practical pathways through which these dimensions may be engaged. The empirical measures do not directly measure the *kośas*; they provide contemporary indicators that can be interpreted alongside lived experience and yoga's historical models of human functioning.

Future research should test this framework using larger and more diverse samples, randomized or carefully matched controls, longer follow-up periods, autonomic monitoring, and designs capable of distinguishing the separate and combined contributions of *āsana*, *prāṇāyāma*, and meditation. Continued integration of neurophysiological, physiological, postural, psychometric, behavioral, and qualitative evidence will be essential for evaluating the durability, sequence, and clinical significance of the observed changes.

Taken together, the findings suggest that yoga may be understood as a coordinated embodied practice whose effects unfold across immediate and cumulative timescales. Its potential significance lies not in any single neural, biochemical, or psychological mechanism, but in the interaction among bodily organization, breath, cortical regulation, behavior, and subjective experience.

Ethics Approval and Informed Consent

The procedures reported in Articles 1 and 2 were conducted in accordance with the Declaration of Helsinki and approved by the Ethics Committee Institutional Review Board of the Coordinación para la Innovación y la Aplicación de la Ciencia y la Tecnología, Universidad Autónoma de San Luis Potosí (CIACYT-CEI-003). Article 3 was approved by the Research Ethics Committee of the Universidad Autónoma de San Luis Potosí (CEI-UASLP/04–2023). All participants provided written informed consent. Consent to publish the human image appearing in Figures 11 and 12a was obtained from Michelle Goodrick, who is both the individual depicted and the first author.

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Conflicts of Interest

Michelle Goodrick is a yoga therapist and owner of Karmuka Yoga. Her professional expertise informed the study design. Potential expectancy-related bias was reduced through separation of responsibilities: independent researchers conducted the postural, biochemical, fNIRS, and qualitative analyses, while participants submitted self-report data directly through an online platform. No author derived monetary gain from the conduct or outcomes of the research, and no additional conflicts of interest are declared.

Data Availability

The data and analysis resources supporting Articles 1 and 2 are openly available in Zenodo [193]. The dataset and analysis scripts supporting Article 3 are openly available in Zenodo [146].

Declaration of Generative AI and AI-Assisted Technologies

Claude (Anthropic) was used to assist with language editing, formatting, manuscript organization, reference-link preparation, and submission checks. No generative AI tool was used for data collection, statistical analysis, or generation of original results. All scientific claims, interpretations, and conclusions were reviewed and approved by the authors, who take full responsibility for the content.

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