

Human–Computer Co-Regulation: A Review of Biofeedback for Meditative Practice

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Biofeedback has been proposed to support meditation and mindfulness practices through wearables, mobile applications, VR/AR systems for decades, and other interactive devices. However, evidence of its effectiveness remains mixed and fragmented across existing research in psychophysiology and Human-Computer Interaction (HCI). This work analyzes 39 studies published between 2015 and 2025 on real-time, user-facing biofeedback for contemplative practice. We first outline a taxonomy of biofeedback interfaces based on sensing modality, feedback channel, interaction context and temporal feedback characteristics, then we synthesize the existing study results on modality-practice fit, showing that the performance of each biofeedback sensing modality in meditative practice is closely related to the meditation practice type: Respiration and heart rate variability (HRV) are the most suitable modalities for paced breathing and stress recovery, and EEG is more appropriate for attention-oriented and experiential targets. Electrodermal activity (EDA) mainly reflects arousal awareness rather than directly measuring meditation quality. In addition, a review-informed co-regulation framework consisting of within-session physiological regulation, experiential mediation, and transfer support is proposed in this work. Finally, we summarize the main gaps in the existing literature and propose design principles for future systems.

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CCS Concepts: • **Human-centered computing** → **Empirical studies in HCI**; **Ubiquitous and mobile computing**; *Interaction paradigms*; *HCI design and evaluation methods*; • **Applied computing** → *Life and medical sciences*; Consumer health.

Additional Key Words and Phrases: biofeedback, meditation, mindfulness, co-regulation, heart rate variability, neurofeedback, systematic review, physiological computing, wearable computing, interoception, self-regulation, digital wellbeing, contemplative computing, human-computer interaction, ubiquitous computing

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1 INTRODUCTION

Meditative and contemplative practices have long been used to cultivate attention, bodily awareness, emotional regulation, and self-understanding [2, 50, 75, 82]. In recent years, growing interest in supporting these practices has motivated interdisciplinary research across digital health, wearable computing, and HCI, where interactive devices using biofeedback information are designed to help users in developing self-regulative and contemplative capacities in everyday life [47, 55, 59, 92, 96]. Rather than treating meditation as an application domain for technology, this review starts from the practice itself and asks how biofeedback technologies may support, mediate, or sometimes complicate meditative experience.

Digital meditation tools now range from smartphone applications that guide mindfulness practice to wearable systems that provide real-time physiological feedback. Randomized trials suggest that some mindfulness applications can reduce stress and anxiety [8, 15, 41], although meta-analyses typically report small-to-moderate effects and highlight methodological limitations, including short follow-up periods, self-selection, and limited active controls [30, 58]. These findings demonstrate the promising potential of digital support for contemplative practice, while also revealing several limitations. However, findings from general mindfulness applications may not transfer directly to biofeedback-assisted meditation, in which physiological signals are actively sensed and presented to users as part of the practice loop.

Biofeedback-assisted meditation introduces a different design and research problem: physiological processes such as breathing, heart activity, electrodermal activity, or neural activity are sensed and translated into feedback that may shape the user's awareness, interpretation, and regulation of experience as shown in Figure 1. In this sense, biofeedback technologies do not simply deliver meditation content; they participate in a feedback loop between body, attention, system representation, and subjective experience. Thus Biofeedback-assisted meditation is closely related to the research topics in wearable and ubiquitous computing, embodied interaction, calm technology, and digital well-being. Following calm-technology principles, these systems can support contemplative practice without requiring users' constant attention [14, 98, 99]. From an embodied-interaction perspective, they integrate bodily processes as active components of the interaction loop [23, 40, 64]. More broadly, these systems aim to support digital well-being while remaining aligned with the experiential and contemplative goals of the practices they are designed to support [8, 54, 58, 72].

Despite growing interest in biofeedback-assisted meditation, the evidence base remains mixed. For consumer-grade neurofeedback devices, recent meta-analyses provide limited support for claims of brain-target modulation or substantially deepened meditation [91]. In addition, current research often examines the psychophysiological aspects of meditative states separately from HCI perspectives on interaction, user experience, and system design [13, 61, 62, 90]. This separation makes it difficult to evaluate how biofeedback influences not only physiological regulation but also subjective awareness, meaning-making, and longer-term contemplative learning. The gap

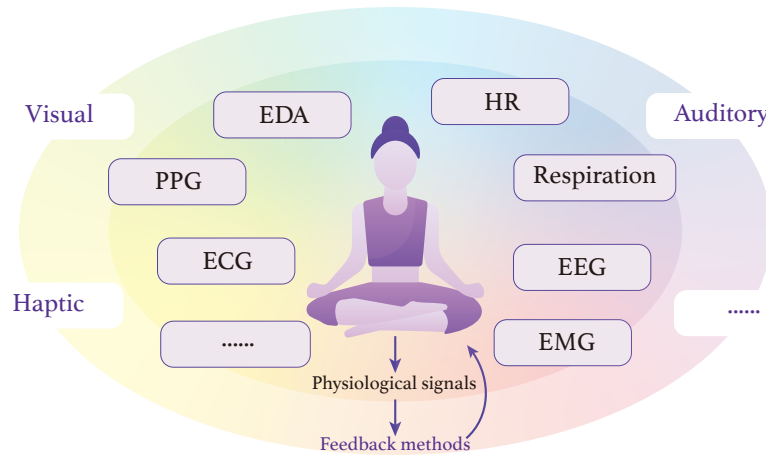


Fig. 1. Physiological signals for biofeedback in meditative practice.

between the conceptual appeal of biofeedback-assisted meditation and the current mixed evidence motivates a systematic review of the field.

A major challenge in understanding biofeedback-assisted meditation is the lack of integrative models that connect physiological feedback mechanisms with users' subjective and contemplative experiences. Psychophysiology has mainly examined the physiological correlates of meditative states, while HCI has focused on the design of interactive systems for well-being and self-regulation. However, these two research streams remain insufficiently integrated [39, 89]. Bridging them is crucial for understanding when, how, and under what conditions technology can meaningfully support meditative practice, rather than merely instrumenting or optimizing it.

This review takes meditative practice, rather than technology adoption, as its starting point. We systematically examine interactive biofeedback systems that aim to support contemplative and self-regulative experiences, synthesizing knowledge from both psychophysiology and HCI. Through this synthesis, we address the following research questions:

- (1) How have interactive biofeedback systems been used to mediate meditative or contemplative experiences?
- (2) What methodological challenges exist in current interactive systems?
- (3) What mechanisms and design strategies enable human-computer co-regulation in ways that support meditative experience and mindful awareness?

To answer these questions, this paper makes four contributions to ubiquitous computing, digital well-being, and contemplative HCI. First, we present a systematic review of 39 studies on concurrent biofeedback-assisted meditative practice, offering a structured synthesis of work across HCI, psychophysiology, and contemplative technology. Second, we introduce a taxonomy of biofeedback interfaces, organized by sensing modality, feedback channel, interaction context, and temporal characteristics of feedback, which provides a practical map of the current design space. Third, we also introduced an review-informed co-regulation framework that distinguishes within-session physiological regulation, experiential mediation, and transfer supporting as non-hierarchical functions of biofeedback systems. This framework highlights both the promise and the limits of the current literature. Finally, we synthesize these findings into design implications and a research direction for future works.

2 METHODOLOGY FOR LITERATURE REVIEW

This section outlines the systematic methodology employed to identify, select, and analyze relevant literature on interactive biofeedback and neurofeedback systems within the context of meditative practices. Our approach was designed to ensure rigor, reproducibility, and comprehensive coverage, aligning with established systematic review guidelines.

2.1 Operational Definition

For this review, meditative practice does not refer to any generic relaxation or wellness activity. We use the term to denote trainable practices in which attention is intentionally oriented toward present-moment experience, bodily sensation, or compassion-related content, and repeatedly regulated as distraction or reactivity arises [20, 39, 48, 63]. On this basis, we included focused-attention meditation, open-monitoring meditation, loving-kindness or compassion practices, body-scan and breath-awareness practices, and closely related contemplative exercises when the paper explicitly framed them as meditation, mindfulness, or contemplative training.

This lens also clarifies the role of technology in the reviewed papers. We were interested in systems where technology acts as a biofeedback by returning physiological information to the user during meditation, or by embedding that information into an interactive environment [24, 88]. We therefore excluded systems that used breathing or relaxation only as generic wellness techniques without a contemplative framing (e.g., [42]), rehabilitation protocols in which meditation was not the primary activity, and systems that sensed physiology without providing real-time, user-perceptible feedback during practice. This operational boundary keeps the review focused on interactive contemplative systems rather than on physiology logging tools or relaxation media more broadly.

2.2 Search Strategy and Sources

Our review specifically targeted interactive biofeedback applications for meditative practice, focusing on publications from 2015 to 2025. To address the terminology variance in this interdisciplinary field, we employed a two-stage hybrid retrieval strategy designed to maximize recall (sensitivity) in the initial fetch and maximize precision (specificity) in the subsequent filtering.

At stage 1, we conduct a broad semantic retrieval. We queried the Semantic Scholar (S2) API, which indexes many digital libraries (e.g., ACM Digital Library, IEEE Xplore, and PubMed). To mitigate S2's relevance-ranked fuzzy matching, we utilized broad queries combining contemplative terms with physiological indicators. (e.g., "meditation (HRV OR ECG OR EEG) biofeedback"). This stage prioritized high recall to ensure relevant papers using non-standard terminology were not missed.

At stage 2, the raw results from Stage 1 were subjected to a strict, rule-based Boolean filter applied locally to the title, abstract, and keywords. This filter enforced the following inclusion logic:

$$\text{Include} \iff \text{Contemplative} \wedge (\text{Feedback} \vee (\text{RealTime} \wedge \text{Physiological}))$$

Where,

- **Contemplative:** Any term from the contemplative bundle (e.g., meditation, mindfulness).
- **Feedback:** Explicit mention of biofeedback or neurofeedback.
- **RealTime $\wedge$ Physiological:** In the absence of the explicit "biofeedback" label, the record was required to contain both a temporal interaction term (e.g., real-time, closed-loop) AND a physiological signal (e.g., HRV, EEG).

This nested logic was crucial for capturing HCI systems that describe the technical implementation of a closed loop without explicitly self-identifying as "biofeedback" research.

2.3 Deduplication and Screening Pipeline

Following initial retrieval, we implemented a three-pass deduplication process to ensure a unique set of papers: first, by exact DOI match; second, by Semantic Scholar's unique paperId; and third, by comparing normalized titles (Unicode NFKD, lowercase, punctuation/stopword stripping, and a Levenshtein distance threshold for near-duplicates). The record with the richest metadata was retained in cases of duplication.

The screening of records then proceeded in three distinct stages:

Stage 1: Heuristic Prefilter. An initial rule-based filter was applied, requiring the co-occurrence of at least one contemplative term, one feedback term, and one physiological term within the paper's title, abstract, or keywords. This stage also included explicit exclusion criteria: we filtered out studies solely focused on clinical rehabilitation (e.g., stroke recovery, ADHD treatment) unless they clearly prioritized contemplative practice for general or sub-clinical populations, thus maintaining our focus on digital well-being. Furthermore, non-interactive systems, those using physiological sensors merely for data collection without real-time user feedback, were excluded to ensure our analysis focused on the interactive loop and user experience design.

Stage 2: Word Embedding Classification. Records that passed the heuristic prefilter were then subjected to classification by Large Language Model (LLM). The LLM (chatgpt-4o-mini) was guided by strict inclusion/exclusion criteria and prompted to output structured JSON data, including fields like `include_flag`, `rationale`, `signals used`, `feedback_modality`, `interface details`, `study_design`, and `observed outcomes`. Cases where the LLM's classification was ambiguous were automatically flagged for the next manual review stage. The prompt is shown in List 1.

Stage 3: Manual Review. All records flagged as ambiguous by the LLM classification in Stage 2, as well as a random subset of confidently classified records, underwent thorough manual review. This human intervention ensured the accuracy of inclusion/exclusion decisions for challenging cases and validated the overall performance of the automated classification. Decisions made during this stage were logged with justifications.

2.4 Quality Control and Limitations

To ensure the robustness of our review, we performed spot-check validation on a random subset (20%) of the LLM's classification decisions and meticulously reviewed all flagged borderline cases. The precision of the LLM's classification decision is around 92%. Reasons for the erroneous selections include the absence of a biofeedback component and publication dates falling outside the lens of our review. We acknowledge inherent limitations, including potential index coverage bias, the possibility of imperfect keyword recall for atypical terminology, and the risk of LLM misclassification, particularly with sparse abstracts.

2.5 Flow Summary

As shown in Figure 2, our literature search and selection process followed PRISMA conventions: initial retrieval, followed by deduplication, then a heuristic prefilter, leading to LLM classification and manual review, and finally inclusion of relevant studies. Additionally, two publicly available master's theses ([34, 73]) were included as exceptions due to their high relevance and unique empirical results.

3 CONCEPTUAL FOUNDATIONS

This review is grounded in three conceptual foundations: meditation as a family of self-regulatory practices, biofeedback as an instrument-mediated approach to physiological awareness, and HCI perspectives on interaction, embodiment, and feedback temporality. These foundations clarify the lens of the review and guide our analysis of concurrent biofeedback systems for meditative practice.

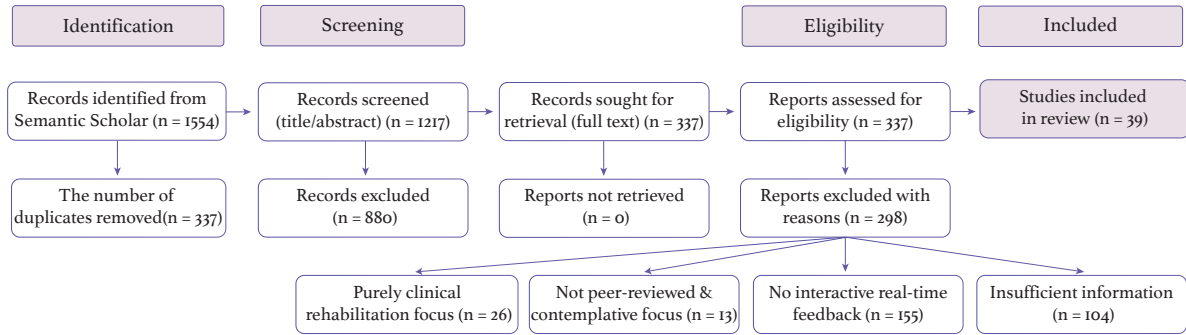


Fig. 2. PRISMA flow diagram of the literature search process. (Insufficient information: eligibility could not be verified from title/abstract/metadata (e.g., missing abstracts, unclear peer-review status, or unspecified real-time biofeedback use).)

3.1 Meditation and Interoception

Meditation is not a single uniform technique, but a family of trainable contemplative practices that cultivate attention, emotion, bodily awareness, and self-regulation [39], as shown in Figure 3. We distinguish meditation from mindfulness while recognizing their substantial overlap in the reviewed literature. In this work, we use meditation as an umbrella term to refer to a diverse set of practices, including focused-attention, open-monitoring, and affective practices such as loving-kindness or compassion, as well as body- or breath-oriented techniques [20, 38, 48, 63]. We use mindfulness more specifically to denote a present-moment, nonjudgmental mode of awareness. Although mindfulness is commonly cultivated through meditation practices, it is also explicitly targeted in structured mindfulness-based interventions and may arise in other interaction contexts.

This diversity matters for biofeedback design because different practices emphasize different regulatory skills and therefore align with different physiological signals. Focused-attention practices train sustained attention on an object such as the breath, a mantra, or bodily sensation; they may therefore be supported by signals related to attentional stability and breath regulation, including EEG features, respiratory rhythm, and cardio respiratory measures such as HRV [39, 63]. Open-monitoring practices emphasize non-reactive awareness of changing thoughts, sensations, and affective states. In this context, physiological signals such as EEG, EDA, respiration, and HRV can provide indirect proxies for attentional dynamics and affective fluctuations, but feedback should generally remain ambient and non-directive to avoid encouraging over-control. Constructive practices, such as loving-kindness and compassion meditation, aim to cultivate prosocial and affective orientations rather than merely attentional stability or physiological calmness [20, 38]. Because their intended outcomes are not primarily defined by low arousal or relaxation, biofeedback systems designed for these practices should not reduce success to proxies such as calmness, low arousal, or interoceptive accuracy. Somatic and breath-based practices, such as body scan, breath awareness, and pranayama, explicitly train attention to bodily sensation and are therefore especially aligned with respiration, HRV, cardiac activity, muscle tension, and peripheral temperature feedback [48, 66].

Interoception, broadly defined as the perception of internal bodily signals such as heartbeat, respiration, and visceral sensation, provides one important bridge between physiological state and conscious experience [17, 48, 74]. Prior work identifies interoceptive awareness as one mechanism through which some meditation practices support attention regulation, emotional awareness, and embodied self-knowledge [25, 26, 66]. Neuroimaging research further links meditation practice to large-scale networks involved in salience detection, executive control, and self-referential processing, including the salience network, frontoparietal control network, and default mode network

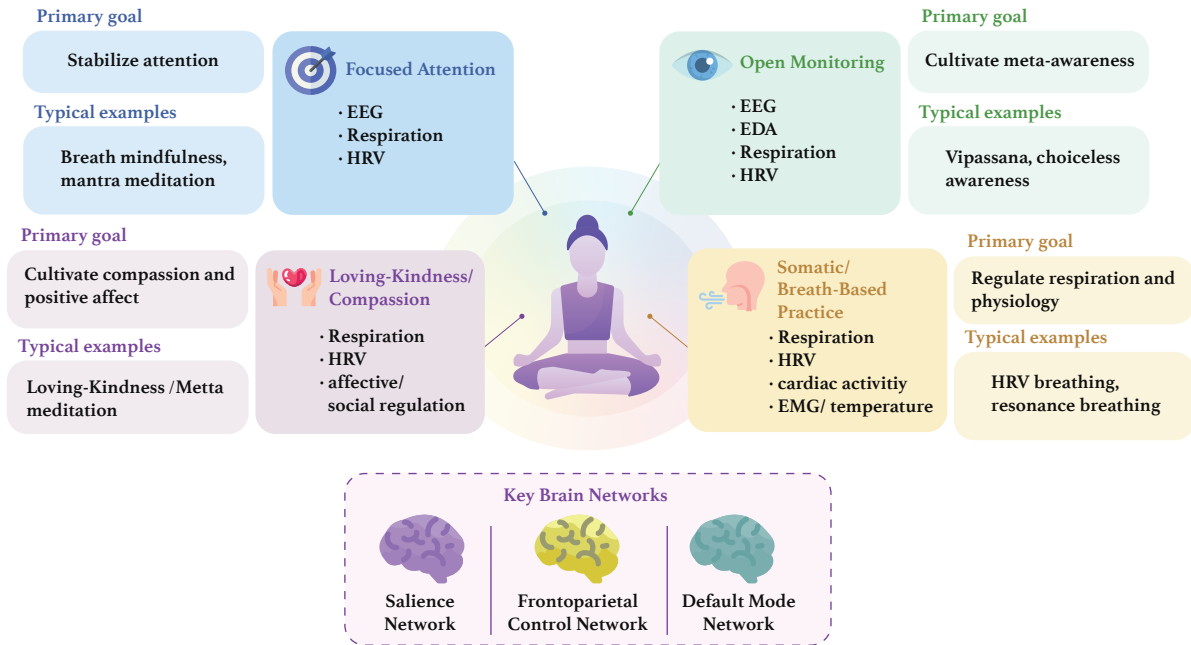


Fig. 3. Types of meditation and their commonly used physiological signals.

[28]. However, we do not treat interoception as a universal mechanism underlying all forms of meditation. Rather, it is a practice-relevant dimension whose importance varies across contemplative traditions: central in somatic and breath-based practices, relevant in focused-attention practices when the breath or body is the attentional object, and less central in constructive practices that primarily cultivate affective and prosocial orientations.

3.2 Principles of Biofeedback and Operant Conditioning

For the purposes of this review, we use the distinction between internal and external regulation as an analytic heuristic rather than a field-wide consensus. Internal regulation refers to the user's own attentional, bodily, respiratory, or affective strategies during practice, whereas external regulation refers to technological cues, feedback, or guidance that scaffold these strategies. This distinction is useful for analyzing biofeedback systems because such systems often mediate between internally cultivated skills and externally presented physiological information. However, the boundary is not fixed: feedback can initially function as external scaffolding and later become internalized as users develop self-regulatory skill.

This technological approach to self-regulation has historical links to early psychophysiological research that challenged the prevailing view that the autonomic nervous system (ANS) was beyond voluntary control [69, 70]. Intriguingly, this research often drew inspiration from reports and laboratory observations of yogis and meditation masters who demonstrated unusual control over bodily functions, thereby bridging ancient contemplative practices with modern scientific inquiry [5, 33, 56]. Within this context, biofeedback was conceived as a means to accelerate the acquisition of self-regulatory skills by providing instrument-mediated feedback to guide learning [29, 83].

Table 1. Integrated taxonomy of biofeedback modalities for meditation. The table combines physiological targets with interface design dimensions: feedback channel, context, timing, personalization, and limitations.

Modality	Targets and features	Feedback channels and contexts	Temporal profile and personalization	Design value and limitations
EEG neurofeedback	Attention, relaxed wakefulness, frontal asymmetry, synchrony, and bandpower features such as α , θ , $\text{fm}-\theta$, and γ [28, 62].	Auditory soundscapes, abstract visuals, AR/VR, social VR, games, and post-session summaries [43, 45, 96].	Fast bandpower loop, typically $\sim 0.25\text{--}2\text{ s}$; personalize alpha peak, channels, baselines, and thresholds.	Useful for attention and relaxation proxies, but artifact-sensitive and vulnerable to proxy-construct gaps.
HRV and cardiorespiratory feedback	ANS regulation through vagal activity, RSA, rMSSD, HF power, LF/HF, and heart-respiration coupling [57, 84].	Visual breathing guides, auditory pacing, haptic entrainment, coherence displays, mobile apps, wearables, desktop systems, and VR/social VR [16, 44].	Slower HRV loop, often $\sim 5\text{--}60\text{ s}$; personalize resonance frequency, comfort range, ECG/PPG artifact handling.	Strong fit for paced breathing and stress recovery, but added value over simple breathing guidance must be demonstrated.
Respiration feedback	Breath rate, depth, phase, abdominal/chest movement, and regularity [57].	Pacers, expanding visuals, VR objects, haptic breathing cushions, mobile/watch feedback, audio rhythms, and games [1, 7, 49, 71].	Rapid continuous loop; personalize target rate, comfort, inhale/exhale ratio, and movement calibration.	Highly interpretable for paced breathing, but controls must separate closed-loop feedback from simple pacing.
EDA/GSR	Sympathetic arousal through tonic SCL and phasic SCRs [9].	Abstract visuals, mobile games, auditory cues, desktop feedback, and stress/arousal displays [22, 37, 53].	Sweat-gland latency $\sim 1\text{--}5\text{ s}$; personalize tonic baseline, SCR threshold, smoothing, and context gating.	Sensitive to arousal but not valence-specific; motion, temperature, hydration, and novelty confound interpretation.
EMG/Temperature	Muscle tension, frontalis/trapezius activity, distal temperature, and peripheral vasodilation [12, 67].	Visual or audiovisual relaxation feedback, desktop systems, and mixed biofeedback protocols [32].	EMG can update quickly; temperature is slower. Personalize placement, muscle baseline, ambient temperature, and clothing effects.	Useful for tension reduction, but sparse in meditation-specific work and often confounded by mixed protocols.
Multimodal sensing	EEG+respiration, EDA+HRV+respiration, or EMG+temperature+respiration combinations [78, 86, 88].	Multisensory installations, VR worlds, social synchrony displays, games, and combined protocols [27, 46, 65, 81].	Bounded by slowest/noisiest channel; personalize thresholds, fusion policy, confidence, and movement/context gating.	Improves robustness and richness, but increases complexity, latency, calibration burden, and attribution problems.

3.3 Feedback Timing in Contemplative Biofeedback

In HCI, interaction is not limited to immediate input-output loops: systems may also shape experience through episodic prompts, delayed summaries, post-session visualizations, or longitudinal reflection. In this review, we focus on real-time user-facing biofeedback systems for meditative practice, where physiological signals are sensed, processed, and returned to users during practice to support ongoing attentional, bodily, or affective regulation. This focus is especially relevant in contemplative contexts, where continuous feedback can support awareness but may also distract from nonjudgmental attention or encourage performance-oriented monitoring. It allows us to examine moment-to-moment regulatory loops among biosensing, feedback mapping, user perception, and bodily or attentional adjustment, while treating delayed and reflective physiological-feedback systems as an adjacent design space.

4 TAXONOMY OF BIOFEEDBACK INTERFACES FOR CONTEMPLATIVE PRACTICE

Interactive systems for contemplative practice use physiological sensing to close a biofeedback loop: bodily activity is sensed, transformed into features or lightweight state estimates, mapped to audio, visual, haptic, or multisensory cues, and perceived by the practitioner during meditation. The loop closes when the practitioner adjusts attention, breathing, posture, or bodily awareness, thereby changing the sensed physiology, as shown in Fig. 4. This architecture is shared across EEG, HRV, respiration, EDA, EMG, temperature, and multimodal systems, but each modality exposes different aspects of practice and creates different design constraints.

Table 1 summarizes this design space by sensing modality, which is often the first design commitment in a biofeedback system. Each row includes a modality to typical feedback channels, contexts, temporal profiles, personalization needs, and limitations. To make this map analytically useful, we organize the taxonomy around four interface dimensions that recur across modalities. Sensing modality determines what physiological process is made measurable; feedback channel determines how that process is rendered; interaction context determines where practice occurs, from laboratory desktops to mobile, wearable, VR, AR, and social VR systems; and temporal characteristics determine whether feedback is continuous, paced, event-triggered, post-session, or used only for monitoring/classification. This structure preserves a modality-centered view while making explicit the interaction choices that shape usability, interpretation, and evaluation.

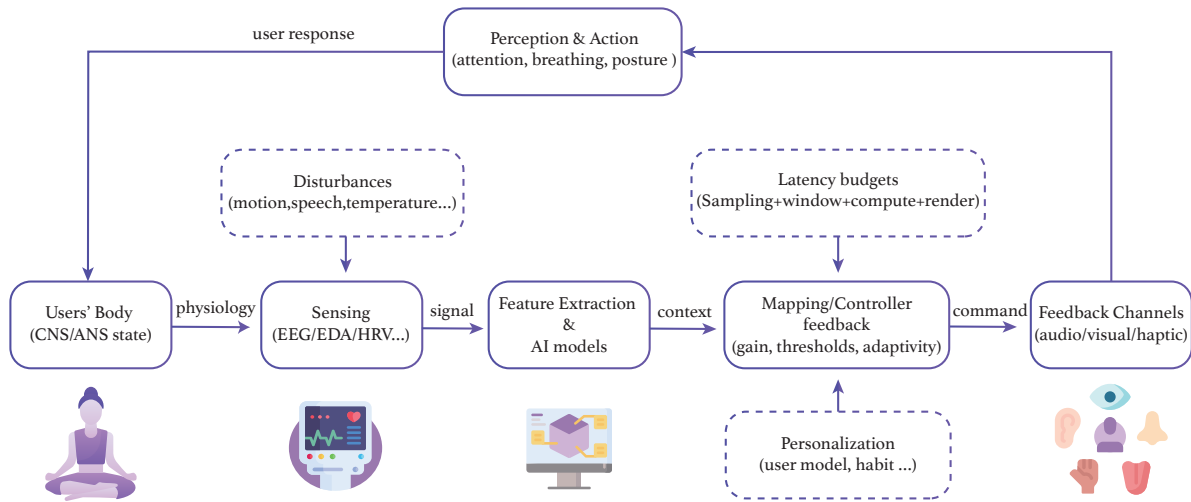


Fig. 4. Closed-loop biofeedback architecture for contemplative interfaces. Physiology is sensed, transformed into features or state estimates, and mapped to audio, visual, haptic, or multisensory cues.

4.1 Sensing Modality

Sensing modality determines both what can be made visible to the practitioner and how cautiously that signal must be interpreted. EEG provides rich but indirect proxies for attention and relaxed wakefulness; reported α , θ , γ , and coherence patterns vary with practice type, expertise, baseline, and analysis choices, so they should not be treated as definitive neural signatures [28, 62]. Mobile and consumer-grade EEG further introduces ocular, facial EMG, motion, cable, and impedance artifacts [6, 52, 68, 79]. Feature windows of roughly 0.25–1.5 s are common for bandpower estimates, making smoothing, artifact rejection, re-referencing, and individual alpha peak calibration central design choices.

Cardiorespiratory biofeedback is more directly tied to breath regulation, but designers should distinguish controllable inputs, such as breath rate, depth, and phase, from outcome indices such as rMSSD, HF power, RSA, and coherence-like measures [57, 84]. Slow breathing near baroreflex resonance, approximately 0.1 Hz or 5–7 breaths/min, can strengthen heart–respiration coupling [31, 57]. ECG provides stronger cardiac timing, while PPG improves deployability but is more vulnerable to motion, skin perfusion, and optical confounds. Respiration may be sensed through belts, nasal thermistors, microphones, ultrasound, inertial sensors, smartphones, bio-impedance or watches [36, 49, 60].

Peripheral signals expose autonomic and somatic processes beyond cardiac measures. EDA reflects sympathetic sudomotor activity, EMG captures muscle tension, and distal temperature changes slowly with peripheral vasodilation [9, 12, 67]. These signals are useful but context-sensitive: EDA is confounded by movement, temperature, hydration, and baseline drift; EMG depends on placement and shielding; and temperature is affected by ambient conditions and clothing. Multimodal systems combine EDA, HRV, respiration, EEG, EMG, or temperature to distinguish states that a single signal cannot separate, such as calm engagement versus anxious arousal [86, 88]. Fusion can improve richness and robustness, but increases latency, calibration burden, system complex, and attribution difficulty.

4.2 Feedback Channel

Feedback channels shape how biofeedback enters the phenomenology of practice. Visual feedback can make abstract signals legible, but may also draw attention away from the meditation object [45, 80, 94, 97]. Auditory feedback, including Muse-style soundscapes and HRV or breathing sonification, supports eyes-free practice but can become distracting or incongruent with subjective experience [3, 43, 85]. Haptic and vibrotactile feedback can provide peripheral guidance, especially in wearable and trauma-focused mindfulness systems [25, 47, 78]. Multisensory and gamified feedback may increase engagement [27, 71], but can obscure whether benefits arise from physiological contingency, stimulation, novelty, or game mechanics. Across channels, many neurofeedback meditation designs favor continuous ambient cues to reduce attentional capture during practice [10, 92].

4.3 Interaction Context

Interaction context determines the trade-off between ecological validity and causal control. Desktop and laboratory systems support controlled measurement and early efficacy testing [11, 21, 35]. Mobile and wearable systems enable everyday deployment but introduce challenges in sensor quality, adherence, movement, and context noise [51, 55, 92]. VR, AR, and metaverse systems make biofeedback embodied and spatial [59, 95, 96, 100], while social VR and dyadic systems extend biofeedback from individual regulation to shared presence, empathy, and synchrony [45, 46, 81]. These contexts can make biofeedback more meaningful, but they also add active factors such as immersion, novelty, social co-presence, and game mechanics, complicating causal attribution.

4.4 Temporal Characteristics

Temporal design determines whether feedback guides the current session, nudges users at opportune moments, or supports reflection afterward. Real-time continuous feedback is common in respiration, HRV, EEG, EDA, and synchrony systems [7, 21, 37, 49]. Quickly estimable features such as respiration rate, EMG Root Mean Square (RMS), and EEG bandpower can update within roughly 0.25–2 s, supporting pacing, sonification, or immersive visual changes. HRV-driven loops require longer inter-beat-interval windows, often around 5–60 s depending on the feature, trading immediacy for physiological specificity [84]; EDA has sweat-gland latency of roughly 1–5 s. Event-triggered feedback appears in stress-responsive smartwatch interventions [47]. Other systems use biosignals only for monitoring or classification, such as Anapana monitoring or EEG-based distraction classification [76, 77]. These systems provide useful sensing infrastructure, but should not be treated as evidence that feedback itself improves meditation.

Table 2. Detailed study list of biofeedback modalities for contemplative practice.

Work	Feedback channels	Study type	N	Intervention platform	Meditation type	Primary outcomes
Neurofeedback						
Wang et al. [96]	Visual & auditory (VR)	RCT	36	VR	Mindfulness ¹	Emotion regulation was measured via EEG relaxation/emotion indices, VAS anxiety, 6-item STAI, SWEMWBS, and interviews. EEG outcomes and perceived feedback usefulness improved, but anxiety reductions were not specific to feedback.
Liu et al. [59]	Visual (AR)	Prototype	—	AR	Mindfulness (Social)	<i>Mindful Garden</i> uses AR and real-time EEG to enhance social mindfulness and mutual support during co-located meditation.
Järvelä et al. [45]	Visual (social VR)	Within-subject	78	Social VR	Loving-kindness	Shared dyadic biofeedback improved self-reported empathy and social presence, assessed via empathy ratings and social presence scales, while physiological synchrony outcomes based on EDA/SCR and ECG-derived HRV were weak or mostly non-robust.
Järvelä et al. [46]	Visual (social VR)	Within-subject	42	Social VR	Loving-kindness	Shared VR compassion meditation used self-reports and EEG to assess empathy/synchrony, with combined EEG-respiration dyadic neurofeedback showing the strongest benefits.
Wang et al. [97]	Visual (VR)	Prototype	5	VR	Mindfulness	Proof-of-concept for a VR meditation system with integrated neuro- and biofeedback to provide personalized suggestions.
Salminen et al. [81]	Visual (social VR)	Within-subject	72	Social VR	Loving-kindness	Social VR biofeedback increased self-reported empathy, especially with combined EEG and respiration feedback. EEG frontal asymmetry synchrony was associated with higher empathy, but respiration synchrony was not.
Allen et al. [3]	Auditory	Within-subject	12	Desktop	Mindfulness	Subjective distress decreased on DASS-21 anxiety and stress subscales, but Muse EEG alpha activity and salivary cortisol showed no significant improvement.
Soriano et al. [85]	Auditory	Within-subject	31	Desktop	Focused attention	EEG neurofeedback enabled alpha modulation during focused attention meditation, especially alpha reduction during downregulation, but effects did not transfer to resting-state EEG and self-reported meditation experience showed no training-specific changes.
Hunkin et al. [43]	Auditory (Muse)	Within-subject	68	Wearable	Focused-attention	State mindfulness during focused attention meditation was assessed via breath counting and Muse-derived mind-wandering metrics. Feedback improved attentional engagement and reduced device-measured mind wandering, though users reported mixed experiences.
De Vuyst et al. [21]	Auditory	RCT	30	Desktop	Focused attention	EEG neurofeedback during focused attention meditation modulated global non-harmonic alpha-theta cross-frequency ratios, with transfer to resting-state EEG. Local Pz effects were null, and psychological improvements were exploratory and correlational.
Viczko et al. [94]	Visual (AR)	Between-group	40	AR	Loving-kindness	AR Loving-kindness based open-heart meditation improved mood with or without Muse neurofeedback; Mood improved in both groups, while neurofeedback mainly increased engagement, with limited added mood or EEG benefits.
Da Costa et al. [19]	Auditory & visual (game)	RCT	62	Desktop	Focused-attention	Neurofeedback self-regulation was assessed as EEG alpha-band up-regulation at Pz during NFT. Mindfulness priming improved eyes-open alpha self-regulation compared with no priming, while TMS, POMS, FFMQ, DASS, ERQ, GSR, and HRV were mainly explanatory or correlational measures.
Van der Schoot et al. [92]	Auditory (Muse)	Pilot	8	Wearable	Mindfulness	Feasibility and usability of Muse-based neuromeditation were assessed through therapist/patient ratings, SUS, tension ratings, Muse metrics, and pre/post behavioral measures, with descriptive evidence of reduced tension and perceived relaxation/impulsivity benefits, but small pilot sample.

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¹Generic mindfulness meditation, subtype unspecified.

Table 2 — continued from previous page

Work	Feedback channels	Study type	N	Intervention platform	Meditation type	Primary outcomes
Chow et al. [18]	Auditory	RCT	61	Wearable	Focused attention	Compared mindfulness meditation, EEG alpha neurofeedback, and sham neurofeedback. Both mindfulness and neurofeedback significantly increased global EEG alpha power compared with sham after a single 15-minute session. Mindfulness, but not neurofeedback, reduced frontal upper-alpha event-related desynchronization (ERD) during the Stroop task, suggesting enhanced neural efficiency of attentional processing.
Mazgelytė et al. [65]	et Audiovisual (VR)	Crossover	43	VR	Mixed relaxation / sparse practices	Acute stress-related changes were assessed using mood, fatigue, and strain ratings, salivary cortisol/cortisone, GSR, and heart rate. Strain and salivary glucocorticoids decreased, GSR increased across techniques, fatigue decreased for three techniques, and no VR relaxation modality clearly outperformed the others.
Lee et al. [55]	Auditory	RCT	49	Wearable	Mindfulness	Wearable neurofeedback-assisted meditation reduced PSS scores more than controls, with a trend toward greater state-anxiety reduction; depression and sleep improved in both groups, while qEEG and blood biomarkers showed no significant between-group effects.
Salminen et al. [80]	et Visual (VR)	Within-subject	43	VR	Focused-attention and Body-scan	Presence, meditation depth, and EEG responses during VR neurofeedback-supported focused attention meditation were assessed using abbreviated ITC-SOPI, MEDEQ Hindrances, and EEG theta/alpha/gamma power. HMD-based VR increased presence and reduced meditation hindrances; neurofeedback increased presence and frontal theta, but not alpha, while gamma was higher with HMD use and neurofeedback.
Cardiorespiratory (HRV)						
Finck et al. [27]	Visual & multisensory	Between-subject	68	Lab installation	Focused attention	Anxiety, nature connectedness, mindfulness, HRV, and subjective experience were assessed using STAI, CNS, MAAS/TMS, Polar H10 HRV metrics, and ratings. Anxiety decreased and nature connectedness increased in both groups, with treatment-specific effects mainly on relaxation/attention ratings and LF/HF during olfactory stimulation.
Kizakevich et al. [51]	et Auditory & visual (app)	RCT	328	Mobile app	Paced breathing	This interim BART report assessed feasibility, adherence, and HRV data quality, showing usable HRV collection and expected stress/breathing-related HRV changes, but not whether HRV biofeedback improved resilience or mental-health outcomes.
Jetelina et al. [47]	Haptic (smartwatch)	Pilot	22	Wearable	Paced breathing	Smartwatch-based stress notifications and self-help features were acceptable and useful for stress awareness, but stress-reduction effectiveness was not established.
Fani et al. [25]	Haptic (vibrotactile)	RCT	65	Wearable	Focused-attention	Vibration-enhanced breath-focused mindfulness improved interoception and sustained attention more than control via analysing MAIA, MDI, HRV and fMRI; dissociation decreased in both groups, interoception gains more clearly linked to reduced dissociation and increased HRV in vibration group.
Brinkmann et al. [11]	et Visual	RCT	52	Desktop	Mindfulness	HRV biofeedback and mindfulness training did not outperform wait-list control for workplace stress; stress and cortisol decreased across groups, while mindfulness/self-compassion improved mainly after mindfulness training.
Chelidoni et al. [16]	et Auditory & visual (app)	RCT	75	Mobile app	Paced breathing	BioBase app-based breathing improved post-stress HRV recovery, with higher RMSSD, pNN50, and HF than mindfulness body scan or control.
Field et al. [35]	Visual (HeartMath)	Pilot	13	Desktop	Focused attention	HeartMath HRV biofeedback training was assessed using psychological self-reports and emWave-derived HRV coherence. Negative mood/stress decreased, while sense of coherence, relaxation, mindfulness, and HRV coherence increased after training.

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Table 2 — continued from previous page

Work	Feedback channels	Study type	N	Intervention platform	Meditation type	Primary outcomes
Tabor et al. [87]	Visual	RCT	28	Desktop	Paced breathing	Acute physiological effects of HRV biofeedback versus paced breathing were assessed using breathing rate, HRV amplitude, and ln(LF) from nasal thermistor and Polar H10 data. Both interventions reduced breathing rate and increased HRV, with no significant advantage of HRV biofeedback.
Amores et al. [4]	Auditory	RCT (pilot)	32	Wearable	Mindfulness	Anxiety reduction was assessed mainly with STAI Form Y-1. Participants with elevated baseline anxiety showed improvement, but physiological evidence was mixed: HR decreased in both groups, HRV showed a between-group difference, and EEG showed no clear treatment-specific effect.
Gunzenhauser ² [34]	Visual	Prototype	17	Desktop	focused attention	Real-time HRV biofeedback was perceived as usable and useful for meditation support, with improved HRV during meditation, especially lower LF/HF and heart rate and higher HF, though rMSSD was less consistent.
van der Zwan et al. [93]	Visual (mobile app)	RCT	126	Mobile app	Mindfulness	Physical activity, mindfulness meditation, and HRV biofeedback were compared as self-help stress-reduction interventions using DASS-21, PSQI, and SPW. All interventions reduced stress, anxiety, and depressive symptoms, improved psychological well-being, and slightly improved sleep quality.
Morris ³ [73]	Auditory & visual (Inner Balance)	RCT	12	Mobile app	Mindfulness	HeartMath Inner Balance HRV biofeedback was evaluated as an addition to workplace mindfulness using PSS, focus/motivation ratings, session logs, coherence scores, and interviews. Biofeedback showed no consistent added benefit; stress and focus improved more clearly, while users reported weaker changes and mixed experiences, including distraction.
Respiration						
Khan et al. ⁴ [49]	Visual (smartphone)	RCT	40	Mobile app	Paced breathing	Respiration-based feedback in a mindfulness app was assessed using SUS, engagement metrics, self-rated mindfulness-skill changes, and accelerometer-derived respiration/mindfulness estimates. Biosignal feedback improved usability, engagement, and perceived skill gains; the respiration and mindfulness models also showed promising prediction performance.
Blum et al. [7]	Visual (VR)	RCT	72	VR	Paced breathing	User experience, breath focus, abdominal breathing, and RSA were assessed during a VR breathing exercise using UEQ, breath-focus ratings, VR-controller-derived abdominal movement, and Polar H10-derived HRV indices. Biofeedback increased breath focus, promoted slower and stronger abdominal breathing, and improved RSA-related HRV indices.
Miner et al. [71]	Visual (gamified VR)	Pilot	21	VR	Paced breathing	The gamified VR respiration-biofeedback system was evaluated for breathing self-regulation and user experience using respiration-belt data, SUS, presence scales, and interviews. The system showed good usability, reduced breathing frequency, and supported slow diaphragmatic breathing, mainly demonstrating feasibility and interaction design rather than clinical stress or mindfulness effects.
Yu et al. [100]	Visual (metaverse)	Pilot	31	VR / Metaverse	Mindfulness	Psychological distress, mindfulness, psychological flexibility, self-compassion, self-esteem, and user satisfaction were assessed using validated questionnaires and a custom MCSA measure. Distress decreased, while mindfulness-related and self-evaluative outcomes improved.

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²Master thesis.³Master thesis.⁴Feedback was presented after the session rather than during meditation, specifically to avoid interrupting the meditation experience

Table 2 — continued from previous page

Work	Feedback channels	Study type	N	Intervention platform	Meditation type	Primary outcomes
Wagner & Wiczorek [95]	Visual (Meta Quest 2)	Crossover RCT	34	VR	Mindfulness	Motor skill performance under pressure was assessed using basketball free-throw and football penalty-kick scores, with ego depletion measured as a manipulation check. Flowborne VR mindfulness breathing with biofeedback improved both task scores and counteracted ego-depletion-related decline in penalty-kick performance.
Electrodermal activity (EDA)						
Patarathipakorn et al. [77]	Abstract visuals	Pilot	28	Desktop	Focused Attention	Stress reduction after Anapana meditation training was assessed in dental students using Thai PSS-10, skin conductance biofeedback, and skin temperature biofeedback. Perceived stress decreased, and biofeedback measures also indicated reduced physiological stress over time, but biofeedback was used mainly for monitoring rather than intervention.
Dillon et al. [22]	Gamified (mobile)	Between-subject	50	Mobile app	Mixed relaxation / sparse practices	Acute stress reduction after smartphone-based skin-conductance biofeedback games was assessed using VAS perceived stress, heart rate, UWIST mood ratings, and Pip skin-conductance data. Biofeedback games reduced perceived stress and heart rate more than the control game, while mood ratings showed no significant changes.
Hinterberger et al. [37]	Auditory	Within-subject	30	Desktop	Open monitoring	Skin-conductance feedback meditation was assessed using subjective meditation experience, mindfulness traits, and skin-conductance responses. SCFM increased perceived calmness/balance and integration, with effects similar to ordinary mindfulness meditation; however, skin-conductance responses showed no clear training effect or between-group difference.
Larradet et al. [53]	Gamified	RCT	18	Desktop	Mixed relaxation / sparse practices	Gaze-controlled gaming with GSR-based relaxation biofeedback was assessed using perceived session duration, a custom questionnaire, and game-performance metrics. Biofeedback reduced perceived session duration, suggesting lower mental workload, but questionnaire and performance outcomes showed no significant.
EMG						
Gholami Tahsini et al. [32]	Auditory & visual	RCT	29	Desktop	Mixed relaxation / sparse practices	BFRT reduced examination-related emotional distress on DASS depression, anxiety, and stress subscales and improved physiological relaxation markers, including EMG, respiration rate, and skin temperature; however, physiological effects were not compared with controls and no follow-up was reported.

5 EMPIRICAL SYNTHESIS OF BIOFEEDBACK-SUPPORTED MEDITATION

In this section, we conducted an empirical synthesis of the bio-feedback for meditation based on the 39 studies as list in Table 2 to answer the following questions: which modality–practice pairings are most supported by the reviewed meditation studies, and where are claims still limited to feasibility, usability, short-term regulation, classification accuracy, or experiential value? This distinction is important because a physiological signal can be theoretically relevant and still lack evidence that feedback based on that signal improves meditation skill or wellbeing.

5.1 Biofeedback Modality and Meditation Type

Table 3 summarizes qualitative evidence patterns in the reviewed papers rather than meta-analytic effect estimates.

5.1.1 Paced Breathing: The Clearest Modality–Practice Match. In the reviewed studies, paced breathing supported by respiration-based biofeedback demonstrated the clearest match between the biofeedback modality and the meditation practice. This is because respiration is not only the target that users can intentionally regulate, but also the physiological signal used to provide feedback. The results of paced-breathing meditation studies showed that

Table 3. At-a-glance empirical fit between biofeedback modalities and meditation types. “Clearest fit” indicates repeated positive or partly positive findings with a plausible mechanism match. “Promising but mixed” indicates beneficial findings with important caveats, weak transfer, null biomarkers, or unclear added value over simpler controls.

Meditation type	Most supported pairing	Evidence pattern	Concrete interpretation
Paced breathing	Respiration; HRV/ cardiorespiratory	Clearest fit, with HRV caveats	Respiration feedback directly supports breath regulation and improves proximal outcomes such as breath focus, abdominal breathing, and RSA-related HRV [7, 49, 71]. HRV feedback can improve acute recovery or anxiety, but may not outperform simple paced breathing [16, 87].
Focused attention	EEG	Mechanistically plausible, empirically mixed	EEG feedback can support within-session attentional regulation by enabling alpha or alpha-theta modulation and reducing device-estimated mind wandering [19, 21, 43, 85]. However, transfer to resting-state EEG and meditation-specific subjective outcomes is inconsistent, and successful regulation of an EEG feature does not necessarily translate into broader attentional improvement [18, 21, 85].
Loving-kindness	EEG; HRV/respiration in some systems	Broad but heterogeneous	EEG-based dyadic feedback in social VR can support the interpersonal aims of loving-kindness meditation by increasing self-reported empathy and social presence, particularly when EEG and respiration synchrony feedback are combined [45, 46, 81]. However, physiological synchrony effects are weak or inconsistent, and AR neurofeedback appears to improve engagement more reliably than mood or resting-state EEG, indicating stronger evidence for experiential and social benefits than for physiological change [45, 94].
Open-monitoring	EDA	Broad but heterogeneous	EDA feedback can make fluctuations in physiological arousal perceptible during open-monitoring meditation and may support subjective calmness, balance, and integration. However, these experiential benefits were comparable to ordinary mindfulness meditation, while skin-conductance responses showed no clear training effect or between-condition difference, indicating limited evidence that EDA feedback adds meditation-specific physiological benefits [37].
Mixed relaxation / sparse practices	EMG/temperature; mixed multimodal feedback	Insufficient for modality- specific claims	Across mixed or insufficiently described relaxation practices, EEG-, EDA-, and multimodal biofeedback were associated with reduced acute stress, strain, emotional distress, or physiological arousal [22, 32, 53, 65]. However, no feedback modality consistently outperformed comparison conditions, and sparse descriptions of the underlying practice prevent these effects from being attributed to a specific meditation mechanism.
Mindfulness (subtype unspecified)	-	Insufficient for modality- specific claims	Because these studies did not specify a distinct meditation subtype, their findings support only broad conclusions about biofeedback-assisted mindfulness. EEG, HRV, and respiration feedback were associated with outcomes such as relaxation, perceived stress reduction, attentional engagement, breath awareness, and physiological self-regulation [4, 49, 55, 96]

respiration-based biofeedback systems can support users’ practice by improving breath focus, promoting slower and stronger abdominal breathing, reducing breathing frequency, improving RSA-related HRV, and supporting slow diaphragmatic breathing. [7, 49, 71]. In addition, the user studies also reported good usability, engagement, and perceived skill development.[71]

The coherent relationship between HRV/cardiorespiratory feedback and paced breathing has also been demonstrated in the reviewed studies, although HRV represents a downstream autonomic response rather than breathing itself. An app-based breathing intervention resulted in higher RMSSD, pNN50, and HF during post-stress recovery than a mindfulness body scan or control condition [16]. However, the benefits of HRV feedback were not consistently greater than those of simple breath pacing. In one RCT, both HRV biofeedback and paced breathing reduced breathing rate and increased HRV, with no significant advantage of biofeedback [87]. Other studies demonstrated feasibility, adherence, acceptable stress notifications, or the collection of usable HRV data, but did not determine whether the feedback improved resilience or stress-related outcomes [47, 51]. Therefore, respiration feedback demonstrated the clearest suitability for paced-breathing meditation, while HRV-based

systems need to demonstrate what additional physiological information or benefits they can provide beyond an ordinary breath-pacing cue.

5.1.2 *Focused Attention: Feedback Can Support Engagement, But Neural Control Does not Guarantee Transfer.*

The relationship between focused-attention meditative practices and EEG neurofeedback is plausible because attention engagement, distraction, and self-regulation can be represented through selected neural features. The reviewed studies demonstrated that participants could modulate alpha activity or global alpha–theta relationships during training [19, 21, 85]. For example, a consumer-grade EEG headband based feedback via auditory channel improved breath-counting performance and reduced device-estimated mind wandering, suggesting that EEG feedback can help users sustain or restore attention during practice [43]. Neurofeedback delivered through a VR platform also increased presence and frontal theta activity and reduced self-reported meditation hindrances, although the effects differed across EEG frequency bands [80].

One limitation of EEG neurofeedback is that the transfer of meditation skills after training has not been clearly demonstrated in the existing studies. For example, alpha modulation did not persist in post-training resting-state EEG, and self-reported meditation experience also showed no clear improvement [85]. Another study found transfer in a global alpha–theta measure, but not at the prespecified local Pz site, while the associations with psychological outcomes remained exploratory [21]. In addition, global alpha power could be increased by both mindfulness meditation and neurofeedback, but only mindfulness practice changed Stroop-related upper-alpha activity. These results suggested that EEG variations caused by neural self-regulation and focused-attention processing cannot be treated as interchangeable outcomes [18]. Furthermore, user experience is related to the feedback channel and sensing configuration and therefore requires additional attention, because the feedback interface and modality may also make practitioners stressful, distracting, or incongruent with focused-attention meditative practice [43].

Focused-attention processing can also be supported by non-EEG modalities by making bodily states more perceptible. For example, HRV-based vibroacoustically augmented breath-focused practice improved interoceptive awareness and sustained attention [25]. Multisensory systems also demonstrated improvements in subjective relaxation, attention, usability, mood, or autonomic regulation, although several findings were based on small, uncontrolled, or primarily pre-post studies [27, 34, 35]. Overall, focused-attention practice can be supported by biofeedback, but extending momentary regulation to sustained attention, unsupported meditation, and longer-term skill transfer remains a challenge.

5.1.3 *Loving-kindness Meditation: Social and Experiential Gains Exceed Synchrony Evidence.*

Biofeedback in loving-kindness meditation has primarily been used to externalize interpersonal states in shared VR or AR environments. Self-reported empathy and social presence were increased by dyadic systems combining EEG and respiration feedback, often producing the strongest experiential results [45, 46, 81]. These results demonstrated a distinctive modality–practice relationship: shared biofeedback can provide a common representational object through which participants organize compassion, interpersonal attention, and a sense of connection. However, physiological synchrony was less consistent than the experiential findings. For example, synchrony measures based on EDA, SCR, and ECG information were weak or lacked robustness in one study [45]. Although combined biofeedback increased self-reported empathy, respiratory synchrony was not consistently associated with empathy [81]. In an AR open-heart meditation study, mood improved both with and without neurofeedback, while the clearer contribution of the feedback was increased engagement rather than distinct effects on mood or resting-state EEG [94]. Thus, social EEG feedback may be better used as an experiential and interpersonal design resource than as a validated mechanism for training physiological synchrony.

5.1.4 *Open Monitoring: EDA Supports Arousal Awareness but is not Meditation-Specific.*

Evidence for open-monitoring meditation is limited to skin-conductance feedback. Auditory EDA feedback was associated with

Table 4. Empirical and methodological trends in the 39-study corpus. Counts are based on Table 2; interpretation reflects whether the reviewed studies isolate biofeedback-specific effects.

Trend	Corpus pattern	Interpretation for the survey	Examples
Evaluation maturity	17 randomized designs, but many pilots, prototypes, short interventions, and within-subject studies.	The field has moved beyond pure demonstration, yet many studies remain exploratory or acute rather than confirmatory and longitudinal.	[25, 43, 51, 55, 59]
Sample scale	Reported N ranges from 5 to 328; median $N = 35$; 27/38 reporting studies have $N \leq 50$.	Small samples are acceptable for early HCI systems, but they limit claims about durable wellbeing, clinical benefit, subgroup effects, and mechanism transfer.	[51, 73, 92, 93, 97]
Evidence profile	Most findings are positive or mixed-positive for at least one outcome; fewer studies show clear added value over active comparators.	The corpus supports feasibility and proximal regulation more strongly than biofeedback-specific superiority.	[7, 11, 49, 87]
Outcome selection	Studies combine self-report, physiology, biomarkers, task performance, model accuracy, usability, and interviews.	Multimethod evaluation is a strength, but it often produces ambiguous patterns when subjective and physiological outcomes diverge.	[3, 55, 95]
Comparator quality	Comparators range from wait-list or no-feedback controls to active mindfulness, physical activity, simple paced breathing, and multi-arm VR comparisons.	Stronger comparators often reduce the apparent added value of biofeedback, especially for HRV and mindfulness systems.	[11, 73, 87, 93, 94]
Platform shift	Desktop systems remain common, but mobile/wearable and VR/AR/social-VR systems are now prominent.	Ecological and immersive systems improve reach and experience, but add measurement noise and component-attribution problems.	[45, 47, 51, 80, 100]

greater perceived calmness, balance, and integration, suggesting that externalizing fluctuations in autonomic arousal may help practitioners notice changes in their moment-to-moment state [37]. However, these experiential effects were comparable to ordinary mindfulness meditation, and skin-conductance responses showed no clear training effect or between-condition difference [37]. EDA feedback therefore appears more suitable for supporting acute arousal awareness than for representing open-monitoring skill or meditative quality directly.

5.2 Empirical and Methodological Trends

The reviewed studies demonstrated that the field is moving from prototype development toward controlled evaluation, while the current evidence remains mainly short-term, proximal, and interface-focused. Table 4 summarizes the main methodological trends. Among the 39 reviewed studies, 17 used randomized designs when RCT, pilot RCT, and crossover RCT studies were combined; eight used within-subject designs; six were pilot studies; four focused on prototype evaluation; three used between-group or between-subject comparisons; and one used a crossover design without being described as an RCT. Among the 38 studies that reported sample size, the number of participants ranged from 5 to 328, with a median of 35, and 26 studies included 50 or fewer participants.

Proximal outcomes are better supported than durable meditation outcomes. The clearest empirical results occur when outcomes are close to the feedback loop. Respiration feedback improves breath focus, slows or deepens breathing, and changes RSA-related HRV indices during paced-breathing tasks [7, 49, 71]. HRV/cardiorespiratory feedback can improve acute physiological recovery after stress or anxiety in selected participants [4, 16]. EEG feedback can support within-session alpha or alpha–theta regulation and attentional engagement [19, 21, 43, 85]. EDA feedback can reduce acute perceived stress or support calmness and workload regulation [22, 37, 53]. In contrast, durable outcomes such as clinical stress reduction, mindfulness skill transfer, long-term emotion regulation, or biomarker change are less consistently demonstrated. Several studies report improvements in self-report while biomarkers, EEG transfer, or physiological synchrony remain null or mixed [3, 45, 55, 81]. Thus,

the corpus does not show that biofeedback broadly improves meditation; it more strongly supports biofeedback for immediately regulable processes and proximal outcomes.

Comparators and component attribution shape interpretation. The most informative studies are not necessarily the most technologically complex; they are the ones that compare biofeedback against plausible simpler alternatives. HRV biofeedback appears less distinctive when compared with simple paced breathing, because both reduce breathing rate and increase HRV [87]. Workplace and self-help studies show that HRV biofeedback may not outperform mindfulness training, wait-list control, physical activity, or non-feedback mindfulness programs on broad stress outcomes [11, 73, 93]. AR mindfulness can improve mood with or without neurofeedback, suggesting that guidance, immersion, or meditation itself may drive the main effect [94]. Similarly, VR, AR, metaverse, and social VR systems expand the outcome space toward presence, empathy, embodiment, social connection, and performance under pressure [45, 46, 80, 81, 95, 100], but they bundle physiological contingency with novelty, social co-presence, guided instruction, and immersive media. These findings do not make biofeedback unhelpful; they show that biofeedback-specific claims require active controls that match instruction, expectancy, interface attention, practice time, and non-feedback system components.

Deployment expands reach but weakens measurement control. Mobile apps, smartwatches, consumer EEG headsets, and wearable HRV systems make contemplative biofeedback more deployable, but introduce adherence, artifact, missing-data, and context-noise problems [43, 47, 51, 55, 92]. Laboratory and desktop studies provide cleaner measurement and stronger causal control, but may not reflect everyday meditation practice [11, 21, 35]. Immersive systems provide ecological richness of a different kind: they make meditation more embodied and engaging, but add active ingredients that are hard to disentangle [45, 80, 96]. A mature empirical program should therefore pair controlled mechanism studies with field deployments, rather than treating either setting as sufficient on its own.

Overall, these trends limit strong claims about durable meditation skill or wellbeing. Many studies remain small, short-term, and heterogeneous in outcome selection; several do not specify primary outcomes; and active ingredients are often difficult to isolate when feedback is bundled with guidance, immersion, pacing, novelty, or social interaction. Thus, we treat the corpus as stronger evidence for feasibility, proximal regulation, and experiential value than for long-term meditation-training efficacy.

6 AN REVIEW-INFORMED CO-REGULATION FRAMEWORK FOR BIOFEEDBACK MEDITATION

The empirical synthesis above suggests that biofeedback meditation systems should not be understood only as pipelines that translate physiological signals into feedback cues. We use co-regulation to describe the limited role of real-time biofeedback in making selected bodily or attentional processes perceptible, interpretable, and actionable during practice. This framing does not imply that the system is an autonomous meditation partner or that current studies demonstrate durable human-computer partnership. Instead, it synthesizes recurring patterns across the 39 reviewed studies: proximal physiological regulation is better supported than durable outcomes, feedback often changes subjective experience even when physiological effects are mixed, stronger comparators reduce apparent added value, and off-device transfer is rarely discussed or tested. We therefore distinguish three non-hierarchical functions: proximal physiological regulation, experiential mediation, and transfer supporting.

6.1 Three Co-Regulation Functions

Table 5 summarizes the empirical patterns. The core observation is that the reviewed systems repeatedly succeed at making a physiological or experiential state actionable in the moment, but they less often isolate the biofeedback-specific mechanism or test whether the learned regulation persists beyond the device or mentioned it in future work direction.

Table 5. Corpus patterns motivating the review-informed co-regulation framework.

Pattern in the reviewed corpus	Representative evidence	Implication for the framework
Practice-matched signals produce the clearest proximal effects.	Respiration feedback improves breath focus, abdominal breathing, and slow-breathing behavior [7, 49, 71]; HRV feedback can support acute post-stress recovery but may not outperform simple paced breathing [16, 87].	Co-regulation first concerns whether a real-time signal supports an immediately regulable process.
Neural and autonomic proxies do not automatically equal meditation skill.	EEG feedback can support alpha or alpha-theta modulation, yet transfer to resting-state EEG or meditation-specific self-report is limited or mixed [21, 85]; EDA reflects arousal but is not meditation-specific [22, 37, 53].	The framework separates physiological regulation from claims about meditation quality or learning.
Subjective experience often diverges from physiological evidence.	Muse feedback improved attentional engagement but was also experienced as active, stressful, distracting, or incongruent [43]; neurofeedback studies can improve self-report while cortisol, qEEG, or blood biomarkers remain null or mixed [3, 55].	Feedback must be analyzed as experiential mediation, not only as signal control.
Immersive and social systems expand the outcome space but complicate attribution.	Social VR biofeedback improves empathy, presence, and meditation depth, while physiological synchrony evidence is weaker [45, 46, 80, 81]; mixed VR systems reduce strain without identifying a superior modality [65].	Co-regulation includes social and experiential value, but such claims require component-sensitive evaluation.
Durable transfer remains a gap rather than a demonstrated corpus finding.	Focused-attention EEG feedback shows within-session regulation with limited transfer in some studies [85]; several systems are feasibility, usability, monitoring, or classification studies rather than longitudinal training evaluations [51, 92].	transfer supporting is a forward-looking function and evaluation target, not a confirmed property of the reviewed systems.

6.1.1 Proximal Physiological Regulation. This function concerns the moment-to-moment loop between a sensed physiological process, a feedback cue, and the user's regulatory action. It is best supported when the target is both interpretable and controllable within the meditation task. Respiration feedback is the clearest example because users can directly alter breath rate, depth, or phase, and reviewed studies report proximal changes in breath focus, abdominal breathing, and slow diaphragmatic breathing [7, 49, 71]. HRV, EEG, and EDA feedback can also support proximal regulation, but their features require more careful interpretation: HRV may not outperform simple paced breathing [87], EEG remains a proxy for attention or relaxation [19, 21, 85], and EDA indexes arousal rather than meditation quality [22, 37]. The design implication is specific to biofeedback meditation: choose a signal only after specifying the practice mechanism and the action available to the practitioner. A paced-breathing system can legitimately optimize for breath rate or resonance-related HRV. A focused-attention system should specify whether it trains attentional stability, distraction recovery, alpha regulation, or some other construct. A social meditation system should distinguish experiential synchrony, physiological synchrony, and social presence. Without this mapping, the system may be technically closed-loop but conceptually ambiguous.

6.1.2 Experiential Mediation. This function concerns how feedback changes the felt quality of meditation. User experience is not a secondary usability issue: it can determine whether biofeedback supports or disrupts practice. For example, auditory neurofeedback improved attentional engagement and reduced device-measured mind wandering, but was also experienced as active, stressful, distracting, or incongruent by some participants [43]. Vibroacoustic and haptic feedback channels can support interoception when bodily awareness is the intended mechanism [25], while social and immersive systems may work by shaping presence, empathy, or shared contemplative experience rather than by producing a clean physiological training effect [45, 46, 80, 81]. The design implication is that feedback channel, salience, and timing should match the meditation object and intended experience, and should be evaluated through measures of meditation quality, attention, interoception, congruence, workload, presence, or social connection alongside physiological outcomes.

6.1.3 Transfer Supporting. This function concerns whether a system can help users regulate attention, breathing, arousal, or interoceptive awareness beyond the immediate feedback moment. It represents the weakest empirical

area in the reviewed studies because many works were acute, involved small samples, or mainly focused on feasibility, usability, classification performance, or within-session physiological changes [51, 92]. Conceptually, physiological improvements during biofeedback do not demonstrate that users can later regulate these states without feedback. For example, focused-attention EEG studies demonstrated within-session neural regulation, but the transfer to resting-state EEG, meditation-specific outcomes, or psychological changes remained limited, mixed, or exploratory [21, 85]. Therefore, we consider transfer support as a design and evaluation gap rather than a demonstrated pattern across the reviewed corpus. Mechanisms such as adaptive calibration, fading feedback, intermittent feedback, unguided transfer blocks, and post-session reflection should be treated as hypotheses unless they are evaluated through no-feedback practice blocks, retention follow-ups, or measures of everyday practice.

6.2 Framework Boundary: Real-Time Findings Versus Reflective Feedback Opportunities

Because the review excluded systems without real-time user-facing biofeedback, the corpus-derived analysis should not be read as evidence about delayed-only or reflective-feedback systems. Our empirical claims concern real-time loops in which physiology is sensed, processed, and returned to the practitioner during meditation. This includes continuous, paced, event-triggered, or otherwise in-session feedback, but not systems whose main intervention is only a daily, weekly, or post-hoc summary without real-time feedback.

Reflective feedback therefore occupies a different status in this framework. Post-session, daily, or weekly summaries are not presented as a finding from systematically reviewed non-real-time systems. They are a forward-looking design opportunity motivated by a gap in the real-time studies: many studies show short-term regulation or experiential effects, while fewer examine or discuss interpretation, longitudinal learning, off-device practice, or retention. Reflective summaries may help users make sense of patterns across sessions, plan practice, or notice transfer, but such claims require future studies that explicitly include delayed-feedback designs or hybrid real-time-plus-reflective systems. In this review, reflective feedback should be understood as a proposed direction for addressing the transfer gap, not as an empirical conclusion from the included studies.

7 DESIGN PRINCIPLES AND FUTURE DIRECTIONS

The taxonomy and empirical synthesis suggest that biofeedback meditation may be most useful when they are designed around an explicit practice mechanism. Across the reviewed studies, the most defensible claims occur when the meditation task, physiological signal, feedback channel, timing, and outcome measure form a coherent chain. The weakest claims occur when systems combine many attractive components, such as VR, social interaction, EEG, respiration, and gamified feedback, but do not isolate which component supports which meditation mechanism. Table 6 summarizes the main design principles. The subsections that follow translate these principles into a research agenda for future HCI and IMWUT work.

7.1 Principle 1: Design From the Meditation Mechanism

The central design principle is practice-mechanism fit. Biofeedback is easier to interpret when researchers specify what the meditation practice asks the user to regulate before selecting sensors or feedback cues. For paced breathing, the target is comparatively direct: users can alter respiration rate, depth, and rhythm, while respiration and HRV measures can index the resulting cardiorespiratory response [7, 49, 87]. For focused attention, the target is less direct: EEG alpha, theta, or alpha-theta features can support attentional regulation, but they remain proxies whose transfer to meditation skill must be tested rather than assumed [21, 85]. For mindfulness, open monitoring, and social or compassion-oriented practice, the target may be interoception, attentional stability, arousal awareness, presence, empathy, or shared experience rather than a single physiological optimum [25, 43, 45, 81].

Table 6. Design principles for biofeedback-supported meditation, grounded in the taxonomy and modality-practice fit analysis.

Design decision	Principle	Evidence-based rationale
Choose the physiological signal	Start from the meditation mechanism, not sensor availability.	Respiration and HRV fit paced breathing [7, 49, 87]; EEG fits attention-oriented or experiential targets [21, 45, 85]; EDA fits arousal awareness but not meditation quality in general [22, 37].
Choose the feedback channel	Match feedback salience to the practice demand.	Visual feedback channel is expressive but attention-demanding [94, 96]; auditory feedback can support eyes-free practice but may be distracting [43]; haptic feedback can support interoception and discreet guidance [25, 47].
Choose the interaction context	Decide whether the goal is controlled training, everyday deployment, immersive experience, or shared practice.	Desktop/lab systems support causal testing [11, 21]; mobile/wearable systems support scale [51, 55]; VR/social VR systems support presence and social meaning but complicate attribution [45, 80].
Choose feedback timing	Use real-time feedback when immediate correction is central to the practice.	Continuous feedback can train regulation [49, 85], but may disrupt meditation when users experience it as active or distracting [43]; event-triggered feedback may better fit some field contexts [47].
Define the outcome	Separate proximal regulation outcomes from distal wellbeing outcomes.	Breathing rate, HRV recovery, alpha modulation, or mind-wandering reduction are easier to attribute [7, 16, 43, 85] than broad stress, mood, or biomarker outcomes [3, 55].
Evaluate effectiveness	Use component comparisons when systems include VR, social interaction, or multimodal feedback.	Immersion, novelty, guidance, and physiological contingency can all drive outcomes; active controls and component comparisons are needed to isolate biofeedback-specific effects [11, 65, 87, 94].
Claim contribution	Match claims to evidence maturity.	Feasibility, usability, and classification accuracy are valuable [51, 59, 92], but should not be framed as clinical or meditation-training efficacy without controlled outcome evidence.

7.2 Principle 2: Make Feedback Actionable Without Turning Practice Into Performance Monitoring

Biofeedback is useful when it helps practitioners notice and regulate a process that would otherwise remain opaque. It becomes counterproductive when it makes meditation feel like score chasing or error correction. The reviewed studies show this tension clearly. Muse-based auditory neurofeedback improved objective attentional engagement and reduced device-measured mind wandering, yet participants also described the feedback as active, stressful, distracting, or inconsistent with their own experience [43]. HRV biofeedback in workplace mindfulness increased some engagement indicators but did not produce stronger broad self-report outcomes than comparison conditions [73]. In contrast, haptic and vibroacoustic feedback can be appropriate when the intended mechanism is interoceptive awareness rather than visual monitoring [25].

7.3 Principle 3: Match Claims to the Temporal Scale of Evidence

The corpus supports proximal regulation more strongly than durable meditation outcomes. Respiration feedback can improve breath focus and breathing behavior during practice [7, 49, 71]. HRV and cardiorespiratory feedback can support acute recovery in some contexts [4, 16]. EEG feedback can modulate alpha or alpha-theta activity within sessions [19, 21, 85]. However, these effects do not automatically imply long-term mindfulness, durable emotion regulation, stress reduction, or independent meditation skill. Several studies report subjective improvements while biomarkers, resting-state transfer, or physiological synchrony remain null or mixed [3, 45, 55, 81].

7.4 Principle 4: Treat Personalization and Signal Confidence as Part of the Interface

Biofeedback meditation systems often depend on baselines, thresholds, smoothing windows, artifact handling, and individual physiological differences. EEG systems require attention to channel placement, artifacts, individual alpha frequency, and the proxy status of bandpower features [21, 43, 85]. HRV feedback depends on time-window

choice, respiration pattern, posture, and sometimes resonance-frequency personalization [57, 84, 87]. EDA feedback depends on tonic baseline, skin properties, movement, temperature, and context [22, 37, 53]. Mobile and wearable deployments further introduce adherence, missing data, movement noise, and everyday-context variability [47, 51, 55].

7.5 Future Directions

The reviewed studies suggest several opportunities for strengthening cumulative evidence about mechanisms, contexts, and transfer in biofeedback-supported meditation. First, future work could more clearly distinguish primary outcomes from exploratory measures. The current corpus often combines physiology, self-report, biomarkers, usability, interviews, and model accuracy, which is valuable for HCI but can be difficult to interpret when outcomes diverge. Second, active-comparator and component-comparison studies would be especially useful for HRV and multimodal systems, where benefits may arise from guidance, novelty, immersion, social interaction, or feedback contingency. Third, when systems make claims about training meditation skill, transfer could be evaluated through no-feedback blocks, follow-up sessions, or everyday-practice measures. Fourth, longitudinal work could examine how personalization changes over time, including thresholds, feedback salience, and modality choice as users gain experience. Fifth, more detailed reporting of implementation choices, such as sensor placement, feature windows, smoothing, latency, calibration, artifact handling, and feedback mapping, would support comparison and replication.

Rather than asking only whether biofeedback improves meditation in general, future studies may be better positioned by specifying a narrower design question: *which physiological signal, rendered through which feedback channel, in which interaction context, at what temporal scale, supports which meditation mechanism, for which users, and relative to which alternative?* This framing keeps claims specific to biofeedback meditation while leaving room for diverse HCI outcomes, including regulation, interoception, presence, empathy, engagement, and long-term contemplative learning.

8 LIMITATION

Several limitations shape the interpretation of this review. First, the reviewed studies are heterogeneous in practice type, sensor modality, feedback design, population, study design, and outcome measures, which prevents a meaningful meta-analysis. Second, many studies are small, short, exploratory, or prototype-oriented; positive findings may be amplified by publication bias and novelty effects. Third, our focus on real-time user-facing biofeedback excludes delayed, episodic, and reflective physiological-feedback systems. These systems are interactive in an HCI sense, but they fall outside the lens of the present corpus and should be reviewed systematically in future work. Fourth, the screening process used automated assistance followed by manual validation; this improves scale but cannot eliminate the risk of misclassification when abstracts or metadata are sparse. Finally, much of the reviewed research reflects a Western, secular, and instrumental understanding of meditation. Contemplative practices are often operationalized as tools for stress reduction, attention training, or self-optimization, while their ethical, communal, cultural, and philosophical dimensions receive less attention. Future research on biofeedback-supported meditation should therefore examine not only whether a system changes a physiological signal, but also what kind of relationship with practice, the body, attention, and technology it encourages. The goal is not simply to develop more responsive systems, but to ensure that this responsiveness supports contemplative practice rather than replacing or narrowing it.

9 CONCLUSION

This review synthesized 39 studies of real-time, user-facing biofeedback for meditative and contemplative practice. We organized the design space through a taxonomy of sensing modalities, feedback channels, interaction contexts,

and temporal feedback characteristics, and used this taxonomy to interpret empirical evidence across meditation types. The evidence does not support a general claim that biofeedback improves meditation in all contexts. Instead, the clearest findings occur when the physiological signal is closely matched to the practice mechanism: respiration and HRV are most defensible for paced breathing and stress recovery, EEG is plausible for attention-oriented and experiential targets when the construct is explicit, and EDA is better understood as arousal awareness than as a direct index of meditation quality. We also introduced an review-informed co-regulation lens that distinguishes within-session physiological regulation, experiential mediation, and transfer supporting as non-hierarchical functions of biofeedback systems. This framework highlights both the promise and the limits of the current literature. Biofeedback can make subtle bodily and attentional processes actionable, but it can also distract users, encourage performance monitoring, or overstate what physiological proxies can reveal. Future work should therefore align claims with evidence, use active and component-sensitive comparators, evaluate transfer beyond the feedback session, and treat reflective feedback as an important adjacent design opportunity. Overall, biofeedback meditation systems should be designed to serve contemplative practice, not to reduce it to signal optimization.

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Listing 1. LLM screening prompt for inclusion/exclusion

```
""""You are reviewing academic papers to decide STRICT inclusion in a survey of interactive systems
that combine meditation/mindfulness/contemplative practice with *real-time physiological
biofeedback*.
```

```
Inclusion (ALL must be true):
```

- ```
1) Peer-reviewed study describing or evaluating a system that combines meditation/mindfulness (or
 closely related contemplative practice) with *real-time* physiological biofeedback.
2) The system is *interactive*: the user's physiological state is sensed and fed back via a
 computational interface to influence the contemplative experience (closed-loop).
3) Population is general or sub-clinical; studies focused purely on clinical rehabilitation are
 EXCLUDED unless contemplative practice is the *primary* focus for a general/sub-clinical
 population.
```

```
Exclusion:
```

- ```
- Purely clinical rehab focus (e.g., stroke recovery) with no primary contemplative component for
  general/sub-clinical users.
- Non-interactive sensing-only studies (no real-time feedback to the user).
```

```
Given a paper's TITLE, ABSTRACT, VENUE, and YEAR, return a STRICT JSON object:
```

```
{
  "decision": "include" | "exclude" | "unsure",
  "reasons": "short rationale tied to criteria",
  "flags": {
    "interactive_realtime_feedback": true/false,
    "contemplative_focus": true/false,
    "clinical_only": true/false,
    "is_peer_reviewed": true/false
  },
  "facets": {
    "physio_signals": ["HRV", "EEG", "EDA", "respiration", "ECG", "PPG", "EMG", "other"],
    "feedback_modalities": ["visual", "auditory", "haptic", "multimodal", "other"],
    "interface_type": ["mobile", "VR/AR", "desktop", "wearable", "installation", "other"],
    "study_type": ["lab", "field", "RCT", "pilot", "case-study", "prototype-demo", "other"],
    "venue_hint": "free text"
  }
}
```

```
Be conservative: choose "exclude" unless you clearly see all inclusion conditions satisfied. Prefer
"unsure" if the abstract is ambiguous.
```

```
""""
```