Attention and Meditative Development: A Review and Synthesis of Long-Term Meditators and Outlook for the Study of Advanced Meditation

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Abstract

Attention regulation is a core mechanism of mindfulness meditation and has been proposed to underlie many of its health-related benefits. Here, we review and synthesize behavioral findings on attentional outcomes in long-term meditators, integrating neurocognitive evidence within a meditative development framework. Key findings indicate trait-level improvements across attentional functions—executive attention, sustained attention, hierarchical and general orienting—and attentional phenomena, such as the attentional blink. Preliminary evidence also identifies trait enhancements in response inhibition, alertness, and reduced mind-wandering. Interaction effects were found for response inhibition, sustained attention, reduced mind-wandering, and alertness, with alertness benefiting most strongly from long-term and intensive acute practice. As expected, attention-based outperformed non-attention-based techniques, while *observe-and-release* practices facilitated attentional orienting and detection of closely spaced or unexpected stimuli during sustained attention tasks. These findings suggest that long-term meditation may enhance attention regulation in accordance with training specificity principles; the cognitive functions most directly targeted are the most likely to improve. Nevertheless, broader findings indicate that meditative development may depend on the balanced cultivation of multiple faculties over time, highlighting the non-linear and multidimensional nature of long-term meditative change. Consistent with traditional goals of cultivating mental faculties, the present findings may reflect attentional adaptations that support the development of advanced meditative states. Despite considerable consistency in empirical results, methodological limitations—including heterogeneous study designs and insufficient differentiation between states and traits—complicate interpretations. Future research should prioritize operationalizing and measuring contemplative constructs within integrative frameworks and using rigorous factorial designs to clarify state-trait interactions and meditation predictors.

Keywords
long-term meditators, mindfulness, advanced meditation, attention regulation, awareness, meditative development

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1. Introduction

1.1. Mindfulness Meditation and Attention

Attention—the ability to focus limited cognitive resources on relevant stimuli (Lindsay, 2020)—is thought to be a central cognitive mechanism underlying the benefits of mindfulness meditation (Jha et al., 2007; Lutz et al., 2008; Malinowski, 2013; Posner et al., 2015; Prakash et al., 2020; Tang et al., 2015). The most common secular scientific definition of mindfulness is 'the nonjudgemental and intentional act of paying attention to the present moment' (Kabat-Zinn, 1995). In contrast, traditional Buddhist definitions—such as those found in the *Satipaṭṭhāna Sutta* of the *Pāli Canon*—describe mindfulness (*sati*, from Pāli, the liturgical language of Theravāda Buddhism) as a form of 'lucid awareness' (Bodhi, 2011; Sharf, 2014) involving sustained attention and meta-awareness of cognitive processes. This mindful meta-awareness enables practitioners to remain grounded and maintain clarity during reactive or uncontrolled mental states (Bodhi, 2011; Dreyfus, 2013; Sharf, 2015; Vago & Zeidan, 2016). Another essential factor in traditional mindfulness meditation is discernment or 'clear comprehension' (Pāli: *sampajañña*), which, if concurrently cultivated with sustained mindfulness, is thought to enable direct insight into what is considered the 'true nature' of phenomenal experience (Anuruddha & Anuruddha, 2000; Bodhi, 2011; Ingram, 2018). Taken together, these traditional accounts suggest that mindfulness is cultivated alongside cognitive, perceptual, and evaluative capacities, highlighting that its attentional effects extend beyond passive observation to include active monitoring and insight-driven processing.

Building on both traditional accounts and secular frameworks, recent mechanistic models of mindfulness have proposed an integrative, multidimensional framework comprising three domains: 1) flexible concentration, 2) sensory clarity, and 3) equanimity (Young, 2016a, 2016b). In this model, flexible concentration, the domain most closely associated with attention, varies along dimensions of wide versus narrow and effortful versus effortless. Sensory clarity, the domain most closely associated with sensation and perception, involves both sensory resolution and detection. Together with equanimity, a nonreactive open stance toward all sensory experience, mindfulness meditation can be viewed as an intentional, skill-based cognitive training, with refinement of attentional and perceptual processes playing central roles (Dahl et al., 2020).

In the following sections, we will first outline neuroscientific perspectives on attention, followed by an examination of the evidence for the impact of mindfulness meditation on neurobehavioral attentional processes. Next, we will explore a potential convergence between the multidimensional mindfulness model and existing neuroscientific literature. Finally, we will discuss the benefits of studying attentional processes within a framework of meditative development, emphasizing how the process and, ultimately, outcomes for long-term meditators (LTMs) and advanced meditators may differ despite apparent superficial similarities.

1.2. Neuroscientific Perspectives on Attention

Attentional models vary depending on the specific goal of the given characterization. The tripartite model of attention, which categorizes attention based on functional characteristics and neural substrates, divides attentional processes into three components: alerting, orienting, and executive control (Petersen & Posner, 2012; Posner & Petersen, 1990). Alerting, which refers to a heightened sensitivity to incoming stimuli, has been linked to the locus coeruleus and regions within the frontoparietal network (FPN) (Xuan et al., 2016). Orienting, or directing attention to specific spatial locations, has been associated with the frontal eye fields (FEF) and the superior colliculus (Xuan et al., 2016). Executive control, which involves attentional allocation during decision-making processes, particularly in the presence of conflicting stimuli, has been correlated with activation in the cerebellum and FPN regions, including the dorsolateral prefrontal cortex (dlPFC), the inferior parietal lobule, and the anterior cingulate cortex (ACC) (Carter et al., 1999; Vincent et al., 2008; Woldorff et al., 2004).

Other models distinguish between bottom-up (exogenous) and top-down (endogenous) attention (Buschman & Miller, 2007). Top-down attention is guided by voluntary task demands, while bottom-up attention is automatically triggered by salient stimuli. Empirical evidence suggests that top-down signals primarily originate from the frontal cortex, whereas bottom-up signals arise from the parietal sensory cortices, with stronger synchrony between these areas in the beta to low-gamma range (22 to

34 Hz) during top-down attention and in the low-to-mid gamma range (35 to 55 Hz) during bottom-up attention (Buschman & Miller, 2007). Extending these findings, both prefrontal and parietal regions are implicated in both modes of attentional control (Katsuki & Constantinidis, 2014). However, during top-down attention, increased firing rates emerge earlier in the prefrontal cortex, whereas bottom-up attention is characterized by more simultaneous increases in firing in both the dlPFC and parietal regions. This suggests a differential temporal pattern of frontoparietal network activation across the two attentional modes. Further supporting this distinction, research has identified two separate neuroanatomical circuits of attention: the ventral and dorsal attentional systems (Vossel et al., 2014). The dorsal attention network involves the FEF, intraparietal sulcus, and visual system, while the ventral attention network includes the ventral frontal cortex, temporoparietal junction (TPJ), and visual cortex. Their dynamic interplay enables flexible shifts in attention to accommodate changing task demands. Top-down control is primarily exerted through the dorsal system, using cognitive information (attentional set) such as stimulus location (perceptual set) and corresponding motor responses (motor set) (Corbetta & Shulman, 2002). In contrast, bottom-up control originates from the ventral system and is responsible for detecting behaviorally relevant stimuli. Notably, while the dorsal system maintains a 'priority map' that integrates both bottom-up salience and top-down relevance to guide attention during tasks like visual search, the ventral system can override dorsal control when behaviorally necessary (Bisley & Mirpour, 2019; Ptak, 2012; Sprague et al., 2018).

Attention subtypes have also been categorized according to the nature of their targets. For example, external attention refers to the selection and modulation of sensory information, such as spatial locations, time points, sensory modalities, features, or integrated object representations, while internal attention refers to the selection of internally generated information, including task rules, response plans, and memory (Chun et al., 2011). Critically, these domains are likely orthogonal to the mechanisms that implement attentional selection: both external and internal attention can be guided by top-down (e.g. goal-directed focus on a visual target or rehearsal of a memory) or bottom-up processes (e.g., reflexive orienting to a sudden sounds or intrusion of an unwanted thought) (Van Calster et al., 2018). This distinction between external and internal attention is particularly relevant in meditation, where attention can be deliberately directed inward or outward, shaping cognitive transformations aligned with the specific goals of the practice. For a parsimonious overview of the attentional functions and targets reviewed here, see Figure 1.

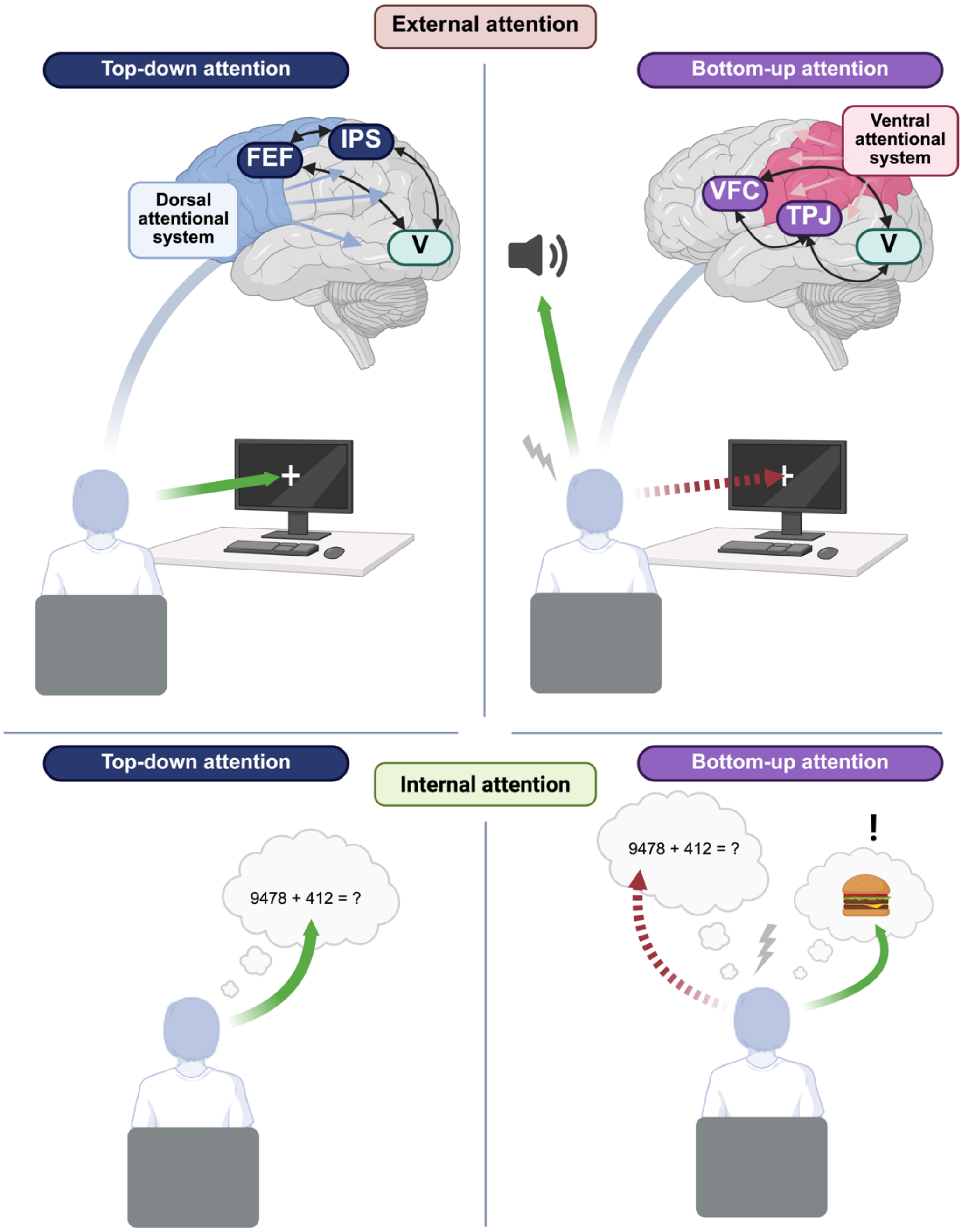

Figure 1. A Schematic Overview of Attentional Functions, Targets, and Neural Correlates. The top-left panel illustrates top-down external attention, where attention is voluntarily directed toward a perceptual target (e.g., a fixation cross), supported by the dorsal attentional system, which includes the frontal eye fields, intraparietal sulcus, and visual system. The top-right panel depicts an example of bottom-up external attention, in which a sudden external stimulus (e.g., sound) captures attention

involuntarily, mediated by the ventral attentional system, involving the ventrolateral prefrontal cortex, temporoparietal junction, and visual system. The bottom-left quadrant represents top-down internal attention, where goal-directed focus is allocated to internally generated content (e.g., mental arithmetic). The bottom-right quadrant illustrates bottom-up internal attention, where attention is involuntarily diverted by internally generated thoughts (e.g., a hunger signal). FEF = frontal eye fields; IPS = intraparietal sulcus; TPJ = temporoparietal junction; V = visual cortex; VFC = ventral frontal cortex.

1.3. A Neuroscientific Perspective on Mindfulness-based Attention Regulation

In addition to emotion regulation, body awareness, and shifts in self-perspective, attention regulation has emerged as a central mechanism of mindfulness meditation in neuroscientific research (Fox et al., 2016; Hölzel et al., 2011; Sezer et al., 2022; Tang et al., 2007, 2015; Treves et al., 2024; Vago & Silbersweig, 2012). Key brain regions implicated in attention regulation include the ACC, which plays a central role in conflict monitoring when processing incompatible or ambiguous stimuli (Botvinick et al., 1999; Carter et al., 1999); the dlPFC, which contributes to sustaining attention, modulating goal-directed selection, and resisting distraction as part of the broader FPN (Corbetta & Shulman, 2002; Ptak, 2012); and the striatum (caudate and putamen), which supports attentional control through goal-directed updating of task-relevant information and, with practice, the automatization of attentional processes (Hölzel et al., 2011; Palmero-Soler et al., 2012; Ptak, 2012; Spielberg et al., 2012; Tang et al., 2015). In a systematic review of 68 studies, trait mindfulness—the intrinsic aptitude of being mindful—has been associated with increased grey matter volume and surface area in these regions (Treves et al., 2024). Although most studies were cross-sectional, converging evidence suggests that mindfulness training may lead to similar brain differences, as training-dependent increases in trait mindfulness have been found.

As meditative expertise increases, attentional strategies appear to shift developmentally—from effortful, top-down control to more automatic, bottom-up regulation (Cooper et al., 2022). For instance, beginner meditators may exhibit increased pre-frontal (dlPFC) activation, which has been interpreted as reflecting greater recruitment of executive resources potentially associated with effortful regulation of attention and reduced self-referential thought (Jensen et al., 2012). Supporting this, neuroimaging studies of trait mindfulness demonstrate increased functional connectivity between the posterior cingulate cortex (PCC)—a core node of the default-mode network (DMN) involved in self-referential processing—and the dlPFC, part of the FPN (Sezer et al., 2022). In contrast, experienced practitioners exhibit reduced reliance on prefrontal control and show sustained activity in midline and subcortical regions, including the ACC, insula, and striatum (Tang et al., 2015). This may be accompanied by a nonlinear shift in FPN–DMN connectivity—from initial anticorrelation to coactivation—potentially reflecting less effortful sustained attention (Brefczynski-Lewis et al., 2007; Cooper et al., 2022; Devaney et al., 2021; Ehmann et al., 2025). Nonetheless, more research is needed to understand these non-linear changes across different meditative populations, activities, dosages, and practice contexts (Galante et al., 2023).

These neurobehavioral patterns of meditative development mirror practice-related changes in attentional style (e.g., aperture and control). Focused attention practices are typically associated with increased anti-correlations between task-positive (e.g., dlPFC) and task-negative (e.g., PCC) networks, engaging executive control while deactivating self-referential processes. Conversely, practices that involve broader attentional aperture show reduced anti-correlation and greater engagement of regions associated with salience and meta-awareness, such as the insula, frontopolar cortex, and inferior frontal gyrus (Fox et al., 2016; Josipovic, 2014; Josipovic et al., 2012; Lutz et al., 2015).

Importantly, despite stylistic differences in meditation practices, converging neural signatures have been observed across meditation types. Meta-analytic and empirical studies suggest that different meditation styles may recruit overlapping brain networks, particularly within the attention, salience, and self-processing systems (Fox et al., 2016; Josipovic, 2014; Josipovic et al., 2012; Lutz et al., 2015). These meditation-driven shifts in attentional aperture are also linked to dissociable neural timescales and oscillatory dynamics: focused attention practices tend to correspond with shorter timescales and increased power in higher-frequency activity, while broader attentional practices exhibit longer timescales and lower-frequency patterns (Lieberman et al., 2024; Lutz et al., 2015; Ventura et al., 2024).

To explore the dispositional effects of mindfulness practice, researchers have extensively psychometrically assessed trait mindfulness, resulting in the development of various self-report questionnaires (Baer et al., 2004, 2008; MacKillop & Anderson, 2007; Walach et al., 2006). Although sustained increases in state mindfulness through regular practice predict changes in trait mindfulness (Kiken et al., 2015), and total meditation experience correlates with higher trait mindfulness scores (Vinchurkar et al., 2014), some trait measures struggle to differentiate between novice and LTMs (Christopher et al., 2009). Importantly, higher trait mindfulness does not consistently predict neurocognitive benefits, especially in the attentional domain, where it showed a limited correlation with performance on attentional tasks (Quickel et al., 2014). Several studies have aimed to address this heterogeneity and proposed solutions (Vago et al., 2019; Van Dam et al., 2018), with unified research frameworks emerging as particularly promising for advancing the study of mindfulness meditative development (Galante et al., 2023).

Progress in the study of trait mindfulness itself suggest that existing scales and their subdomains capture distinct yet overlapping constructs, which may account for the inconsistent findings when correlating mindfulness assessments with neuroanatomical changes (Zhuang et al., 2017). Research indicates that different components of mindfulness are associated with distinct neurobehavioral mechanisms, particularly attention and affect regulation (Treves et al., 2025; Tsai et al., 2024). This aligns with the introduced multidimensional mindfulness model, which proposes that mindfulness consists of separate but interdependent components: an affective factor (equanimity) and an attentional factor (concentration) (Young, 2016a, 2016b). Supporting this model, our comprehensive review of cognitive processing in LTMs and related research suggests that mindfulness operates through opponent-process dynamics, defined as opposing forces that interact to maintain balance in physiological, emotional, or cognitive states over time (Ehmann et al., 2025; Lindsay, 2020). For example, while heightened attentional control (concentration) can enhance focus, it may also increase emotional reactivity if not counterbalanced by acceptance. This suggests that different mindfulness subdomains may interact dynamically to reinforce each other, and also demonstrates the benefit of mapping multidimensional mindfulness models onto neurobehavioral empirical findings (Ehmann et al., 2025).

1.4. Attention and Meditative Development

Lifetime meditation experience appears to influence the degree of neurocognitive change induced by meditation, with LTMs likely exhibiting more persistent and significant transformations (Cooper et al., 2022). A recent meta-analysis of mindfulness meditation and attention, without distinguishing between practice durations, reported substantial improvements in generalized attention, alerting, and executive attention, particularly in inhibitory control and updating, despite notable heterogeneity (Sumantry & Stewart, 2021). While meditation experience (e.g., hours or years of meditation practice) serves as one index of meditative development, it does not comprehensively cover meditative proficiency, including advanced meditation, which is defined by skill-, state-, and/or stage-based criteria and requires insight into the practitioner's phenomenological experience (Sacchet et al., 2024). To address this, we proposed the study of advanced meditation by focusing on the progressive unfolding of meditative states, stages, and endpoints, which are thought to be the result of ongoing practice and mastery thereof (Ehmann et al., 2025; Sacchet et al., 2024). For clarity, we distinguish meditative expertise as a *proxy* for practice duration or cumulative meditation dosage, and meditative proficiency as a measure of skill-, state-, or stage-based criteria, including the depth and quality of phenomenological experience (Sparby & Sacchet, 2022). Hence, meditative development is not a unidimensional construct, but is conceived as a multidimensional, non-linear process, involving dynamic interactions.

Recent phenomenological models have systematized meditative activities and mental states, offering frameworks for understanding attention in meditative development. Lutz et al. proposed a three-dimensional phenomenological matrix composed of object-awareness (focused attention on a specific object), de-reification (reducing the perceived solidity of phenomena), and meta-awareness (monitoring one's experience) (Lutz et al., 2015). Secondary domains such as aperture (the spatial scope over which attention is distributed), clarity (the vividness or distinctness of the attended object), stability (the ability to maintain attention), and effort (the subjective sense of cognitive exertion) contribute to attentional processing. This framework has been effectively operationalized in temporally sensitive scales (Abdoun et al., 2024; Jachs et al., 2022).

Extending this idea, our ‘activity-based phenomenological classification system’ systematically categorizes meditation practices and their associated phenomenological changes (Sparby & Sacchet, 2022). It distinguishes between meditative activities (*observing*/receptive vs. *producing*/active) and objects (specific particulars in the six sense domains: thought, sight, sound, taste, bodily sensation, and smell). Activities are further subdivided into *releasing* and *focusing* (receptive) or *imagining* and *moving* (active). Over time, active and receptive techniques may converge into a non-propositional meta-awareness centered on the object of focus (Dunne et al., 2019). As meditation deepens, the subject-object distinction is thought to dissolve further, while epistemic depth, the capacity of knowing itself, increases (Laukkonen & Chandaria, 2024; Laukkonen & Slagter, 2021). Here, awareness comes to explicitly know itself without mediation (e.g., representations). This reflexive knowing, or *awareness-of-awareness* in Sparby & Sacchet's model, constitutes what has been described as *consciousness-as-such*, a non-dual mode of awareness characterized by intrinsic self-luminosity and minimal conceptual elaboration (Dunne, 2011; Josipovic, 2019, 2021, 2024; Meling, 2021, 2022). These distinctive, advanced meditative states and lasting perceptual shifts are central to mapping the phenomenology of meditative development (Agrawal & Laukkonen, 2024; Anuruddha & Anuruddha, 2000; Galante et al., 2023; Grabovac, 2015; Ingram, 2018; Sayadaw, 1994; Sparby & Sacchet, 2024; Yang et al., 2024).

2. Methods

In the following sections, we synthesize findings on attentional processing in LTMs, integrating behavioral results with neuroscientific evidence and discussing its relevance for the study of advanced meditation and meditative development. Building on our previous work, which examined cognitive processing in LTMs but excluded attention due to scope constraints, we now focus specifically on attention and its relationship to broader patterns of cognitive-affective self-regulation (Ehmann et al., 2025).

To identify LTMs, we applied an inclusive criterion of at least 1,500 hours of lifetime meditation practice. Although no universally accepted standard exists, definitions of LTMs commonly range from 1,000 hours to several years of sustained practice. Thus, our benchmark, equivalent to roughly one hour of practice per day over five years, is consistent with the thresholds used in related research (Wipplinger et al., 2023) and aligns with the approach taken in our prior review (Ehmann et al., 2025).

For the review of these findings, we rely on all introduced attentional models, but specifically focus on Posner's tripartite model, structured around the three attentional domains—executive attention, orienting, and alertness (Petersen & Posner, 2012; Posner & Petersen, 1990). We also include sustained attention as a fourth domain, as it is a distinct and widely studied construct in meditation research, central to many contemplative practices and not fully captured by the original tripartite framework. Study characteristics are introduced in full upon first mention; for subsequent references, readers are referred to Table 1 for study details.

The discussion section summarizes key behavioral outcomes, distinguishing effects by meditation type and context, including state effects—whether induced acutely during experimental meditation or arising from habitual daily practice—and trait effects, which reflect enduring changes in baseline attentional functioning. Methodological limitations are considered, and the findings are discussed in the context of meditative development and advanced meditation.

This review synthesizes previously published studies and involves no new data collection with human or animal participants; therefore, institutional ethics approval was not required. All sources are accurately cited, research integrity has been maintained, and the authors declare no conflicts of interest.

3. Attention and Long-Term Meditators

3.1. Executive Attention

Cognitive control is a multifaceted construct that refers to the set of mental processes that enable individuals to regulate thought and behavior in alignment with internal goals, especially under conditions of uncertainty (Mackie et al., 2013). Within this broader framework, executive attentional control—or executive attention—is a critical component focused specifically on managing and regulating the processing of competing stimuli (Fan et al., 2002). It encompasses key elements such as conflict monitoring, response inhibition, and cognitive flexibility, which together enable goal-directed behavior in the face of distractions or conflicting information (Mackie et al., 2013; Petersen & Posner, 2012; Spagna et al., 2015). These components are commonly assessed using tasks that target specific aspects of conflict resolution, such as the flanker task, which requires participants to focus on a target stimulus while ignoring surrounding distractor stimuli (flankers) that may either align with or conflict with the target, thereby creating interference (Eriksen & Eriksen, 1974). When combined with a spatial cueing task (Posner & Cohen, 1980), the Attentional Network Task (ANT) provides a comprehensive evaluation of all three attentional subsystems: alerting, orienting, and executive control (Fan et al., 2002). Executive attention scores are typically calculated by subtracting reaction times (or error rates) for congruent flanker trials from those for incongruent trials; lower difference scores reflect more efficient conflict resolution and stronger executive control. Notably, executive attention is proposed to be supramodal, meaning it operates across multiple sensory modalities, allowing for conflict resolution between different types of input. Positioned at the apex of a hierarchical structure, it integrates and coordinates information, while lower-level alerting and orienting functions handle sensory input from specific modalities (Mackie et al., 2013; Spagna et al., 2015; Wang & Fan, 2007). Neural correlates of executive attention in mindfulness meditators, independent of expertise, include the ventrolateral prefrontal cortex and dorsal ACC, both components of an integrative frontoparietal network mediating between experiential and narrative self-processing, as well as the dlPFC (Vago & Silbersweig, 2012). In the following section, we summarize ten studies, six on executive attention and four on response inhibition.

Using the ANT, van den Hurk et al. conducted a cross-sectional study of 20 LTMs and 20 age- and gender-matched controls (van den Hurk et al., 2010). The meditators had an average of 14 years of mindfulness meditation experience, ranging from 3 months to 35 years—reflecting a broad range of expertise, from novice to highly experienced practitioners. In this study, the authors equated mindfulness meditation with *Vipassanā*, describing it as comprising two core activities: *observe-and-release* and *observe-and-focus* (*Samatha*) (Sparby & Sacchet, 2022). Both practices can engage internal and/or external attention. For instance, in investigative *observe-and-release* practices, practitioners attend to the arising and passing of phenomena across sensory and cognitive modalities with a discerning intention, distinguishing internal experiences (e.g., thoughts) from external stimuli (e.g., sounds, bodily sensations). In *observe-and-focus* practices, attention may be directed internally, as in sustained attention to a mental image or *nimmita*, a subtle light often emerging as part of concentration, or externally, such as when concentrating on the breath. Although participants did not meditate immediately prior to the task, they maintained a regular weekly practice of 60 to 420 minutes during the study. Results showed significantly lower error rates in the incongruent condition of the ANT for meditators compared to controls, potentially reflecting enhanced executive attention in LTMs. Limitations included the cross-sectional design, which precluded causal inferences, and the inability to disentangle the respective contributions of both practice types due to their concurrent cultivation over time.

Also using the ANT, Tsai and Chou conducted two experiments, the first of which compared the performance of 30 controls and 30 LTMs of *Dandao* meditation (Tsai & Chou, 2016). This technique focuses on *Qi*—the body's bioenergetic flow—as the meditative object. Because *Dandao* meditation can be practiced as both *observe-and-focus* and *observe-and-release* of *Qi*, LTMs were identified as primarily belonging to one of the two groups based on habitual practice. This classification roughly corresponded to internal versus external attentional styles. The LTM participants had an average of 9.8 years of meditation experience, ranging from three to 30 years. Results showed no significant differences between groups for congruent flankers (distracting stimuli that match the target); however, LTM demonstrated significantly faster reaction times for incongruent flankers (distractors that conflict with the target), indicating improved efficiency in ignoring distractions and focusing on task-relevant information (Fan et al., 2002). No significant differences were observed between meditators' habitual practices with respect to executive functioning. Notably, improvements in executive attention were correlated with trait mindfulness scores, suggesting a potential link between meditative experience and enhanced executive attention. In a second experiment, Tsai and Chou randomly assigned 40 meditation-naïve participants to either a control group or an *observe-and-focus* meditation group that practiced for 50 minutes once per week over three months (Tsai & Chou, 2016). While significant improvements in executive attention were observed after the intervention, the effects in LTMs were notably stronger than those in short-term meditators, underscoring the benefits of long-term meditative practice on executive functioning. Limitations included the cross-sectional design and reliance on self-reported meditation styles, as well as the lack of an active control group and nonsignificant between-group effects.

To investigate the potential protective effects of long-term meditation on executive attention in aging, a cross-sectional study compared 16 older LTMs, 16 older meditation-naïve adults, and 19 younger meditation-naïve adults (Sperduti et al., 2016). The meditators practiced within Zen and Tibetan Buddhism, primarily employing *observe-and-release* techniques, with meditation experience ranging from 11 to 44 years (mean: 22.5 years). Results from the ANT revealed that the LTMs exhibited reaction times comparable to those of the younger, meditation-naïve adults, effectively mitigating the age-related decline in executive attention observed in the older, meditation-naïve group. However, the study's small sample size and cross-sectional design constrained the ability to draw causal conclusions about the effects of meditation. For example, unmeasured variables, such as healthier lifestyle choices among meditators, may have contributed to the observed effects.

Converging evidence was found in 82 Isha Yoga practitioners following an intense three-month retreat (Braboszcz et al., 2013). Cognitive interference was assessed using the Stroop task, which asks participants to name the ink color of a word that spells out a different color. Before the retreat, participants had an average of four years of *Shoonya* meditation experience, with 50 having an additional three years of *Samyama* practice. *Shoonya* is an *awareness-of-awareness* practice, in which the meditator is instructed to 'do-nothing' and release any attentional fixation—either directed internally (e.g., thoughts) or externally (e.g., sounds)—dwelling instead in a state of open-presence. Such non-dual *awareness-of-awareness* practices challenge conventional characterizations of internal and external attention and have been described as involving 'non-attention' and 'non-mindfulness,' where the meditator lets 'the mind settle in its natural state' (Dunne, 2011). In contrast, *Samyama* combines both *observe-and-focus* and *observe-and-release* techniques, where practitioners attend to the breath (external attention) while maintaining an open receptivity to arising mental content (internal attention). During the first six weeks of the retreat, participants practiced *Shoonya* for 30 minutes and *Samyama* for 30 to 50 minutes daily. For the last six weeks, they switched to *Lingasanchalana* for 2 to 3 hours daily, an *observe-and-focus* technique likely using external attention (e.g., the breath). The meditators also performed 2 hours of various yoga postures, 40 minutes of physical exercise, and one hour of chanting daily. Using a within-subjects analysis, the results showed improved accuracy in meditators responding to incongruent stimuli after the retreat, suggesting improved executive attention. Prior meditation experience was only weakly associated with pre-retreat performance, showing small positive correlations with accuracy on incongruent and neutral trials, and a slight negative correlation with Stroop interference. These findings indicate that while long-term practice may be modestly linked to baseline attentional control, the more robust improvements appeared to result from the intensive retreat itself rather than cumulative experience alone. However, the absence of a control group and the heterogeneous nature of the contemplative practices limited causal interpretations.

Further research employed the Stroop task in a cross-sectional design, using 50 meditators and 10 non-meditators (Chan & Woollacott, 2007). Meditators were divided into an *observe-and-focus* (n = 20) or *observe-and-release* (n = 30) group based on their habitual practice, and their experience spanned between 82 and 19,200 hours, with daily practice ranging from 6 to 150 minutes, indicating that some participants were not LTMs. Meditators exhibited significantly reduced Stroop interference compared to the control condition. Furthermore, the daily meditation amount was negatively correlated with the Stroop interference scores ($r = -0.31$, $p < 0.01$), with no association between interference scores and total meditation experience, suggesting a stronger acute practice effect than a trait effect. No differences were observed between the meditation practices. Key limitations included a lack of random assignment and potential self-selection or motivational differences between meditators and controls, which could not be addressed due to the study's cross-sectional design.

Lastly, meditators (mean experience: 60 months; range: 4-360 months) who habitually engaged in *observe-and-focus* practices showed improved executive attention compared to naïve controls (n = 17) on the ANT without any prior meditation induction, suggesting trait-level effects (Jha et al., 2007). However, no significant differences were observed between the meditators and meditation-naïve participants once they completed an eight-week Mindfulness-Based Stress Reduction (MBSR) program—a secularized mindfulness intervention commonly used in clinical settings. This was the case even though the meditators attended a much more intense month-long *observe-and-focus* retreat involving 10–12 hours of daily practice. This may reflect ceiling effects, whereby extended training does not yield additional benefits beyond those seen in shorter interventions.

Taken together, these results suggest consistent trait improvements in executive attention in LTMs without a distinct advantage for a specific meditation type (Braboszcz et al., 2013; Chan & Woollacott, 2007; Jha et al., 2007; Sperduti et al., 2016; Tsai & Chou, 2016; van den Hurk et al., 2010).

3.1.1. Response Inhibition and Long-Term Meditators

The inhibitory facet of cognitive control, known as inhibitory control, includes two key components: response inhibition and interference control. Response inhibition refers to the ability to suppress inappropriate or impulsive behaviors, while interference control involves regulating cognitive processes, such as thoughts, emotions, and executive attention, to prevent distraction (Diamond, 2013).

Response inhibition has been primarily neuroanatomically linked to the right inferior frontal gyrus (Aron et al., 2014; Simmonds et al., 2008), the supplementary/pre-supplementary motor area (Floden & Stuss, 2006), and the basal ganglia (Rieger et al., 2003), supporting a fronto-basal-ganglia model (Chambers et al., 2009). Response inhibition is typically assessed using tasks like the Go/No-Go task, Stop-Signal task, Anti-Saccade task, and Stroop task. For instance, the Go/No-Go task involves rapid alternations of target and non-target signals, with inhibitory performance determined by correct withholding of responses to non-targets. However, these tasks may also engage other cognitive control processes, raising concerns about specificity (Chambers et al., 2009; Nigg, 2000).

Sahdra et al. assessed behavioral inhibition in LTMs using a 32-minute response inhibition task (Sahdra et al., 2011). Sixty meditators, averaging 13 years of experience, including at least three 5-10-day retreats, were stratified into a waitlist control group (n = 30) and a retreat group (n = 30), matched by age, sex, years of meditation experience, education, marital status, and income. The details of their habitual meditation practice were not reported. During the three-month retreat, participants meditated for six hours daily using a variety of techniques. Hierarchical linear regression analysis revealed significant improvements in response inhibition accuracy over time in the retreat group, suggesting training-induced gains. In contrast, the control group showed no immediate improvements but achieved similar gains after completing the retreat themselves, further supporting the effects of intense meditation training on enhanced response inhibition accuracy. The study's key limitations included potential confounds such as social support, natural retreat settings, teacher contact, and the use of multiple meditation techniques, which make it difficult to isolate the effects of attentional training alone.

Complementary findings were observed by Zanesco and colleagues in meditators undergoing an intensive one-month-long *Vipassanā* meditation retreat supplemented with *loving-kindness* meditation, a practice primarily involving internal attention (Zanesco et al., 2013). The control group (n = 24) had an average of 1,767 lifetime meditation hours over 9.91 years, while the training group (n = 26) averaged 3,312 hours across 13.67 years. No demographic differences were found between groups. Using the response inhibition task, analyses showed significant post-retreat improvements in response inhibition accuracy, favoring the training group over the control group. Self-reported changes in concentration did not predict increases in accuracy. Nonetheless, the absence of an active control group and the difficulty of matching participants on heterogeneous past meditation experience limited causal interpretations and may have confounded the attribution of effects solely to *Vipassanā* training.

Andreu and colleagues further corroborated this finding by employing the emotional Go/No-Go task, which incorporates emotionally valenced stimuli (e.g., happy, sad, neutral faces) as target and non-target signals, in a study of 31 *Vipassanā* LTMs and 31 athlete controls (Andreu et al., 2019). The LTMs averaged 2,500 hours of *Vipassanā* meditation practice over a span of 5 years. The athletes exhibited no prior meditation experience but had engaged in regular sports activities for the past 7 years, averaging 2,460 hours. There were no differences in hours and years of practice, mean age, or gender ratio between the two groups. Findings revealed significantly fewer commission and emission errors in the meditators, while their reaction times remained comparable to those of the controls, suggesting enhanced response inhibition among LTMs without compromising processing speed. However, the cross-sectional design and use of athletic controls constrained causal interpretations and may have confounded meditation effects with preexisting traits.

Diverging discoveries were reported by Korponay et al. when comparing 105 meditation-naïve individuals to 28 long-term *Theravād*a meditators on trait impulsivity using the Barratt Impulsiveness Scale–11 (BIS–11) and the Go/No-Go task (Korponay et al., 2019). The meditators tallied 9,154 hours of practice, attended at least three retreats, and practiced a minimum of 30 minutes a day. The Go/No-Go task results showed a significant difference in accuracy, favoring the meditation-naïve group. Self-report measures revealed a significant reduction in attentional impulsivity but an increase in motor and non-planning impulsivity among LTMs compared to novice controls, aligning with findings of reduced spontaneous eye blink rate in experts, which is associated with higher motor impulsivity on the BIS–11 (Korponay et al., 2017). However, the more recent results did not replicate an association between spontaneous eye blink rate and Go/No-go impulsivity. Additionally, the authors found no relationship between practice experience and impulsivity, suggesting that differences in self-reported impulsivity may stem from baseline group characteristics. Notably, similar findings in long-term Tai Chi Chuan practitioners—a form of self-defense training that emphasizes purposeful, mindful movement, consistent with the concept of an active, *produce-and-move* meditative practice—showed no differences in BIS-11 scores compared to meditation-naïve controls (Liu et al., 2020).

Collectively, studies employing intense acute mindfulness interventions (e.g., retreats) consistently report enhanced response inhibition accuracy among LTMs (Sahdra et al., 2011; Zanesco et al., 2013). However, the influence of meditation experience (trait effects) on these outcomes remains unclear due to the limited use of meditation-naïve control groups. Short-term mindfulness interventions (e.g., MBSR) generally did not yield consistent reductions in broader trait impulsivity, suggesting that improvements in response inhibition may rely on state-trait interactions (e.g., experienced meditators leveraging brief meditation inductions) or require higher-intensity practices (Korponay et al., 2019). Preliminary evidence for trait-level effects has been provided primarily by an emotional Go/No-Go task, suggesting potential interactions between attentional and emotional processes in LTMs (Andreu et al., 2019). Thus, clearly distinguishing between task-specific inhibitory control (response inhibition) and broader impulsivity traits remains essential for interpreting these mixed findings.

3.2. Orienting

The construct of attentional orienting refers to the directed focus of attention toward external sensory input or internal semantic content stored in memory (Posner, 1980). Unlike simple stimulus detection, it involves an active orienting process rather than merely surpassing a signal threshold for conscious perception. Attentional orienting aligns with Corbetta and Shulman's attentional model, which proposes that the dorsal system enables rapid, deliberate control of attention toward a target stimulus, while the ventral system corrects errors by reorienting attention to the target location (Corbetta & Shulman, 2002; Petersen & Posner, 2012). This construct is commonly assessed using Posner's cueing task, where participants are presented with a central cue directing their attention to a specific screen location (e.g., left or right). A target stimulus then appears either at the cued location (valid cue) or at an uncued location (invalid cue), and participants respond to the target. Reaction time differences between valid and invalid trials provide a measure of orienting network efficiency (Corbetta & Shulman, 2002; Fan et al., 2002; Petersen & Posner, 2012; Posner, 2016). Neuroimaging reviews on mindfulness meditation have identified the FEF, TPJ, precuneus, superior parietal lobe, pulvinar, and superior colliculus as potential neural correlates of attentional orienting (Vago & Silbersweig, 2012). Next, we summarize six studies on attentional orienting, including three that focus specifically on hierarchical attentional orienting.

Paralleling findings on enhanced executive attention in experienced Dandao meditators compared to naïve controls, Tsai and Chou reported increased attentional orienting as demonstrated by faster reaction time trends (Tsai & Chou, 2016). This effect reached significance only among meditators with greater experience in *observe-and-release* practices. These findings are supported by van den Hurk et al., who observed similar effects in mindfulness LTMs proficient in *observe-and-release* and *observe-and-focus* practices, although without identifying meditation-specific effects (van den Hurk et al., 2010). The authors interpreted the improved orienting as contributing to enhanced executive control by facilitating quicker engagement with spatial cues and reducing interference from incongruent flankers. This interaction aligns with prior work suggesting that executive attention operates supramodally, coordinating inputs across attentional systems to optimize task performance (Callejas et al., 2004, 2005). However, while LTMs demonstrated enhanced orienting performance, it remains an open question whether this reflects improvements in the orienting system itself, or whether heightened sustained attention and attentional readiness simply enabled more consistent and effective use of spatial cues.

In contrast to these results, earlier research found no evidence of enhanced attentional orienting in LTMs habitually practicing *observe-and-focus* compared to naïve controls (Jha et al., 2007). Interestingly, an eight-week MBSR program significantly improved attentional orienting in meditation-naïve participants, compared to both LTMs who completed a month-long retreat and a control group. The reasons for this remain unclear but may involve differences in the type of practices emphasized or variations in novelty and motivation between the groups. Another possibility involves cognitive overreaching during the LTMs' retreat. Overreaching, borrowed from exercise science, refers to a temporary decline in performance caused by training-related stress that exceeds the body's capacity for recovery, typically followed by a rebound to higher-than-baseline performance with adequate rest (Kreher & Schwartz, 2012). In this context, it is plausible that the LTMs' orienting performance failed to improve because they were tested at a time of maximal cognitive load induced by the intensive meditation schedule.

In summary, cross-sectional studies have found enhanced attentional orienting in LTMs compared to novice controls, though without clear meditation-specific effects (Tsai & Chou, 2016; van den Hurk et al., 2010). The differing results compared to Jha et al. may be explained by the inclusion of more experienced meditators, better-matched control groups, or the necessity of practicing *observe-and-release* techniques either alone or in conjunction with other practices.

3.2.1. Hierarchical Attentional Orienting

Hierarchical attentional orienting refers to the ability to flexibly switch between different levels of attention, such as between broad contextual features and fine-grained details. Although this phenomenon likely generalizes across sensory modalities, it has been most extensively studied in the visual domain, where experimental paradigms and neural mechanisms are well characterized. In the visual system, hierarchical orienting is often examined through tasks that contrast foreground and background attention (Navon, 1977), and is distinguished from basic spatial orienting, which involves selecting a single stimulus location. This hierarchical processing engages distinct neural pathways: global attention (processing the whole) activates temporal regions in the ventral stream, while local attention (processing details) recruits superior parietal regions in the dorsal stream (Han et al., 2004). These dissociable circuits indicate that the visual system employs distinct strategies for global and local processing, with temporal areas integrating overall shapes and parietal regions supporting precise spatial selection of details. The relationship between hierarchical attentional orienting and top-down and bottom-up processes is complex, as global processing may rely on top-down mechanisms for feature integration, while local processing may also engage top-down control for feature discrimination (Mottron & Soulières, 2013). Thus, top-down and bottom-up systems do not map neatly onto global-local orienting. The global-local task assesses attentional flexibility by presenting composite stimuli (e.g., a large square made of smaller shapes), where global (large) and local (small) elements can be congruent (e.g., a large square of small squares) or incongruent (e.g., a large square of small rectangles). This task often reveals a "global precedence" effect, with faster responses to global features, as focusing on local details requires greater effort (Fink et al., 1997; Kimchi, 1992; Navon, 1977). A congruency effect score, calculated as the reaction time difference between congruent and incongruent trials, measures the impact of conflicting global and local information.

Research on the impact of meditation on hierarchical attentional processing has yielded complex findings. Chan and Woollacott, investigating meditators' performance on a global-local task, observed faster overall reaction times across all conditions in meditators compared to controls, except in the incongruent local condition (Chan & Woollacott, 2007). No significant differences were found between *observe-and-focus* and *observe-and-release* meditators on any trial type or interference score, suggesting similar attentional effects across meditation styles. Reaction times correlated with participants' daily meditation practice duration. Congruency effects were significantly larger in the local condition than in the global condition, suggesting that processing incongruent local features was more challenging than processing incongruent global features. However, this interference effect was not specific to meditators or controls and no significant link to meditation experience was identified. While meditators and controls exhibited a global precedence effect, no group differences in global-local processing were reported. One reported limitation is that ceiling effects may have obscured group differences in orienting.

Conversely, Braboszcz reported significant congruency effects in the global condition, both before and after the retreat, but only a trend in the local condition (Braboszcz et al., 2013). Reaction times for incongruent stimuli were significantly faster in the local condition compared to the global condition before retreat, with this difference only trending toward significance after retreat.

When comparing the two studies, both demonstrated faster reaction times for congruent stimuli than for incongruent stimuli. However, Chan and Woollacott observed a tendency toward global processing, while Braboszcz et al.'s findings suggest a local processing bias in their cohort. These discrepancies may reflect differences in attentional strategies or cognitive styles, influenced by variations in meditation practices, expertise levels, task design, or cognitive fatigue from retreats.

A third study by Leeuwen et al. compared eight Buddhist Zen LTMs to education- and gender-matched meditation-naïve control participants (van Leeuwen et al., 2012). The LTMs had an average of five years of meditation experience (*SD* = 2 years) in both *observe-and-focus* and *observe-and-release* practices. In the global-local task, meditators demonstrated significantly faster reaction times across all conditions. Consistent with findings from the other two studies, accuracy levels remained high and comparable between groups, ruling out a speed-accuracy trade-off. While both groups exhibited a global precedence effect, this effect was reduced by 50% in the meditator group, suggesting an enhanced attentional balance between global and local processing.

Interestingly, in a longitudinal confirmation study, six meditators with three years of primarily *observe-and-focus* experience underwent a four-day *observe-and-release* retreat and subsequently exhibited a significant shift in attentional allocation. Prior to the retreat, they displayed a local processing bias, responding faster to local than global targets. Following the retreat, this local bias diminished, leading to more balanced processing between global and local targets. In contrast, the six age, education, and gender matched meditation naïve control participants maintained a consistent global precedence effect across both sessions. Despite promising results, the study is limited by small sample sizes and potential lifestyle confounds, such as differences in routine, stress levels, or environment between LTMs and controls.

In sum, these results indicate that LTMs exhibit faster reaction times compared to meditation-naïve controls without sacrificing accuracy, suggesting increased attentional orienting speed (Chan & Woollacott, 2007; van Leeuwen et al., 2012). However, meditation-type specific trait effects remain complex. Findings potentially point to a local processing bias associated with long-term *observe-and-focus* practice (Braboszcz et al., 2013; van Leeuwen et al., 2012), reflected in a reduced global precedence effect, whereas this bias may be reversed through *observe-and-release* practices, as evidenced by the longitudinal retreat study (van Leeuwen et al., 2012). Whether simultaneous engagement in both practices enhances bidirectional global-local attentional flexibility remains an open question. Future research should investigate how specific meditation styles and cumulative practice ('meditative dose') shape global-local attentional biases in LTMs, especially since acute state inductions appear insufficient to induce significant changes (Colzato et al., 2016), except when delivered at high intensities, such as during meditation retreats (van Leeuwen et al., 2012).

3.3. Alerting

The third component of the tripartite model of attentional processes involves the ability to perceive and respond to an impending stimulus effectively and efficiently (Brown & Bowman, 2002; Chandrakumar et al., 2019; Matthias et al., 2010; Petersen et al., 2017). Alertness, a cognitive state of readiness, falls under the broader domain of arousal, which encompasses both cognitive and physiological wakefulness and activation. Although these constructs often covary, they can also dissociate—one can be highly aroused but not alert (e.g., in a state of agitation) or alert but not highly aroused (e.g., calmly focused on a task) (Esterman & Rothlein, 2019). This distinction reflects the flexibility of attentional systems in regulating levels of alertness based on task demands.

To investigate alertness, researchers use cued detection tasks, where warning signals precede a target stimulus (Fan et al., 2002; Petersen & Posner, 2012). By manipulating cue conditions, they can isolate the temporal aspect (alerting) from the spatial aspect (orienting) of attention. Notably, alertness enhances orienting speed but does not improve accuracy (Callejas et al., 2004). Moreover, while cue-induced orienting can occur independently of alertness (Fan et al., 2002; Fernandez-Duque & Posner, 1997), these systems typically interact in real-world settings, as most stimuli provide both temporal and spatial cues (Fan et al., 2009; Petersen & Posner, 2012).

Indeed, neuroanatomically, alertness and orienting share overlapping regions, such as the TPJ, which supports response readiness. Meanwhile, alertness and executive attention engage the dlPFC, critical for performance monitoring and regulation (Posner & Rothbart, 2009; Raz & Buhle, 2006; Vago & Silbersweig, 2012). Brain areas specifically linked to alertness include the midbrain, thalamus, and associated substructures (Beas et al., 2018; Vago & Silbersweig, 2012; Van der Werf et al., 2002). The midbrain, particularly the reticular activating system, sustains wakefulness (Sarter et al., 2006), while the locus coeruleus enhances vigilance via noradrenaline-driven cortical modulation (Aston-Jones et al., 2009; Samuels & Szabadi, 2008). Within the thalamus, the intralaminar nuclei maintain alertness (Vertes et al., 2022), and the pulvinar nucleus in particular supports distractor filtering to optimize attentional engagement (Saalmann et al., 2012). The pulvinar has also been found to orchestrate theta-rhythmic (~4–7 Hz) fluctuations that coordinate shifts between focused attention and flexible reorienting across frontoparietal networks (Fiebelkorn et al., 2018, 2019; Fiebelkorn & Kastner, 2019). In the following text within this section, we review five studies on attentional alertness.

An initial investigation into the effects of meditation on attentional alertness, using the ANT, showed positive outcomes among a diverse group of LTMs participating in a month-long mindfulness meditation retreat (Jha et al., 2007). Following the retreat, LTMs demonstrated significantly improved attentional alertness scores compared to both an eight-week MBSR group and a naïve control group, which showed a significant correlation with the LTMs' meditative experience. Jha et al. interpreted these findings as indicative of increased receptive attention, a construct associated with exogenous stimulus detection and attentional readiness; however, the quasi-experimental design, lacking random assignment, limited causal inferences.

In contrast, more recent studies using the same task did not find improvements in attentional alertness in LTMs (Tsai & Chou, 2016; van den Hurk et al., 2010). The reasons for these divergent findings are unclear but may involve an interaction effect between the trait-like changes in LTMs and the intense state changes induced by the meditation retreat. Unlike the cross-sectional designs of the later studies, which involved no or minimal meditation immediately before the attentional task and focused solely on trait-based effects, Jha et al. employed a longitudinal design, allowing for a better assessment of state and state-trait interaction effects.

Kruis et al. examined the impact of *observe-and-focus* and *observe-and-release* meditation practices on spontaneous eye blink rates (sEBR) and inter-eye blink intervals (IEBR) in LTMs (Kruis et al., 2016). Both measures are strongly associated with striatal dopamine activity and other cognitive functions, such as attentional processing. For example, higher sEBR and shorter IEBR are indicative of heightened attentional alertness and cognitive engagement. The authors recruited 31 *Theravād*a and Tibetan LTMs with an average of 9,154 hours of meditation experience, including at least three meditation retreats and a daily meditation practice over the prior three years. Three distinct results were found: 1) the meditators blinked less frequently and regularly than a meditation naïve control; 2) an eight-week MBSR intervention did not change IEBR and sEBR in meditation-naïve individuals; and 3) a full day of either practice did not differently alter IEBR and sEBR in LTMs. No significant relationship was found between meditation experience and eye blink rates (Kruis et al., 2016). These findings suggest that long-term meditation may be associated with trait-like changes in physiological markers that are putatively linked to baseline striatal dopaminergic function. Rather than indicating reduced alertness, these adaptations potentially reflect a shift toward efficient, deliberate, and stable attentional engagement, consistent with the cognitive and emotional regulation improvements observed in LTMs. The lack of changes following an eight-week MBSR intervention suggests these effects require prolonged practice, while the absence of differences between meditation styles indicates a general trait-like adaptation. Furthermore, the plateauing of these effects beyond a certain expertise level suggests enduring baseline shifts rather than continuous dose-dependent changes. However, equating eye-blink rates with attentional alertness, and even further with striatal function, requires more careful neurobehavioral validation. As the authors did not directly evaluate attention or brain function in their study, it's important to interpret these results cautiously.

Together, these studies suggest that there may be trait-like changes in physiological dopaminergic functioning that enhance attentional readiness toward exogenous stimuli. These effects appear independent of specific meditation styles. However, practically meaningful improvements in attentional alertness may require intensive acute practice in LTMs, pointing to a potential interaction effect between state and trait changes. Future work could integrate molecular imaging with behavioral assessments to examine how baseline neurotransmitter function relates to attentional performance in LTMs.

3.4. Sustained Attention

Sustained attention involves maintaining engagement with a task or stimulus over extended periods, particularly in the absence of frequent, predictable, or salient external cues (Esterman et al., 2013; Sarter et al., 2001). Sustained attention is supported by nodes of several large-scale brain networks (Langner & Eickhoff, 2013), including parts of the FPN (dlPFC, ACC, and inferior parietal lobule), which mediates attentional control, cognitive flexibility, and the allocation of cognitive resources (Markett et al., 2013; Singh-Curry & Husain, 2009). The locus coeruleus-noradrenergic system contributes to sustained attention by modulating cortical excitability, vigilance, and signal amplification (Aston-Jones et al., 2009; Posner, 2008), while the thalamus contributes by gating sensory and cognitive inputs and regulating arousal levels (Fan et al., 2005; Sturm & Willmes, 2001). Additionally, the cingulo-opercular network, including the insula and ACC, maintains sustained attention by detecting task-relevant cues, monitoring performance, and integrating interoceptive signals to optimize cognitive effort (Fan et al., 2002; Lawrence et al., 2003).

Recent research highlights sustained attention as inherently fluctuating rather than static. Attentional performance alternates between "in the zone" states, where moderate DMN activity supports focus, and "out of the zone" lapses, marked by increased reaction time variability and reduced dorsal attentional network (DAN) engagement (Esterman et al., 2013; Esterman & Rothlein, 2019).

Rather than reflecting simple resource depletion, these vigilance decrements arise from fluctuations in attentional control across networks, particularly interactions between the DMN, DAN, and the salience network, which dynamically influence task engagement (Fortenbaugh et al., 2017). Recent work further shows that such fluctuations of attention follow a rhythmic pattern, particularly in the theta range (~4–7 Hz), suggesting that attention is governed by intrinsic oscillatory cycles that periodically gate access to task-relevant information, even under conditions of sustained focus (Fiebelkorn et al., 2013; Fiebelkorn & Kastner, 2019; Helfrich et al., 2018). These oscillations may be involved in inhibiting distractors ('interference control') and task performance by coordinating shifts between externally and internally directed attention. Complementing this work, connectome-based predictive modeling has demonstrated that patterns of whole-brain functional connectivity can predict both stable individual differences and moment-to-moment fluctuations in sustained attention across diverse tasks and populations (Rosenberg et al., 2016, 2020; Yoo et al., 2018). Next, we review four studies on sustained attention, one on mind-wandering, and two examining the attentional blink phenomenon.

To assess the effects of mindfulness practices and expertise on attentional stability, Valentine and Sweet recruited 19 Buddhist practitioners and 24 meditation-naïve college students to participate in a sustained attention task, the Wilkins' counting task (Valentine & Sweet, 1999). Meditators were separated into an *observe-and-focus* and an *observe-and-release* group based on habitual practice, as well as into long-term (24 months and more) and short-term (less than 24 months) groups. No further information on their practice was gathered. The counting task was performed immediately after a typical meditation session, with practitioners instructed to maintain their meditative mindset throughout the task. Results showed significantly enhanced stimulus detection in the meditators compared to the controls, suggesting increased sustained attention. Furthermore, the LTMs significantly outperformed the short-term meditators, with no differences found between the two practice conditions. Additional analysis revealed that the *observe-and-release* meditators performed better when faced with unexpected stimuli than the *observe-and-focus* group. This difference could potentially be attributed to expectancy effects within the latter group. However, the study is limited by its small sample size, lack of random assignment, and potential confounding factors such as group differences in age and motivation.

Expanding on these findings, Lutz et al. used a dichotic listening task to investigate meditation's effects on sustained attention (Lutz et al., 2009). The study included 17 LTMs with an average of 2,967 hours of meditation experience (*SD* = 3,162 hours) and 23 age-matched controls. During a three-month retreat, the LTMs engaged in 10 to 12 hours of daily practice, incorporating *observe-and-focus*, *observe-and-release*, and *loving-kindness* techniques. In contrast, the control group practiced 20 minutes of daily meditation and attended hour-long *Vipassanā* group sessions prior to laboratory assessments. Following the retreat, LTMs demonstrated greater attentional stability and reduced perceived task effort compared to the control group. Electroencephalogram (EEG) analyses further revealed improved phase consistency for deviant tones among the LTMs, suggesting an enhanced ability to sustain attention in response to auditory stimuli that deviate from the norm. Key limitations include the self-selection of retreat participants, which may have introduced pre-existing group differences.

Lee and colleagues conducted a study comparing 22 Chinese LTMs practicing *observe-and-focus* or *loving-kindness* meditation to 22 novice meditators on continuous performance test (CPT) scores (Lee et al., 2012). The study design included four groups of 11 participants each to assess interaction effects between state (baseline vs. meditative state) and trait (LTMs vs. beginners). LTMs had practiced for at least five years, with the *observe-and-focus* group averaging 5,248 hours (range: 810–17,850) and the *loving-kindness* group 7,491 hours (range: 588–17,850). Novice meditators engaged in one hour of daily meditation, divided into three 20-minute sessions, prior to testing. During the experiment, participants completed the CPT task both after a 30-minute meditation session (while maintaining their meditative state) and following a 15-minute non-meditative break.

Results revealed that *observe-and-focus* LTMs made significantly fewer omission errors compared to novices during both meditative and baseline testing, indicating a potential trait-like improvement in sustained attention. Additionally, a trend emerged for *observe-and-focus* LTMs to make fewer commission errors than novices, but only during the meditative state, suggesting a state-like effect on inhibitory control. No significant differences were observed in the loving-kindness condition for either type of error. The primary limitations included the use of an all-male, ethnically homogenous convenience sample and the absence of direct measures of attentional engagement (e.g., eye tracking), which limited both the generalizability and interpretability of the findings.

Lastly, Zanesco et al. reported significant reductions in reaction time variability on a response inhibition task among LTMs participating in a *Vipassanā* meditation retreat compared to controls (Zanesco et al., 2013). These improvements were predicted by enhancements in concentration, as measured using a seven-item self-report subscale from the Thinking Style Questionnaire (Matthews et al., 2002), suggesting that intensive meditative practice may lead to an objective stabilization of attention that aligns with participants' subjective experience. Notably, however, increases in felt concentration did not predict improvements in response inhibition accuracy, indicating a partial dissociation between subjective attentional engagement and behavioral control. This distinction highlights that while participants may accurately introspect fluctuations in attentional stability, such awareness does not necessarily extend to all domains of executive functioning.

In summary, these findings suggest enhanced sustained attention in LTMs engaging in attention-based meditations, particularly *observe-and-focus* practices, compared to emotion-based practices, potentially due to specificity-related training effects (Lee et al., 2012). *Observe-and-release* practices appeared more beneficial when LTMs were responding to unexpected stimuli (Valentine & Sweet, 1999). Furthermore, improvements in sustained attention may also become more pronounced with prolonged training, even though earlier studies have shown acute increases in sustained attention following *loving-kindness* practice (Izzetoglu et al., 2020). This finding potentially exemplifies opponent processing dynamics within meditative development, such that more positive affect and reduced emotional reactivity provide an environment in which it is easier to sustain attention. Long-term dose-response changes within sustained attention may thus potentially reflect a cognitive biomarker of advanced meditation, as skillful development across cognitive domains is necessary to achieve the highest levels of sustained attention. Notably, LTMs practicing *observe-and-focus* may demonstrate *far transfer* effects—improved attentional stability not only for meditation objects (e.g., the breath), but also for unrelated sustained attention tasks. This may support the view that *observe-and-focus* is a direct form of "practicing" sustained attention, yielding benefits that generalize beyond the training context. It remains unclear whether the reviewed results reflect interaction or trait effects (Lutz et al., 2009; Valentine & Sweet, 1999), or interaction or state effects (Zanesco et al., 2013). Nevertheless, evidence points to genuine trait improvements in sustained attention (fewer omission errors) in LTMs practicing *observe-and-focus* techniques, as well as state effects for enhanced inhibitory control (fewer commission errors) during meditation (Lee et al., 2012).

3.4.1 Mind-Wandering

Mind-wandering, in contrast to sustained attention, refers to an involuntary shift of focus from a task to unrelated thoughts or feelings (Smallwood & Schooler, 2015). It overlaps with affective, episodic, metacognitive, and executive processes, indirectly indicating reduced sustained attention. In sustained attention tasks, performance relies on vigilance and freedom from task-unrelated distractions. Mind-wandering is commonly measured by periodically asking participants whether their attention was on the task or diverted to distracting thoughts (Seli et al., 2016).

From a neuroscientific perspective, mind-wandering is commonly associated with activity in the DMN, including regions such as the medial prefrontal cortex (mPFC), PCC, and TPJ, which support internally directed cognition, including self-referential thought, autobiographical memory, and future planning (Christoff et al., 2009, 2016; Hasenkamp et al., 2012; Vago et al., 2022). However, recent research challenges the view of the DMN as uniformly 'task-negative,' showing that its activity during mind-wandering is dynamic and context-dependent, with studies reporting both decreases in DMN activation and its involvement in stable task performance or goal-relevant internal processes (Bartoli et al., 2024; Crittenden et al., 2015; Csifcsák & Mittner, 2017; Kajimura et al., 2019; Kucyi et al., 2016; Poerio et al., 2017). Meditation's effects on mind-wandering have been summarized in a putative neurocognitive model, in which enhanced meta-awareness and attentional control reduce the frequency and duration of mind-wandering, alongside shifts in large-scale brain dynamics, including reduced DMN dominance, increased sensory coupling, and strengthened executive control over internal mentation (Brandmeyer & Delorme, 2021; Ganesan et al., 2022; Hasenkamp et al., 2012). Specifically, during *observe-and-focus* practices, increased activity in the anterior insula and dorsal ACC was found during moments when meditators recognized mind-wandering. This recognition produced an attentional shift back to the target, activating the dlPFC and caudate, while decreasing activity in the mPFC (Hasenkamp et al., 2012). These dynamics are thought to support strengthened functional connectivity between the DMN and FPN, improving the regulation of internally directed cognition and sustained attention (see Section 2.1. Executive Attentional Control, and 2.3.1. Sustained Attention) (Brandmeyer & Delorme, 2021; Hasenkamp et al., 2012).

To investigate mind-wandering in LTMs, Brandmeyer and Delorme utilized an experiential sampling probe paradigm, where pre-recorded vocalized probes, delivered at random intervals (30–90 seconds), prompted participants to rate their meditation depth, mind-wandering, and drowsiness using a numeric keypad without disrupting their posture or closing their eyes (Brandmeyer & Delorme, 2018). The study included 11 LTMs and 11 meditation-naïve controls, who engaged in a one-hour *observe-and-focus* practice. LTMs reported a minimum of 2 hours of daily practice (weekly average: 14.8 hours), while controls practiced less frequently (weekly average: 3.2 hours). Findings revealed that LTMs experienced a reduced frequency and depth of mind-wandering alongside an increased depth and frequency of meditative states. The EEG results showed increased frontal midline theta activity in LTMs during meditation compared to mind-wandering, reflecting enhanced cognitive control, with theta power specifically distinguishing between different cognitive control strategies (Eisma et al., 2021). Additionally, elevated somatosensory alpha activity was observed, suggesting the suppression of distracting input (Haegens et al., 2012). Future work could investigate the temporal dynamics of reduced mind-wandering in LTMs across distinct cognitive control strategies and how these relate to theta rhythms that coordinate attentional shifts between focused attention and flexible reorienting (Fiebelkorn et al., 2013; Fiebelkorn & Kastner, 2019; Helfrich et al., 2018). Key limitations include the probe-caught design, limited meditative depth due to frequent interruptions, and potential group differences in metacognitive labeling of mental states.

In sum, this study suggests that LTMs exhibit reduced mind-wandering and enhanced meditative depth. EEG data indicates this may be linked to enhanced cognitive control and sensory processing. These findings align with previous results, which demonstrate improved executive attentional control (Braboszcz et al., 2013; Chan & Woollacott, 2007; Jha et al., 2007; Sperduti et al., 2016; Tsai & Chou, 2016; van den Hurk et al., 2010) and sustained attention in LTMs (Lee et al., 2012; Lutz et al., 2009; Valentine & Sweet, 1999; Zanesco et al., 2013), as well as evidence that intensive three-month *observe-and-focus* meditation retreats significantly reduce mind-wandering in novices (Zanesco et al., 2016).

Further research is needed to draw robust inferences about meditation-specific effects on mind-wandering in LTMs.

3.4.2. Attentional Blink

The attentional blink reflects a temporal bottleneck in attentional resource allocation, such that when two targets are presented in rapid succession, detection of the second is often impaired (Marois & Ivanoff, 2005; Raymond et al., 1992; Ward et al., 1996). This is typically measured using the Attentional Blink Task, in which two targets appear within a rapid stream of distractors. If the second target (T2) follows the first (T1) within ~500 milliseconds, attentional resources are allocated to prioritizing and consolidating the first, often at the cost of the second. Rather than a failure of the system, this phenomenon is increasingly understood as a consequence of adaptive gating mechanisms—protecting working memory from interference, preserving episodic distinctiveness, and enabling flexible allocation based on task demands and stimulus relevance (Dux & Marois, 2009; Martens & Wyble, 2010; Meng et al., 2023; Wyble et al., 2009). While several interventions have been unsuccessful in eliminating the attentional blink (Braun, 1998; Maki & Padmanabhan, 1994; Taatgen et al., 2009), others claimed success (Choi et al., 2012; Reedijk et al., 2015), suggesting that the extent of this trade-off may be modifiable, even if the underlying mechanism remains adaptively motivated.

Identifying the precise brain regions associated with this phenomenon is difficult due to the lack of temporal sensitivity of spatially specific brain imaging modalities. Thus far, differences in brain activity between detected and missed T2s have been observed, with missed T2s primarily engaging occipital and infero-temporal regions for basic perceptual processing but lacking higher-order integration. In contrast, detected T2s involve strong synchronization across the mPFC (target specification), parietal cortex (consolidation), frontopolar cortex (working memory), and ACC (decision-making) (Hommel et al., 2006; Martens & Wyble, 2010). These findings align with theories proposing that the attentional blink may indicate temporal boundaries in the allocation of selective attention (Dux & Marois, 2009).

Initial investigations into mindfulness meditation suggest that meditators allocate fewer limited cognitive resources to the first target, leaving more information-processing resources available for detecting a subsequent target, thereby reducing the attentional blink (Slagter et al., 2007). These changes were observed following an intensive three-month retreat that involved daily meditation sessions lasting 10-12 hours and were associated with enhanced sustained attention.

In a study by van Vugt and Slagter, 30 Dutch LTMs with an average of 6,041 hours of meditation experience (range: 786–31,937 hours) participated in the Attentional Blink Task (van Vugt & Slagter, 2014). Using a counterbalanced design, participants meditated for four minutes in either an *observe-and-focus* or *observe-and-release* condition before performing the task, maintaining a meditative mindset throughout. Results revealed a reduced attentional blink in the *observe-and-release* condition, likely due to decreased T1 capture, an effect observed exclusively in highly experienced meditators averaging 10,704 hours of practice.

Extending these findings, 82 experienced Isha Yoga practitioners displayed a significant 11 percentage point rise in stimulus two capture following an intensive three-month retreat, indicating a diminished attentional blink (Braboszcz et al., 2013). Surprisingly, the magnitude of this improvement mirrors that seen in the control group of Slagter et al. (Slagter et al., 2007). However, the lack of a control group in Braboszcz's study complicates definitive conclusions about the retreat's specific effects. Notably, Isha Yoga meditation emphasizes *observe-and-focus*, differing from the *observe-and-release* practices utilized in Slagter et al. and van Vugt and Slagter's research. Given the more robust meditation protocols and extended meditation experience duration in the latter investigations, this suggests a preference for highly experienced LTMs engaging in *observe-and-release* meditation in mitigating the attentional blink phenomenon.

One plausible mechanism is that *observe-and-release* practices train practitioners to disengage attention more rapidly. Rather than sustaining focus, these practices emphasize noticing and letting go, which may reduce attentional "stickiness" toward T1 and facilitate reallocation of resources to T2. This aligns with research suggesting that reducing object-focused processing can minimize exclusive resource capture, thereby improving detection of closely timed, unexpected stimuli (Taatgen et al., 2009). In addition to the least amount of object-orientation, expert *observe-and-release* practitioners may also possess the greatest meta-awareness compared to other practices (Lutz et al., 2015), sensitizing them to changes in perception, perhaps by reducing the signal detection threshold.

In summary, these findings suggest a more distributed attentional processing style in highly experienced LTMs undergoing an *observe-and-release* meditative induction. This may be characterized by a more even allocation of cognitive resources over time, reflecting a more non-fixated attentional stance. Future research should replicate these activity-specific findings and investigate the cumulative experience required for such improvements, especially in light of recent studies reporting mixed results (Bailey et al., 2023).

4. Discussion

This review examined the long-term effects of mindfulness meditation on attentional processes, synthesizing biobehavioral outcomes in LTMs. Although the field is still in its early stages, the emerging evidence suggests that mindfulness meditation may hold significant promise for enhancing attentional capacities. At the same time, many of the reported effects are based on a limited number of studies—often with small sample sizes—and should be interpreted with caution. Robust replication efforts and larger, more methodologically rigorous studies are needed to establish the reliability and generalizability of these findings.

In the following discussion, we first summarize the trait effects of long-term mindfulness meditation on attention, including the role of trait-state interactions in shaping these findings, while also assessing the potential benefits of specific meditative practices on attentional outcomes. Next, we integrate these findings into a broader model of cognitive processing and meditative development, highlighting how long-term practice enhances self-regulation and facilitates access to meditative states, stages, and endpoints associated with improved objective and subjective well-being. Finally, we address key methodological limitations and provide an outlook for future research on LTMs.

4.1. Trait, Interaction, and Practice Effects

The reviewed studies provide putative evidence for trait improvements in attentional processing broadly. Direct comparisons of groups with varying meditation experience indicated significant between-group differences, in which meditators with the highest levels of expertise showed improved sustained attention and reduced attentional blink (Valentine & Sweet, 1999; van Vugt & Slagter, 2014). Additionally, one study reported a dose-response trend for executive attention, with greater expertise linked to stronger effects (Tsai & Chou, 2016).

Supporting these findings, studies investigating the relationship between meditation expertise and biobehavioral cognitive outcomes report moderate correlations for attentional alertness (Jha et al., 2007) and weak correlations for executive attention (Braboszcz et al., 2013), potentially suggesting progressive improvements with increasing expertise. Trait mindfulness scores have also been positively associated with executive attentional control, a relationship replicated for cognitive control (Samuel & Constanzo, 2020). Notably, LTMs exhibit significantly higher mindfulness scores than controls, whereas short-term meditators do not, suggesting that trait mindfulness may mediate the link between meditation experience and enhanced executive attention.

Besides examining the direct effects of meditative expertise on cognitive-behavioral outcomes, most long-term meditation studies we reviewed employed a cross-sectional design, comparing meditation-naïve participants to LTMs, thereby enabling the assessment of general trait effects. These studies consistently indicate improvements in executive attention among LTMs (Chan & Woollacott, 2007; Tsai & Chou, 2016; van den Hurk et al., 2010), with one study suggesting a reduction in age-related executive functioning decline (Sperduti et al., 2016). Additional evidence points to enhancements in emotional response inhibition (Andreu et al., 2019) , though findings are mixed for non-emotional response inhibition, with some studies reporting better performance in meditation-naïve participants (Korponay et al., 2019). Ambiguous results in the attentional-orienting domain point to potential improvements with long-term practice (Tsai & Chou, 2016; van den Hurk et al., 2010), but also underscore the possible necessity of *observe-and-release* techniques, as short-term practices focused on these have yielded comparable effects to more heterogeneous long-term practices (Jha et al., 2007). Preliminary evidence also suggests trait-level increases in attentional speed for global-local orienting processes (Chan & Woollacott, 2007; van Leeuwen et al., 2012), while a tendency toward global or local processing may be modulated by whether practitioners habitually engage in *observe-and-release* or *observe-and-focus* techniques, respectively (Braboszcz et al., 2013; van Leeuwen et al., 2012). Regarding attentional alertness, the observed stability in eye blink rates among LTMs may suggest enduring changes in physiological markers potentially linked to dopaminergic functioning, though further research is needed to clarify their relationship to attention and underlying neurobiology (Korponay et al., 2019; Kruis et al., 2016). No distinct advantages of specific meditative practices were identified for executive attention, eye blink rates, or executive attention, either due to the heterogeneity of practice regimens among participants, study design, or lack of available data.

Many study designs used in the extant literature make it challenging to delineate state, trait, and interaction effects. For instance, Chan and Woollacott found significant correlations between daily meditation practice in LTMs and measures of executive attention and attentional flexibility while also demonstrating improved performance compared to meditation-naïve controls, suggesting the possibility of trait, state, or interaction effects on attentional performance (Chan & Woollacott, 2007). Similarly, Jha et al. observed improved alertness scores in LTMs following a retreat compared to controls and an MBSR condition (Jha et al., 2007). In contrast, cross-sectional studies found no significant differences compared to control groups (Tsai & Chou, 2016; van den Hurk et al., 2010), suggesting a possible interaction effect or a state effect driven by the intense practice during Jha et al.'s retreat.

Collectively, nine out of the 18 studies either identified interaction or state effects, contingent on the inclusion of a control condition, particularly a meditation-naïve group, in the study design (Braboszcz et al., 2013; Chan & Woollacott, 2007; Jha et al., 2007; Kruis et al., 2016; Lee et al., 2012; Lutz et al., 2009; Sahdra et al., 2011; van Vugt & Slagter, 2014; Zanesco et al., 2013). These studies found improvements in LTMs' executive attention (Braboszcz et al., 2013; Chan & Woollacott, 2007), response inhibition (Lee et al., 2012; Sahdra et al., 2011; Zanesco et al., 2013), attentional flexibility (Braboszcz et al., 2013), attentional alertness (Jha et al., 2007), sustained attention (Lee et al., 2012; Lutz et al., 2009; Zanesco et al., 2013), mind-wandering (Brandmeyer & Delorme, 2018), and reduced attentional blink (Braboszcz et al., 2013; van Vugt & Slagter, 2014).

Considering these methodological limitations, it becomes challenging to delineate the effects of different meditation types on attentional capacities. For instance, Jha et al. stand out as the sole study in the alertness domain to report significant increases among LTMs (Jha et al., 2007). These results may be due to interaction effects, the larger emphasis on *observe-and-focus* activities during the retreat, or both. Other domains may have demonstrated meditation-specific outcomes, but the limited number of studies prevents definitive conclusions about the superiority of one practice over another. For example, heightened sustained attention was observed following attention-based practices, particularly *observe-and-focus* techniques, compared to emotion-based practices, while *observe-and-release* practices appeared more effective for managing unexpected stimuli (Lee et al., 2012; Valentine & Sweet, 1999). This latter result is corroborated by attentional blink studies, which demonstrated a reduction in the attentional blink phenomenon after a short *observe-and-release* but not *observe-and-focus* practice, despite groups not differing in their habitual practice (van Vugt & Slagter, 2014). No meditation-specific effects could be discerned for the response inhibition and mind-wandering domain due to the study design or a lack of studies.

In sum, preliminary evidence suggests that LTMs exhibit trait improvements across attentional domains, with some evidence suggesting greater enhancements with increasing meditative expertise. Domain-specific interaction effects between state inductions, dispositional traits, and meditation types were common, warranting further investigation. For a comprehensive synthesis of findings, refer to Figure 2, and for a more detailed summary, see Table 1. These findings align with Sumantry & Stewart's meta-analysis, which reported improvements in generalized attention, alerting, and executive attention (Sumantry & Stewart, 2021). However, our targeted synthesis also provides additional insight into meditation-specific effects, specifically for LTMs, which were not observed in the meta-analysis.

Next, we contextualize these findings within a broader cognitive science framework, integrating contemplative and neuroscientific perspectives on meditative development. The discussion will focus on how long-term attention-based practices support advanced meditation skills and their role in enhancing self-regulation and well-being.

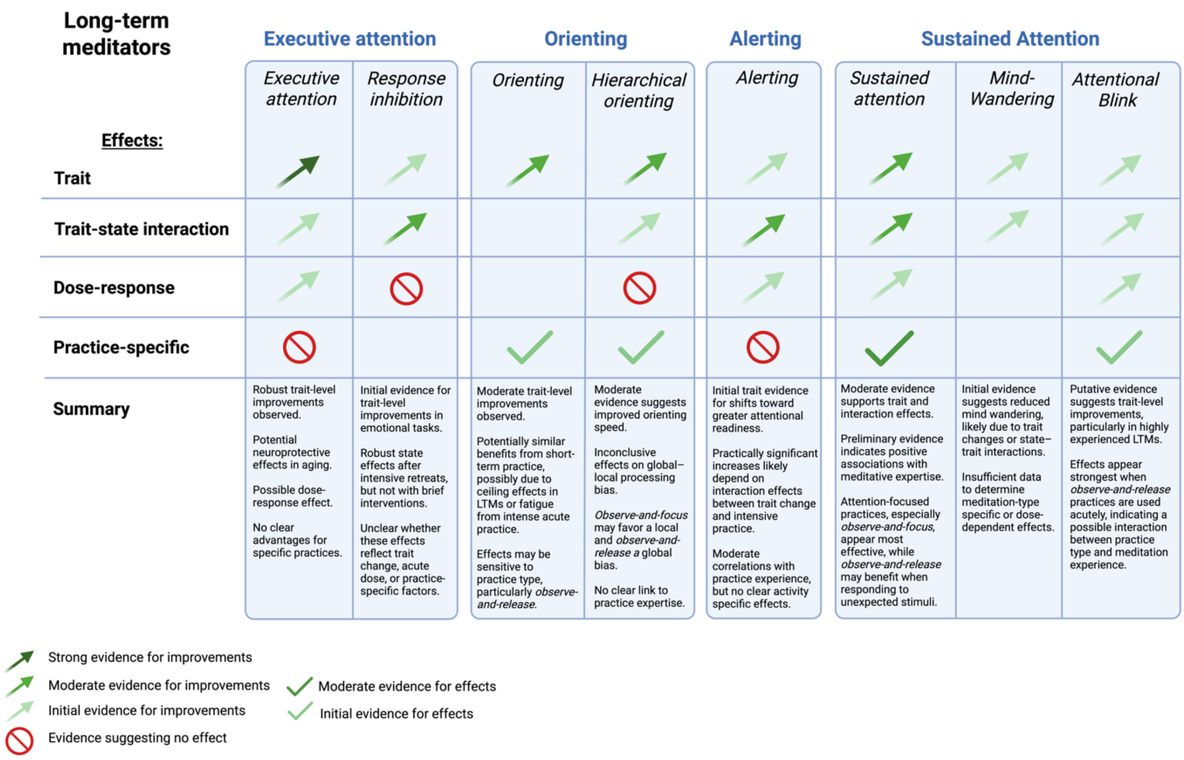

Figure 2. Attentional Results in Long-Term Meditators. This figure summarizes behavioral attentional changes in long-term meditators, organized according to the tripartite model of attention and sustained attention. Given that only 18 studies were reviewed, these findings should be considered preliminary.

4.2. Attention and Meditative Development

The reviewed findings provide evidence for improvements in attentional stability, flexibility in modulating attentional aperture and object orientation, and effortless meta-awareness in LTMs, aligning with Lutz et al.'s neurophenomenological model of meditative development (Lutz et al., 2015). Together, these attentional enhancements suggest that meditation may optimize attentional networks by increasing processing depth and neural efficiency, thereby improving attentional control while reducing cognitive effort (Kozasa et al., 2012; van den Hurk et al., 2010; van Leeuwen et al., 2012). This evidence also converges with Young's multidimensional mindfulness model, which frames mindfulness as a driver of general cognitive enhancement (Young, 2016b, 2016a).

From a dynamical systems perspective, the findings reviewed here highlight a complex, interdependent evolution of attentional and cognitive processes resulting from long-term practice. For instance, previous research suggested enhanced sustained attention may stem from increased perceptual sensitivity, which reduces the cognitive load of target discrimination (MacLean et al., 2010). While there is a general trend toward domain-specific adaptations, such as the finding that attention-based practices exert a stronger effect on attentional outcomes than emotion-based practices, our results indicate a broader pattern of integrative cognitive change (Ehmann et al., 2025). It is noteworthy that this domain specificity aligns with the principle of training specificity, which holds that training effects are strongest in the domains most directly targeted by the intervention, a principle observed across both mental and physical disciplines (Campos et al., 2002; Chiesa et al., 2011; Gallant, 2016; Giesbrecht et al., 2024; Morgan et al., 2015). Nonetheless, the core mindfulness factors—concentration, sensory clarity, and equanimity—appear to mutually reinforce and balance each other, resembling opponent processing dynamics across meditative development. This counterbalancing dynamic parallels traditional Buddhist models of mental development (Anuruddha & Anuruddha, 2000; Ingram, 2018), in which mindfulness (*sati* or 'lucid awareness') acts as a meta-regulator between other existential and cognitive faculties. Accordingly, an overemphasis within practice on one domain (e.g., attention) over another (e.g., emotion regulation) could result in an 'unbalanced' cognitive architecture, defined as a disproportionate development of specific cognitive faculties that limits their integration and overall adaptability. Such an imbalance may constrain the depth and sustainability of practice, hinder meditative development, and reduce overall well-being (Ehmann et al., 2025; Lindsay & Creswell, 2017; Lindsay, 2020; Tsai et al., 2024).

When considering the relevance of the present findings to the study of advanced meditation, one is inquiring into how long-term practice may predispose practitioners to specific meditative states, stages, and endpoints. While there is considerable overlap between long-term and advanced meditators, this relationship is not necessary or linear, highlighting the importance of phenomenological inquiry and computational formalization in distinguishing attentional profiles across meditative development (Tal et al., 2025). One promising avenue lies in translating traditional Buddhist mental factors (*cetasikas*), as outlined in the Theravāda *Abhidhamma*, into constructs amenable to cognitive neuroscience (Anuruddha & Anuruddha, 2000). These factors are thought to occur simultaneously with each moment of consciousness (*citta*) and function to shape ongoing experience by modulating the quality and dynamics of awareness, rendering them foundational for understanding the cultivation of meditative states. Within the attentional domain, *vitakka* (initial application) and *manasikāra* (mental engagement) may loosely correspond to attentional orienting and stimulus selection. *Sati* (mindfulness) and *vīriya* (effort) jointly support an alert, sustained presence of mind—*sati* by maintaining continuity of attention, and *vīriya* by energizing awareness and countering cognitive dullness. In the domain of executive attention, *adhimokkha* (resolve) and *chanda* (aspiration) parallel intentionality and goal-directed persistence. Finally, *vicāra* (sustained application) and *ekaggatā* (one-pointedness) align with sustained attention and absorption, enabling continuity of focus and resistance to distraction or mind-wandering. While these correspondences remain conceptual rather than empirical, they reflect long-standing efforts to classify and cultivate attentional and cognitive faculties and may offer a generative framework for interdisciplinary dialogue and hypothesis development (Wright et al., 2023).

A well-defined subset of advanced meditation involves advanced concentrative absorptive meditation states, specifically the *jhānas* (ACAM-J) (Sparby & Sacchet, 2024). According to Buddhist and empirical research, ACAM-J appears to be facilitated by several attentional functions and associated mental factors, including enhancements in sustained attention (*vicāra*, sustained application; *ekaggatā*, one-pointedness), attentional orienting and executive control (*vitakka*, initial application), and attentional alertness (*vīriya*, energetic effort) (Yang et al., 2024). Marked by “one-pointedness” (*samādhi*)—a mental singularity or unification characterized by sustained attention, ACAM-J is usually cultivated through *observe-and-focus* techniques such as *Samatha* meditation (Tiwari, 1988; Vago & Zeidan, 2016). Through skillful application, it is believed that such concentration practices enable access to increasingly stable and subtle states of awareness, often described as refined, which then culminate in transformative shifts in perception and cognition (Yang et al., 2024). Importantly, these practices are not considered ends in themselves; rather, they serve as gateways to meditative development and endpoints, including psychological transformation and new experiences (e.g., self-insight and transcendence, states of bliss, joy, and contentment) (Berkovich-Ohana et al., 2024). Notably, the capacity to sustain and direct attention is also closely tied to subjective experiences of freedom, suggesting that attentional regulation in LTMs may foster greater mental autonomy (Sparby et al., 2024).

Attaining ACAM-J typically begins with resolving attentional instability—a state marked by frequent distraction and a diffuse, unfocused awareness, sometimes described as “a greyness” (Sparby, 2019). As attentional control improves, this instability gives way to “access concentration”, a state of sustained and uninterrupted focus on the meditation object, often described as a “magnet-like” pull of attention (Sparby, 2019). The ACAM-J model predicts a distinct temporal progression through eight specific states, four of which utilize form-based objects derived from sensory or interoceptive phenomena (e.g., breath), and four formless states, which center on the constitutive elements of experience itself (e.g., space, consciousness, nothingness). Each state is characterized by unique phenomenological qualities and shifts in cognitive-emotional dynamics, such as attentional object orientation and perceptual clarity, as well as the progressive attenuation and emergence of bliss, joy, peace, and equanimity (Anuruddha & Anuruddha, 2000; Sparby & Sacchet, 2024; Yang et al., 2024).

Our model of ACAM-J classifies the trajectory through the eight states as light, intermediate, or deep, with the latter characterized by deeper absorption (stable, immersive focus on a single quality), less discursive thought (reduced internal verbalization or conceptual elaboration), and diminished sensory input (attenuated awareness of external stimuli) (Sparby & Sacchet, 2024).

As the "third wave" of meditation research unfolds—progressing from early work on the clinical efficacy of meditation, to investigations of its neurobiological mechanisms, and now to the neurophenomenological study of advanced meditation—this review seeks to provide an empirical foundation for understanding the current state of attentional functioning and meditative development. We are hopeful that by leveraging interdisciplinary collaboration (Galante et al., 2023), future research can advance the scientific study of advanced meditation and support the development of novel, accessible interventions that facilitate the experiential realization of meditative endpoints.

4.3. Limitations and Future Directions

We note several methodological limitations of this review and the conclusions drawn herein, namely, the studies that we reviewed are inconsistent in defining and reporting meditation practices, have limited consideration of demographic and cultural factors, include insufficient data on advanced meditative states, and are variable with respect to methodological rigor. These challenges highlight the need for a unified research framework to better characterize the behavioral, neural, and phenomenological effects of meditation (Ehmann et al., 2025; Galante et al., 2023).

Many of the reviewed studies included cross-sectional designs or acute meditation inductions of varying durations and intensities, often without testing for interactions between participants' baseline cognitive or attentional traits and observed outcomes. This important omission—present in over half of the studies reviewed—was likely due to design constraints and often precluded a clear differentiation between state and trait effects, particularly in the absence of appropriate control groups. Consequently, studies involving LTMs frequently lack clarity regarding whether observed effects reflected enduring trait changes, transient induction effects, or their interaction. Of the 18 studies explicitly examining trait effects, only five assessed correlations between behavioral performance and meditation expertise, with three reporting no significant associations (Chan & Woollacott, 2007; Korponay et al., 2019; Kruis et al., 2016). Additionally, few studies directly compared meditators at different expertise levels (e.g., short-term vs. long-term practitioners), making it difficult to establish developmental trajectories in attentional capacities. While findings generally indicate improvements in dispositional attention in LTMs, these benefits are often inferred from comparisons across multiple studies rather than from direct trait-level assessments. The absence of clear dose-response relationships, combined with the robust effects observed in some short-term interventions, raises questions about the necessity of intensive, prolonged practice and suggests the possibility of diminishing returns from long-term meditation.

To improve the differentiation of state, trait, and practice-specific effects in meditation research, future studies should employ mixed-factorial designs that systematically assess participants' baseline traits, practice history, and acute state changes. Key baseline measures should include regular meditation type (Sparby & Sacchet, 2022), average daily meditation duration, history of intensive practice (e.g., retreats), and total lifetime meditation hours. Incorporating a meditation-naïve control group as a between-group factor would facilitate clearer identification of trait-specific effects. Additionally, stratifying participants by expertise level (e.g., short-term vs. long-term practitioners) would enable more precise comparisons.

To isolate genuine state effects related to LTMs, and ultimately advanced meditation, both meditation-naïve controls and experienced meditators could engage in one or more acute meditation sessions, enabling the construction of a time by practice by trait design matrix. This approach would allow researchers to systematically disentangle state effects, trait effects, and their interactions. Furthermore, incorporating incentive conditions could help control for attentional effort, clarifying the influence of motivation and general arousal on attentional performance (Jensen et al., 2012).

To bridge the gap between phenomenological experiences in advanced meditation and underlying neurobiological mechanisms, future studies should leverage recent integrative frameworks to translate subjective experiences into testable neuroscientific hypotheses (Wright et al., 2023). Investigating meditative development through the lens of attentional processes may offer a particularly promising approach. This is because both empirical and contemplative traditions provide detailed models of attention that can guide the initial formalization of hypotheses. Such an approach would allow for a more structured mapping between first-person reports and objective neurobiological measures, thereby enhancing our understanding of how meditative development shapes cognition and brain function.

We acknowledge that such designs require substantial resources and statistical power, which may be impractical for many studies and research teams. However, even when full implementation is not feasible, careful consideration of these interactions during study design and explicit discussion of methodological constraints in published reports would enhance the interpretability of findings. Strengthening methodological rigor in this way will improve our ability to investigate meditative development and better delineate the distinct effects of various meditation practices and intensities.

4.4. Conclusion

Here we synthesized the attentional biobehavioral outcomes of LTMs, including evidence for trait improvements in executive and sustained attention, classical and hierarchical attentional orienting, and attentional blink. Additionally, more putative evidence points to enhancements in response inhibition, alertness, and reductions in mind-wandering. However, methodological limitations in over half of the studies restricted definitive interpretations of trait effects. Thus, while improvements in response inhibition were observed, it remains uncertain whether these effects stem from state-trait interactions or the influence of intensive acute practice regimens (e.g., meditation retreats). Similar ambiguities were identified for mind-wandering and sustained attention, where improvements may depend on either trait or interaction effects. Attentional alertness, in particular, appears to rely on an interaction between intense acute practice and long-term meditation experience. Certain domains exhibited overlaps between trait, state, and practice-related effects. For attentional orienting, moderate evidence supports trait effects; however, short-term practice in *observe-and-release* techniques may offer comparable benefits to long-term practice, underscoring the importance of the meditative activity itself. Similarly, reductions in the attentional blink were most pronounced in LTMs actively engaging in *observe-and-release* practices, suggesting an interaction effect between practice condition and long-term experience. In the context of practice-specific effects, attention-based practices outperformed emotion-based practices for sustained attention, and *observe-and-release* practices seemed generally beneficial for temporally or spatially unexpected stimuli.

Overall, the observed cognitive changes align with the principle of training specificity, whereby improvements emerge most strongly in the domains directly targeted by practice activity. Yet, in light of our findings, productive advancement within meditative development may depend not only on intensive training within a single domain but on the balanced cultivation of multiple faculties, reflecting the inherent non-linearity and multidimensionality of the meditative path. Consistent with traditional meditative goals of refining mental faculties, the present findings may suggest neurobehavioral adaptations that could provide a foundation for cultivating cognitive and mental faculties associated with advanced meditative states, such as ACAM-J. However, to fully elucidate the relationship between advanced meditation and long-term practice, interdisciplinary and multimethod research is needed, with clearer distinctions among stimulus-driven, state-dependent, and entrained trait effects.

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Figure 1 was created in BioRender. Ehmann, S. and Sezer, I. (2025) https://BioRender.com/k64c646
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Figure 3 was created in BioRender. Ehmann, S and Sezer, I. (2025) https://BioRender.com/iqv1ziv

Data Code and Availability
As this article is a narrative review and does not involve the collection or analysis of original data, no datasets or code are associated with this work.

Author Contributions:
Sebastian Ehmann contributed to Conceptualization, Methodology, Investigation, Data Curation, Writing – Original Draft, Writing – Review & Editing, Visualization, and Project Administration. **Idil Sezer** contributed to Conceptualization, Methodology, Investigation, Data Curation, Writing – Original Draft, Writing – Review & Editing, Visualization, and Supervision. **Arielle S. Keller** contributed to Conceptualization, Methodology, Investigation, Data Curation, Writing – Original Draft, Writing – Review & Editing, Visualization, and Supervision. **Isaac N. Treves** contributed to Conceptualization and Writing – Review & Editing. **Matthew D. Sacchet** contributed to Conceptualization, Methodology, Resources, Writing – Original Draft, Writing – Review & Editing, Supervision, and Project Administration.

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Glossary

ACAM-J — advanced concentrative absorption meditation–jhana, encompasses eight progressively more refined mental states of concentrative absorption, with the first four using form (e.g., the breath) as their object and the latter four focusing on formlessness (e.g., infinite space).

ACC — anterior cingulate cortex

ANT — attentional network task

CPT — continuous performance test

DMN — default mode network; associated with self-referential thought, autobiographical memory, and mental time travel.

dlPFC — dorsolateral prefrontal cortex

FEF — frontal eye fields

FPN — frontoparietal network

LTMs — long-term meditators

PCC — posterior cingulate cortex

mPFC	medial prefrontal cortex
Mindfulness meditation	mindfulness meditation typically comprises *Samatha* and *Vipassanā*, both *observing* type practices, with the former based on *focusing* attention and the latter a combination of *focusing* and *releasing* activities.
Tai Chi Chuan	Tai Chi Chuan is a form of self-defense training that emphasizes purposeful movement, making it consistent with the concept of an active, *produce-and-move* meditative practice.
Theravāda Buddhism	Theravāda practices include investigative *observe-and-release* and *observe-and-focus* activities as well as compassion and loving-kindness (*metta*) practices.
Tibetan Buddhism	Tibetan Buddhism practices integrate *receptive observation-based* practices with *active* visualizations, mantra recitations, and compassion-based meditations like Tonglen, aimed at transforming the self and developing universal compassion.
TPJ	temporoparietal junction
Vipassanā	An investigatory mediation type typically utilizing both *observe-and-focus*, and *observe-and-release* practices.

Declaration of generative AI and AI-assisted technologies in the writing process

During the preparation of this work, the first author used Chat GPT-4o (OpenAI, 2025) in order to improve the clarity of the written content (but not for adding any new content or citations). After using this tool/service, the first author reviewed and edited the content as needed. All authors take full responsibility for the publication.

References

Abdoun, O., Poublan, A., Offort, S., Pagnoni, G., & Lutz, A. (2024). *Shedding light on changes in subjective experience during an intensive contemplative retreat: The Lyon Assessment of Meditation Phenomenology (LAMP) questionnaire*. https://doi.org/10.31234/osf.io/qs53h

Agrawal, V., & Laukkonen, R. E. (2024). *Nothingness in meditation: Making sense of emptiness and cessation*. OSF. https://doi.org/10.31234/osf.io/tygdf

Andreu, C. I., Palacios, I., Moënne-Loccoz, C., López, V., Franken, I. H. A., Cosmelli, D., & Slagter, H. A. (2019). Enhanced response inhibition and reduced midfrontal theta activity in experienced Vipassana meditators. *Scientific Reports*, *9*(1), 13215. https://doi.org/10.1038/s41598-019-49714-9

Anuruddha, & Anuruddha. (2000). *A comprehensive manual of Abhidhamma: The Abhidhammattha sangaha of Ācariya Anuruddha* (Bodhi, Ed.; 1. BPS Pariyatti ed). BPS Pariyatti Ed.

Aron, A. R., Robbins, T. W., & Poldrack, R. A. (2014). Inhibition and the right inferior frontal cortex: One decade on. *Trends in Cognitive Sciences*, *18*(4), 177–185. https://doi.org/10.1016/j.tics.2013.12.003

Aston-Jones, G., Meijas-Aponte, C. A., & Waterhouse, B. (2009). Norepinephrine: CNS Pathways and Neurophysiology. In L. R. Squire (Ed.), *Encyclopedia of Neuroscience* (pp. 1237–1248). Academic Press. https://doi.org/10.1016/B978-008045046-9.01153-0

Baer, R. A., Smith, G. T., & Allen, K. B. (2004). Assessment of Mindfulness by Self-Report: The Kentucky Inventory of Mindfulness Skills. *Assessment*, *11*(3), 191–206. https://doi.org/10.1177/1073191104268029

Baer, R. A., Smith, G. T., Lykins, E., Button, D., Krietemeyer, J., Sauer, S., Walsh, E., Duggan, D., & Williams, J. M. G. (2008). Construct Validity of the Five Facet Mindfulness Questionnaire in Meditating and Nonmeditating Samples. *Assessment*, *15*(3), 329–342. https://doi.org/10.1177/1073191107313003

Bailey, N. W., Baell, O., Payne, J. E., Humble, G., Geddes, H., Cahill, I., Hill, A. T., Chung, S. W., Emonson, M., Murphy, O. W., & Fitzgerald, P. B. (2023). Experienced Meditators Show Multifaceted Attention-Related Differences in Neural Activity. *Mindfulness*, *14*(11), 2670–2698. https://doi.org/10.1007/s12671-023-02224-2

Bartoli, E., Devara, E., Dang, H. Q., Rabinovich, R., Mathura, R. K., Anand, A., Pascuzzi, B. R., Adkinson, J., Kenett, Y. N., Bijanki, K. R., Sheth, S. A., & Shofty, B. (2024). Default mode network electrophysiological dynamics and causal role in creative thinking. *Brain: A Journal of Neurology*, *147*(10), 3409–3425. https://doi.org/10.1093/brain/awae199

Beas, B. S., Wright, B. J., Skirzewski, M., Leng, Y., Hyun, J. H., Koita, O., Ringelberg, N., Kwon, H.-B., Buonanno, A., & Penzo, M. A. (2018). The locus coeruleus drives disinhibition in the midline thalamus via a dopaminergic mechanism. *Nature Neuroscience*, *21*(7), 963–973. https://doi.org/10.1038/s41593-018-0167-4

Berkovich-Ohana, A., Brown, K. W., Gallagher, S., Barendregt, H., Bauer, P., Giommi, F., Nyklíček, I., Ostafin, B., Raffone, A., Slagter, H. A., Trautwein, F.-M., Vago, D., & Amaro, A. (2024). Pattern Theory of Selflessness: How Meditation May Transform the Self-Pattern. *Mindfulness*. https://doi.org/10.1007/s12671-024-02418-2

Bisley, J. W., & Mirpour, K. (2019). The neural instantiation of a priority map. *Current Opinion in Psychology*, *29*, 108–112. https://doi.org/10.1016/j.copsyc.2019.01.002

Bodhi, B. (2011). What does mindfulness really mean? A canonical perspective. *Contemporary Buddhism*, *12*(1), 19–39. https://doi.org/10.1080/14639947.2011.564813

Botvinick, M., Nystrom, L. E., Fissell, K., Carter, C. S., & Cohen, J. D. (1999). Conflict monitoring versus selection-for-action in anterior cingulate cortex. *Nature*, *402*(6758), 179–181. https://doi.org/10.1038/46035

Braboszcz, C., Cahn, B. R., Balakrishnan, B., Maturi, R. K., Grandchamp, R., & Delorme, A. (2013). Plasticity of visual attention in Isha yoga meditation practitioners before and after a 3-month retreat. *Frontiers in Psychology*, *4*. https://doi.org/10.3389/fpsyg.2013.00914

Brandmeyer, T., & Delorme, A. (2018). Reduced mind wandering in experienced meditators and associated EEG correlates. *Experimental Brain Research*, *236*(9), 2519–2528. https://doi.org/10.1007/s00221-016-4811-5

Brandmeyer, T., & Delorme, A. (2021). Meditation and the wandering mind: A theoretical framework of underlying neurocognitive mechanisms. *Perspectives on Psychological Science : A Journal of the Association for Psychological Science*, *16*(1), 39–66. https://doi.org/10.1177/1745691620917340

Braun, J. (1998). Vision and attention: The role of training. *Nature*, *393*(6684), 424–425. https://doi.org/10.1038/30875

Brefczynski-Lewis, J. A., Lutz, A., Schaefer, H. S., Levinson, D. B., & Davidson, R. J. (2007). Neural correlates of attentional expertise in long-term meditation practitioners. *Proceedings of the National Academy of Sciences*, *104*(27), 11483–11488. https://doi.org/10.1073/pnas.0606552104

Brown, V. J., & Bowman, E. M. (2002). Alertness. In V. S. Ramachandran (Ed.), *Encylopedia of the Human Brain* (pp. 99–110). Academic Press/Elsevier.

Buschman, T. J., & Miller, E. K. (2007). Top-Down Versus Bottom-Up Control of Attention in the Prefrontal and Posterior Parietal Cortices. *Science*, *315*(5820), 1860–1862. https://doi.org/10.1126/science.1138071

Callejas, A., Lupiàñez, J., Funes, M. J., & Tudela, P. (2005). Modulations among the alerting, orienting and executive control networks. *Experimental Brain Research*, *167*(1), 27–37. https://doi.org/10.1007/s00221-005-2365-z

Callejas, A., Lupiáñez, J., & Tudela, P. (2004). The three attentional networks: On their independence and interactions. *Brain and Cognition*, *54*(3), 225–227. https://doi.org/10.1016/j.bandc.2004.02.012

Cameron S. Carter, Matthew M. Botvinick, & Jonathan D. Cohen. (1999). The Contribution of the Anterior Cingulate Cortex to Executive Processes in Cognition. *Reviews in the Neurosciences*, *10*(1), 49–58. https://doi.org/10.1515/REVNEURO.1999.10.1.49

Campos, G. E., Luecke, T. J., Wendeln, H. K., Toma, K., Hagerman, F. C., Murray, T. F., Ragg, K. E., Ratamess, N. A., Kraemer, W. J., & Staron, R. S. (2002). Muscular adaptations in response to three different resistance-training regimens: Specificity of repetition maximum training zones. *European Journal of Applied Physiology*, *88*(1), 50–60. https://doi.org/10.1007/s00421-002-0681-6

Chambers, C. D., Garavan, H., & Bellgrove, M. A. (2009). Insights into the neural basis of response inhibition from cognitive and clinical neuroscience. *Neuroscience & Biobehavioral Reviews*, *33*(5), 631–646. https://doi.org/10.1016/j.neubiorev.2008.08.016

Chan, D., & Woollacott, M. (2007). Effects of Level of Meditation Experience on Attentional Focus: Is the Efficiency of Executive or Orientation Networks Improved? *The Journal of Alternative and Complementary Medicine*, *13*(6), 651–658. https://doi.org/10.1089/acm.2007.7022

Chandrakumar, D., Keage, H. A. D., Gutteridge, D., Dorrian, J., Banks, S., & Loetscher, T. (2019). Interactions between spatial attention and alertness in healthy adults: A meta-analysis. *Cortex*, *119*, 61–73. https://doi.org/10.1016/j.cortex.2019.03.016

Chiesa, A., Calati, R., & Serretti, A. (2011). Does mindfulness training improve cognitive abilities? A systematic review of neuropsychological findings. *Clinical Psychology Review*, *31*(3), 449–464. https://doi.org/10.1016/j.cpr.2010.11.003

Choi, H., Chang, L.-H., Shibata, K., Sasaki, Y., & Watanabe, T. (2012). Resetting capacity limitations revealed by long-lasting elimination of attentional blink through training. *Proceedings of the National Academy of Sciences*, *109*(30), 12242–12247. https://doi.org/10.1073/pnas.1203972109

Christoff, K., Gordon, A. M., Smallwood, J., Smith, R., & Schooler, J. W. (2009). Experience sampling during fMRI reveals default network and executive system contributions to mind wandering. *Proceedings of the National Academy of Sciences*, *106*(21), 8719–8724. https://doi.org/10.1073/pnas.0900234106

Christoff, K., Irving, Z. C., Fox, K. C. R., Spreng, R. N., & Andrews-Hanna, J. R. (2016). Mind-wandering as spontaneous thought: A dynamic framework. *Nature Reviews Neuroscience*, *17*(11), 718–731. https://doi.org/10.1038/nrn.2016.113

Christopher, M. S., Christopher, V., & Charoensuk, S. (2009). Assessing "Western" Mindfulness Among Thai Theravāda Buddhist Monks. *Mental Health, Religion & Culture*, *12*(3), 303–314. https://doi.org/10.1080/13674670802651487

Chun, M. M., Golomb, J. D., & Turk-Browne, N. B. (2011). A taxonomy of external and internal attention. *Annual Review of Psychology*, *62*, 73–101. https://doi.org/10.1146/annurev.psych.093008.100427

Colzato, L. S., van der Wel, P., Sellaro, R., & Hommel, B. (2016). A single bout of meditation biases cognitive control but not attentional focusing: Evidence from the global–local task. *Consciousness and Cognition*, *39*, 1–7. https://doi.org/10.1016/j.concog.2015.11.003

Cooper, A. C., Ventura, B., & Northoff, G. (2022). Beyond the veil of duality—Topographic reorganization model of meditation. *Neuroscience of Consciousness*, *2022*(1), niac013. https://doi.org/10.1093/nc/niac013

Corbetta, M., & Shulman, G. L. (2002). Control of goal-directed and stimulus-driven attention in the brain. *Nature Reviews Neuroscience*, *3*(3), 201–215. https://doi.org/10.1038/nrn755

Crittenden, B. M., Mitchell, D. J., & Duncan, J. (2015). Recruitment of the default mode network during a demanding act of executive control. *eLife*, *4*, e06481. https://doi.org/10.7554/eLife.06481

Csifcsák, G., & Mittner, M. (2017). Linking brain networks and behavioral variability to different types of mind-wandering. *Proceedings of the National Academy of Sciences of the United States of America*, *114*(30), E6031–E6032. https://doi.org/10.1073/pnas.1705108114

Dahl, C. J., Wilson-Mendenhall, C. D., & Davidson, R. J. (2020). The plasticity of well-being: A training-based framework for the cultivation of human flourishing. *Proceedings of the National Academy of Sciences*, *117*(51), 32197–32206. https://doi.org/10.1073/pnas.2014859117

Devaney, K. J., Levin, E. J., Tripathi, V., Higgins, J. P., Lazar, S. W., & Somers, D. C. (2021). Attention and Default Mode Network Assessments of Meditation Experience during Active Cognition and Rest. *Brain Sciences*, *11*(5), Article 5. https://doi.org/10.3390/brainsci11050566

Diamond, A. (2013). Executive Functions. *Annual Review of Psychology*, *64*(Volume 64, 2013), 135–168. https://doi.org/10.1146/annurev-psych-113011-143750

Dreyfus, G. (2013). Is Mindfulness Present-Centred and Non-Judgmental? A Discussion of the Cognitive Dimensions of Mindfulness. In *Mindfulness*. Routledge.

Dunne, J. (2011). Toward an understanding of non-dual mindfulness. *Contemporary Buddhism*, *12*(1), 71–88. https://doi.org/10.1080/14639947.2011.564820

Dunne, J. D., Thompson, E., & Schooler, J. (2019). Mindful meta-awareness: Sustained and non-propositional. *Current Opinion in Psychology*, *28*, 307–311. https://doi.org/10.1016/j.copsyc.2019.07.003

Dux, P. E., & Marois, R. (2009). The attentional blink: A review of data and theory. *Attention, Perception, & Psychophysics*, *71*(8), 1683–1700. https://doi.org/10.3758/APP.71.8.1683

Ehmann, S., Sezer, I., Treves, I. N., Gabrieli, J. D. E., & Sacchet, M. D. (2025). Mindfulness, cognition, and long-term meditators: Toward a science of advanced meditation. *Imaging Neuroscience*. https://doi.org/10.1162/IMAG.a.82

Eisma, J., Rawls, E., Long, S., Mach, R., & Lamm, C. (2021). Frontal midline theta differentiates separate cognitive control strategies while still generalizing the need for cognitive control. *Scientific Reports*, *11*(1), 14641. https://doi.org/10.1038/s41598-021-94162-z

Eriksen, B. A., & Eriksen, C. W. (1974). Effects of noise letters upon the identification of a target letter in a nonsearch task. *Perception & Psychophysics*, *16*(1), 143–149. https://doi.org/10.3758/BF03203267

Esterman, M., Noonan, S. K., Rosenberg, M., & DeGutis, J. (2013). In the Zone or Zoning Out? Tracking Behavioral and Neural Fluctuations During Sustained Attention. *Cerebral Cortex*, *23*(11), 2712–2723. https://doi.org/10.1093/cercor/bhs261

Esterman, M., & Rothlein, D. (2019). Models of sustained attention. *Current Opinion in Psychology*, *29*, 174–180. https://doi.org/10.1016/j.copsyc.2019.03.005

Fan, J., Gu, X., Guise, K. G., Liu, X., Fossella, J., Wang, H., & Posner, M. I. (2009). Testing the behavioral interaction and integration of attentional networks. *Brain and Cognition*, *70*(2), 209–220. https://doi.org/10.1016/j.bandc.2009.02.002

Fan, J., McCandliss, B. D., Fossella, J., Flombaum, J. I., & Posner, M. I. (2005). The activation of attentional networks. *NeuroImage*, *26*(2), 471–479. https://doi.org/10.1016/j.neuroimage.2005.02.004

Fan, J., McCandliss, B. D., Sommer, T., Raz, A., & Posner, M. I. (2002). Testing the efficiency and independence of attentional networks. *Journal of Cognitive Neuroscience*, *14*(3), 340–347. https://doi.org/10.1162/089892902317361886

Fernandez-Duque, D., & Posner, M. I. (1997). Relating the mechanisms of orienting and alerting. *Neuropsychologia*, *35*(4), 477–486. https://doi.org/10.1016/S0028-3932(96)00103-0

Fiebelkorn, I. C., & Kastner, S. (2019). A Rhythmic Theory of Attention. *Trends in Cognitive Sciences*, *23*(2), 87–101. https://doi.org/10.1016/j.tics.2018.11.009

Fiebelkorn, I. C., Pinsk, M. A., & Kastner, S. (2018). A Dynamic Interplay within the Frontoparietal Network Underlies Rhythmic Spatial Attention. *Neuron*, *99*(4), 842-853.e8. https://doi.org/10.1016/j.neuron.2018.07.038

Fiebelkorn, I. C., Pinsk, M. A., & Kastner, S. (2019). The mediodorsal pulvinar coordinates the macaque fronto-parietal network during rhythmic spatial attention. *Nature Communications*, *10*(1), 215. https://doi.org/10.1038/s41467-018-08151-4

Fiebelkorn, I. C., Saalmann, Y. B., & Kastner, S. (2013). Rhythmic Sampling within and between Objects despite Sustained Attention at a Cued Location. *Current Biology*, *23*(24), 2553–2558. https://doi.org/10.1016/j.cub.2013.10.063

Fink, G. R., Halligan, P. W., Marshall, J. C., Frith, C. D., Frackowiak, R. S., & Dolan, R. J. (1997). Neural mechanisms involved in the processing of global and local aspects of hierarchically organized visual stimuli. *Brain*, *120*(10), 1779–1791. https://doi.org/10.1093/brain/120.10.1779

Floden, D., & Stuss, D. T. (2006). Inhibitory Control is Slowed in Patients with Right Superior Medial Frontal Damage. *Journal of Cognitive Neuroscience*, *18*(11), 1843–1849. https://doi.org/10.1162/jocn.2006.18.11.1843

Fortenbaugh, F. C., DeGutis, J., & Esterman, M. (2017). Recent theoretical, neural, and clinical advances in sustained attention research. *Annals of the New York Academy of Sciences*, *1396*(1), 70–91. https://doi.org/10.1111/nyas.13318

Fox, K. C. R., Dixon, M. L., Nijeboer, S., Girn, M., Floman, J. L., Lifshitz, M., Ellamil, M., Sedlmeier, P., & Christoff, K. (2016). Functional neuroanatomy of meditation: A review and meta-analysis of 78 functional neuroimaging investigations. *Neuroscience and Biobehavioral Reviews*, *65*, 208–228. https://doi.org/10.1016/j.neubiorev.2016.03.021

Galante, J., Grabovac, A., Wright, M., Ingram, D. M., Van Dam, N. T., Sanguinetti, J. L., Sparby, T., van Lutterveld, R., & Sacchet, M. D. (2023). A Framework for the Empirical Investigation of Mindfulness Meditative Development. *Mindfulness*, *14*(5), 1054–1067. https://doi.org/10.1007/s12671-023-02113-8

Gallant, S. N. (2016). Mindfulness meditation practice and executive functioning: Breaking down the benefit. *Consciousness and Cognition*, *40*, 116–130. https://doi.org/10.1016/j.concog.2016.01.005

Ganesan, S., Beyer, E., Moffat, B., Van Dam, N. T., Lorenzetti, V., & Zalesky, A. (2022). Focused attention meditation in healthy adults: A systematic review and meta-analysis of cross-sectional functional MRI studies. *Neuroscience & Biobehavioral Reviews*, *141*, 104846. https://doi.org/10.1016/j.neubiorev.2022.104846

Giesbrecht, B., Bullock, T., & Garrett, J. (2024). Physically activated modes of attentional control. *Trends in Cognitive Sciences*. https://doi.org/10.1016/j.tics.2024.11.006

Grabovac, A. (2015). The stages of insight: Clinical relevance for mindfulness-based interventions. *Mindfulness*, *6*(3), 589–600. https://doi.org/10.1007/s12671-014-0294-2

Haegens, S., Luther, L., & Jensen, O. (2012). Somatosensory anticipatory alpha activity increases to suppress distracting input. *Journal of Cognitive Neuroscience*, *24*(3), 677–685. https://doi.org/10.1162/jocn_a_00164

Han, S., Jiang, Y., & Gu, H. (2004). Neural substrates differentiating global/local processing of bilateral visual inputs. *Human Brain Mapping*, *22*(4), 321–328. https://doi.org/10.1002/hbm.20044

Hasenkamp, W., Wilson-Mendenhall, C. D., Duncan, E., & Barsalou, L. W. (2012). Mind wandering and attention during focused meditation: A fine-grained temporal analysis of fluctuating cognitive states. *NeuroImage*, *59*(1), 750–760. https://doi.org/10.1016/j.neuroimage.2011.07.008

Helfrich, R. F., Fiebelkorn, I. C., Szczepanski, S. M., Lin, J. J., Parvizi, J., Knight, R. T., & Kastner, S. (2018). Neural Mechanisms of Sustained Attention Are Rhythmic. *Neuron*, *99*(4), 854-865.e5. https://doi.org/10.1016/j.neuron.2018.07.032

Hölzel, B. K., Lazar, S. W., Gard, T., Schuman-Olivier, Z., Vago, D. R., & Ott, U. (2011). How Does Mindfulness Meditation Work? Proposing Mechanisms of Action From a Conceptual and Neural Perspective. *Perspectives on Psychological Science: A Journal of the Association for Psychological Science*, *6*(6), 537–559. https://doi.org/10.1177/1745691611419671

Hommel, B., Kessler, K., Schmitz, F., Gross, J., Akyürek, E., Shapiro, K., & Schnitzler, A. (2006). How the brain blinks: Towards a neurocognitive model of the attentional blink. *Psychological Research*, *70*(6), 425–435. https://doi.org/10.1007/s00426-005-0009-3

Ingram, D. M. (2018). *Mastering the Core Teachings of the Buddha: 2.* Aeon.

Izzetoglu, M., Shewokis, P. A., Tsai, K., Dantoin, P., Sparango, K., & Min, K. (2020). Short-Term Effects of Meditation on Sustained Attention as Measured by fNIRS. *Brain Sciences*, *10*(9), Article 9. https://doi.org/10.3390/brainsci10090608

Jachs, B., Camino Garcia, M., Canales-Johnson, A., & Bekinschtein, T. A. (2022). *Drawing the experience dynamics of meditation* [Preprint]. Neuroscience. https://doi.org/10.1101/2022.03.04.482237

Jensen, C. G., Vangkilde, S., Frokjaer, V., & Hasselbalch, S. G. (2012). Mindfulness training affects attention—Or is it attentional effort? *Journal of Experimental Psychology: General*, *141*(1), 106–123. https://doi.org/10.1037/a0024931

Jha, A. P., Krompinger, J., & Baime, M. J. (2007). Mindfulness training modifies subsystems of attention. *Cognitive, Affective, & Behavioral Neuroscience*, *7*(2), 109–119. https://doi.org/10.3758/CABN.7.2.109

Josipovic, Z. (2014). Neural correlates of nondual awareness in meditation. *Annals of the New York Academy of Sciences*, *1307*(1), 9–18. https://doi.org/10.1111/nyas.12261

Josipovic, Z. (2019). Chapter 12 - Nondual awareness: Consciousness-as-such as non-representational reflexivity. In N. Srinivasan (Ed.), *Progress in Brain Research* (Vol. 244, pp. 273–298). Elsevier. https://doi.org/10.1016/bs.pbr.2018.10.021

Josipovic, Z. (2021). Implicit–explicit gradient of nondual awareness or consciousness as such. *Neuroscience of Consciousness*, *2021*(2), niab031. https://doi.org/10.1093/nc/niab031

Josipovic, Z. (2024). Reflexivity gradient—Consciousness knowing itself. *Frontiers in Psychology*, *15*. https://doi.org/10.3389/fpsyg.2024.1450553

Josipovic, Z., Dinstein, I., Weber, J., & Heeger, D. (2012). Influence of meditation on anti-correlated networks in the brain. *Frontiers in Human Neuroscience*, *5*. https://www.frontiersin.org/articles/10.3389/fnhum.2011.00183

Kabat-Zinn, J. (1995). Wherever you go, there you are: Mindfulness meditation in everyday life. *Behaviour Research and Therapy*, *33*(8), 996. https://doi.org/10.1016/0005-7967(95)90133-7

Kajimura, S., Kochiyama, T., Abe, N., & Nomura, M. (2019). Challenge to Unity: Relationship Between Hemispheric Asymmetry of the Default Mode Network and Mind Wandering. *Cerebral Cortex (New York, N.Y.: 1991)*, *29*(5), 2061–2071. https://doi.org/10.1093/cercor/bhy086

Katsuki, F., & Constantinidis, C. (2014). Bottom-up and top-down attention: Different processes and overlapping neural systems. *The Neuroscientist: A Review Journal Bringing Neurobiology, Neurology and Psychiatry*, *20*(5), 509–521. https://doi.org/10.1177/1073858413514136

Kiken, L. G., Garland, E. L., Bluth, K., Palsson, O. S., & Gaylord, S. A. (2015). From a state to a trait: Trajectories of state mindfulness in meditation during intervention predict changes in trait mindfulness. *Personality and Individual Differences*, *81*, 41–46. https://doi.org/10.1016/j.paid.2014.12.044

Kimchi, R. (1992). Primacy of wholistic processing and global/local paradigm: A critical review. *Psychological Bulletin*, *112*(1), 24–38. https://doi.org/10.1037/0033-2909.112.1.24

Korponay, C., Dentico, D., Kral, T., Ly, M., Kruis, A., Goldman, R., Lutz, A., & Davidson, R. J. (2017). Neurobiological correlates of impulsivity in healthy adults: Lower prefrontal gray matter volume and spontaneous eye-blink rate but greater resting-state functional connectivity in basal ganglia-thalamo-cortical circuitry. *NeuroImage*, *157*, 288–296. https://doi.org/10.1016/j.neuroimage.2017.06.015

Korponay, C., Dentico, D., Kral, T. R. A., Ly, M., Kruis, A., Davis, K., Goldman, R., Lutz, A., & Davidson, R. J. (2019). The Effect of Mindfulness Meditation on Impulsivity and its Neurobiological Correlates in Healthy Adults. *Scientific Reports*, *9*(1), 11963. https://doi.org/10.1038/s41598-019-47662-y

Kozasa, E. H., Sato, J. R., Lacerda, S. S., Barreiros, M. A. M., Radvany, J., Russell, T. A., Sanches, L. G., Mello, L. E. A. M., & Amaro, E. (2012). Meditation training increases brain efficiency in an attention task. *NeuroImage*, *59*(1), 745–749. https://doi.org/10.1016/j.neuroimage.2011.06.088

Kreher, J. B., & Schwartz, J. B. (2012). Overtraining Syndrome. *Sports Health*, *4*(2), 128–138. https://doi.org/10.1177/1941738111434406

Kruis, A., Slagter, H. A., Bachhuber, D. R. W., Davidson, R. J., & Lutz, A. (2016). Effects of meditation practice on spontaneous eyeblink rate. *Psychophysiology*, *53*(5), 749–758. https://doi.org/10.1111/psyp.12619

Kucyi, A., Esterman, M., Riley, C. S., & Valera, E. M. (2016). Spontaneous default network activity reflects behavioral variability independent of mind-wandering. *Proceedings of the National Academy of Sciences*, *113*(48), 13899–13904. https://doi.org/10.1073/pnas.1611743113

Langner, R., & Eickhoff, S. B. (2013). Sustaining attention to simple tasks: A meta-analytic review of the neural mechanisms of vigilant attention. *Psychological Bulletin*, *139*(4), 870–900. https://doi.org/10.1037/a0030694

Laukkonen, R. E., & Chandaria, S. (2024). *A beautiful loop: An active inference theory of consciousness*. OSF. https://doi.org/10.31234/osf.io/daf5n

Laukkonen, R. E., & Slagter, H. A. (2021). From many to (n)one: Meditation and the plasticity of the predictive mind. *Neuroscience & Biobehavioral Reviews*, *128*, 199–217. https://doi.org/10.1016/j.neubiorev.2021.06.021

Lawrence, N. S., Ross, T. J., Hoffmann, R., Garavan, H., & Stein, E. A. (2003). Multiple Neuronal Networks Mediate Sustained Attention. *Journal of Cognitive Neuroscience*, *15*(7), 1028–1038. https://doi.org/10.1162/089892903770007416

Lee, T. M. C., Leung, M.-K., Hou, W.-K., Tang, J. C. Y., Yin, J., So, K.-F., Lee, C.-F., & Chan, C. C. H. (2012). Distinct Neural Activity Associated with Focused-Attention Meditation and Loving-Kindness Meditation. *PLOS ONE*, *7*(8), e40054. https://doi.org/10.1371/journal.pone.0040054

Lieberman, J., McConnell, P., Estarellas, M., & Sacchet, M. (2024). *Neurophysiological Mechanisms of Focused Attention Meditation: A Scoping Systematic Review*. OSF. https://doi.org/10.31234/osf.io/rg7w6

Lindsay, E. K., & Creswell, J. D. (2017). Mechanisms of mindfulness training: Monitor and Acceptance Theory (MAT). *Clinical Psychology Review*, *51*, 48–59. https://doi.org/10.1016/j.cpr.2016.10.011

Lindsay, G. W. (2020). Attention in Psychology, Neuroscience, and Machine Learning. *Frontiers in Computational Neuroscience*, *14*, 29. https://doi.org/10.3389/fncom.2020.00029

Liu, Z., Li, L., Liu, S., Sun, Y., Li, S., Yi, M., Zheng, L., & Guo, X. (2020). Reduced feelings of regret and enhanced fronto-striatal connectivity in elders with long-term Tai Chi experience. *Social Cognitive and Affective Neuroscience*, *15*(8), 861–873. https://doi.org/10.1093/scan/nsaa111

Lutz, A., Jha, A. P., Dunne, J. D., & Saron, C. D. (2015). Investigating the Phenomenological Matrix of Mindfulness-related Practices from a Neurocognitive Perspective. *The American Psychologist*, *70*(7), 632–658. https://doi.org/10.1037/a0039585

Lutz, A., Slagter, H. A., Dunne, J. D., & Davidson, R. J. (2008). Attention regulation and monitoring in meditation. *Trends in Cognitive Sciences*, *12*(4), 163–169. https://doi.org/10.1016/j.tics.2008.01.005

Lutz, A., Slagter, H. A., Rawlings, N. B., Francis, A. D., Greischar, L. L., & Davidson, R. J. (2009). Mental Training Enhances Attentional Stability: Neural and Behavioral Evidence. *Journal of Neuroscience*, *29*(42), 13418–13427. https://doi.org/10.1523/JNEUROSCI.1614-09.2009

Mackie, M.-A., Van Dam, N. T., & Fan, J. (2013). Cognitive Control and Attentional Functions. *Brain and Cognition*, *82*(3), 301–312. https://doi.org/10.1016/j.bandc.2013.05.004

MacKillop, J., & Anderson, E. J. (2007). Further psychometric validation of the Mindful Attention Awareness Scale (MAAS). *Journal of Psychopathology and Behavioral Assessment*, *29*(4), 289–293. https://doi.org/10.1007/s10862-007-9045-1

MacLean, K. A., Ferrer, E., Aichele, S. R., Bridwell, D. A., Zanesco, A. P., Jacobs, T. L., King, B. G., Rosenberg, E. L., Sahdra, B. K., Shaver, P. R., Wallace, B. A., Mangun, G. R., & Saron, C. D. (2010). Intensive meditation training improves perceptual discrimination and sustained attention. *Psychological Science*, *21*(6), 829–839. https://doi.org/10.1177/0956797610371339

Maki, W. S., & Padmanabhan, G. (1994). Transient suppression of processing during rapid serial visual presentation: Acquired distinctiveness of probes modulates the attentional blink. *Psychonomic Bulletin & Review*, *1*(4), 499–504. https://doi.org/10.3758/BF03210954

Malinowski, P. (2013). Neural mechanisms of attentional control in mindfulness meditation. *Frontiers in Neuroscience*, *7*. https://doi.org/10.3389/fnins.2013.00008

Markett, S., Reuter, M., Montag, C., Voigt, G., Lachmann, B., Rudorf, S., Elger, C. E., & Weber, B. (2013). Assessing the function of the fronto-parietal attention network: Insights from resting-state fMRI and the attentional network test. *Human Brain Mapping*, *35*(4), 1700–1709. https://doi.org/10.1002/hbm.22285

Marois, R., & Ivanoff, J. (2005). Capacity limits of information processing in the brain. *Trends in Cognitive Sciences*, *9*(6), 296–305. https://doi.org/10.1016/j.tics.2005.04.010

Martens, S., & Wyble, B. (2010). The attentional blink: Past, present, and future of a blind spot in perceptual awareness. *Neuroscience & Biobehavioral Reviews*, *34*(6), 947–957. https://doi.org/10.1016/j.neubiorev.2009.12.005

Matthews, G., Campbell, S. E., Falconer, S., Joyner, L. A., Huggins, J., Gilliland, K., Grier, R., & Warm, J. S. (2002). Fundamental dimensions of subjective state in performance settings: Task engagement, distress, and worry. *Emotion (Washington, D.C.)*, *2*(4), 315–340. https://doi.org/10.1037/1528-3542.2.4.315

Matthias, E., Bublak, P., Müller, H. J., Schneider, W. X., Krummenacher, J., & Finke, K. (2010). The influence of alertness on spatial and nonspatial components of visual attention. *Journal of Experimental Psychology: Human Perception and Performance*, *36*(1), 38–56. https://doi.org/10.1037/a0017602

Meling, D. (2021). Knowing Groundlessness: An Enactive Approach to a Shift From Cognition to Non-Dual Awareness. *Frontiers in Psychology*, *12*. https://doi.org/10.3389/fpsyg.2021.697821

Meling, D. (2022). Knowing the Knowing. Non-dual Meditative Practice From an Enactive Perspective. *Frontiers in Psychology*, *13*. https://doi.org/10.3389/fpsyg.2022.778817

Meng, Z., Chen, Q., Zhou, L., Xu, L., & Chen, A. (2023). The role of distractors in rapid serial visual presentation reveals the mechanism of attentional blink by EEG-based univariate and multivariate analyses. *Cerebral Cortex (New York, N.Y.: 1991)*, *33*(21), 10761–10769. https://doi.org/10.1093/cercor/bhad316

Morgan, J. A., Corrigan, F., & Baune, B. T. (2015). Effects of physical exercise on central nervous system functions: A review of brain region specific adaptations. *Journal of Molecular Psychiatry*, *3*(1), 3. https://doi.org/10.1186/s40303-015-0010-8

Mottron, L., & Soulières, I. (2013). Global Versus Local Processing. In F. R. Volkmar (Ed.), *Encyclopedia of Autism Spectrum Disorders* (pp. 1445–1451). Springer. https://doi.org/10.1007/978-1-4419-1698-3_1732

Navon, D. (1977). Forest before trees: The precedence of global features in visual perception. *Cognitive Psychology*, *9*(3), 353–383. https://doi.org/10.1016/0010-0285(77)90012-3

Nigg, J. T. (2000). On inhibition/disinhibition in developmental psychopathology: Views from cognitive and personality psychology and a working inhibition taxonomy. *Psychological Bulletin*, *126*(2), 220–246. https://doi.org/10.1037/0033-2909.126.2.220

Palmero-Soler, E., Dujardin, K., Defebvre, L., Destée, A., Bocquillon, P., Bourriez, J., & Derambure, P. (2012). Role of Basal Ganglia Circuits in Resisting Interference by Distracters: A swLORETA Study. *PLoS ONE*, *7*. https://doi.org/10.1371/journal.pone.0034239

Petersen, A., Petersen, A. H., Bundesen, C., Vangkilde, S., & Habekost, T. (2017). The effect of phasic auditory alerting on visual perception. *Cognition*, *165*, 73–81. https://doi.org/10.1016/j.cognition.2017.04.004

Petersen, S. E., & Posner, M. I. (2012). The Attention System of the Human Brain: 20 Years After. *Annual Review of Neuroscience*, *35*, 73. https://doi.org/10.1146/annurev-neuro-062111-150525

Poerio, G. L., Sormaz, M., Wang, H.-T., Margulies, D., Jefferies, E., & Smallwood, J. (2017). The role of the default mode network in component processes underlying the wandering mind. *Social Cognitive and Affective Neuroscience*, *12*(7), 1047–1062. https://doi.org/10.1093/scan/nsx041

Posner, M. I. (1980). Orienting of attention. *The Quarterly Journal of Experimental Psychology*, *32*(1), 3–25. https://doi.org/10.1080/00335558008248231

Posner, M. I. (2008). Measuring alertness. *Annals of the New York Academy of Sciences*, *1129*, 193–199. https://doi.org/10.1196/annals.1417.011

Posner, M. I. (2016). Orienting of Attention: Then and Now. *Quarterly Journal of Experimental Psychology*, *69*(10), 1864–1875. https://doi.org/10.1080/17470218.2014.937446

Posner, M. I., & Petersen, S. E. (1990). The attention system of the human brain. *Annual Review of Neuroscience*, *13*, 25–42. https://doi.org/10.1146/annurev.ne.13.030190.000325

Posner, M. I., & Rothbart, M. K. (2009). Toward A Physical Basis of Attention and Self Regulation. *Physics of Life Reviews*, *6*(2), 103–120. https://doi.org/10.1016/j.plrev.2009.02.001

Posner, M. I., Rothbart, M. K., & Tang, Y.-Y. (2015). Enhancing attention through training. *Current Opinion in Behavioral Sciences*, *4*, 1–5. https://doi.org/10.1016/j.cobeha.2014.12.008

Prakash, R. S., Fountain-Zaragoza, S., Kramer, A. F., Samimy, S., & Wegman, J. (2020). Mindfulness and Attention: Current State-of-Affairs and Future Considerations. *Journal of Cognitive Enhancement : Towards the Integration of Theory and Practice*, *4*(3), 340. https://doi.org/10.1007/s41465-019-00144-5

Ptak, R. (2012). The frontoparietal attention network of the human brain: Action, saliency, and a priority map of the environment. *The Neuroscientist: A Review Journal Bringing Neurobiology, Neurology and Psychiatry*, *18*(5), 502–515. https://doi.org/10.1177/1073858411409051

Quickel, E. J. W., Johnson, S. K., & David, Z. L. (2014). Trait Mindfulness and Cognitive Task Performance: Examining the Attentional Construct of Mindfulness. *Sage Open*, *4*(4), 2158244014560557. https://doi.org/10.1177/2158244014560557

Raymond, J. E., Shapiro, K. L., & Arnell, K. M. (1992). Temporary suppression of visual processing in an RSVP task: An attentional blink? *Journal of Experimental Psychology: Human Perception and Performance*, *18*(3), 849–860. https://doi.org/10.1037/0096-1523.18.3.849

Raz, A., & Buhle, J. (2006). Typologies of attentional networks. *Nature Reviews. Neuroscience*, *7*(5), 367–379. https://doi.org/10.1038/nrn1903

Reedijk, S. A., Bolders, A., Colzato, L. S., & Hommel, B. (2015). Eliminating the Attentional Blink through Binaural Beats: A Case for Tailored Cognitive Enhancement. *Frontiers in Psychiatry*, *6*, 82. https://doi.org/10.3389/fpsyt.2015.00082

Rieger, M., Gauggel, S., & Burmeister, K. (2003). Inhibition of ongoing responses following frontal, nonfrontal, and basal ganglia lesions. *Neuropsychology*, *17*(2), 272–282. https://doi.org/10.1037/0894-4105.17.2.272

Rosenberg, M., Scheinost, D., Greene, A., Avery, E. W., Kwon, Y., Finn, E., Ramani, R., Qiu, M., Constable, R., & Chun, M. (2020). Functional connectivity predicts changes in attention observed across minutes, days, and months. *Proceedings of the National Academy of Sciences*, *117*, 3797–3807. https://doi.org/10.1073/pnas.1912226117

Rosenberg, M., Zhang, S., Hsu, W., Scheinost, D., Finn, E., Shen, X., Constable, R., Li, C., & Chun, M. (2016). Methylphenidate Modulates Functional Network Connectivity to Enhance Attention. *The Journal of Neuroscience*, *36*, 9547–9557. https://doi.org/10.1523/JNEUROSCI.1746-16.2016

Saalmann, Y. B., Pinsk, M. A., Wang, L., Li, X., & Kastner, S. (2012). The pulvinar regulates information transmission between cortical areas based on attention demands. *Science (New York, N.Y.)*, *337*(6095), 753–756. https://doi.org/10.1126/science.1223082

Sacchet, M. D., Fava, M., & Garland, E. L. (2024). Modulating self-referential processing through meditation and psychedelics: Is scientific investigation of self-transcendence clinically relevant? *World Psychiatry: Official Journal of the World Psychiatric Association (WPA)*, *23*(2), 298–299. https://doi.org/10.1002/wps.21214

Sahdra, B. K., MacLean, K. A., Ferrer, E., Shaver, P. R., Rosenberg, E. L., Jacobs, T. L., Zanesco, A. P., King, B. G., Aichele, S. R., Bridwell, D. A., Mangun, G. R., Lavy, S., Wallace, B. A., & Saron, C. D. (2011). Enhanced response inhibition during intensive meditation training predicts improvements in self-reported adaptive socioemotional functioning. *Emotion*, *11*(2), 299–312. https://doi.org/10.1037/a0022764

Samuel, I. B. H., & Constanzo, M. (2020). *Mindfulness and Cognitive Control: A Review on their Dual Mode Mechanisms* (2020120411). Preprints. https://www.preprints.org/manuscript/202012.0411/v1

Samuels, E. R., & Szabadi, E. (2008). Functional Neuroanatomy of the Noradrenergic Locus Coeruleus: Its Roles in the Regulation of Arousal and Autonomic Function Part I: Principles of Functional Organisation. *Current Neuropharmacology*, *6*(3), 235–253. https://doi.org/10.2174/157015908785777229

Sarter, M., Bruno, J. P., & Berntson, G. G. (2006). Reticular Activating System. In *Encyclopedia of Cognitive Science*. John Wiley & Sons, Ltd. https://doi.org/10.1002/0470018860.s00401

Sarter, M., Givens, B., & Bruno, J. P. (2001). The cognitive neuroscience of sustained attention: Where top-down meets bottom-up. *Brain Research Reviews*, *35*(2), 146–160. https://doi.org/10.1016/S0165-0173(01)00044-3

Sayadaw, M. (1994). *The Progress of Insight: (Visuddhiñana-katha)*. Buddhist Publication Society. https://www.accesstoinsight.org/lib/authors/mahasi/progress.html

Seli, P., Risko, E. F., & Smilek, D. (2016). On the Necessity of Distinguishing Between Unintentional and Intentional Mind Wandering. *Psychological Science*, *27*(5), 685–691. https://doi.org/10.1177/0956797616634068

Sezer, I., Pizzagalli, D. A., & Sacchet, M. D. (2022). Resting-state fMRI functional connectivity and mindfulness in clinical and non-clinical contexts: A review and synthesis. *Neuroscience and Biobehavioral Reviews*, *135*, 104583. https://doi.org/10.1016/j.neubiorev.2022.104583

Sharf, R. (2014). Mindfulness and Mindlessness in Early Chan. *Philosophy East and West*, *64*(4), 933–964.

Sharf, R. H. (2015). Is mindfulness Buddhist? (And why it matters). *Transcultural Psychiatry*, *52*(4), 470–484. https://doi.org/10.1177/1363461514557561

Simmonds, D. J., Pekar, J. J., & Mostofsky, S. H. (2008). Meta-analysis of Go/No-go tasks demonstrating that fMRI activation associated with response inhibition is task-dependent. *Neuropsychologia*, *46*(1), 224–232. https://doi.org/10.1016/j.neuropsychologia.2007.07.015

Singh-Curry, V., & Husain, M. (2009). The functional role of the inferior parietal lobe in the dorsal and ventral stream dichotomy. *Neuropsychologia*, *47*(6), 1434–1448. https://doi.org/10.1016/j.neuropsychologia.2008.11.033

Slagter, H. A., Lutz, A., Greischar, L. L., Francis, A. D., Nieuwenhuis, S., Davis, J. M., & Davidson, R. J. (2007). Mental Training Affects Distribution of Limited Brain Resources. *PLOS Biology*, *5*(6), e138. https://doi.org/10.1371/journal.pbio.0050138

Smallwood, J., & Schooler, J. W. (2015). The Science of Mind Wandering: Empirically Navigating the Stream of Consciousness. *Annual Review of Psychology*, *66*(Volume 66, 2015), 487–518. https://doi.org/10.1146/annurev-psych-010814-015331

Spagna, A., Mackie, M.-A., & Fan, J. (2015). Supramodal executive control of attention. *Frontiers in Psychology*, *6*, 65. https://doi.org/10.3389/fpsyg.2015.00065

Sparby, T. (2019). Phenomenology and Contemplative Universals: The Meditative Experience of Dhyana, Coalescence, or Access Concentration. *Journal of Consciousness Studies*, *26*(7–8), 130–156.

Sparby, T., Cysarz, D., Hornemann v. Laer, D., Edelhäuser, F., Tauschel, D., & Weger, U. W. (2024). The phenomenology of attentional control: A first-person approach to contemplative science and the issue of free will. *Frontiers in Psychology*, *15*, 1349826. https://doi.org/10.3389/fpsyg.2024.1349826

Sparby, T., & Sacchet, M. D. (2022). Defining Meditation: Foundations for an Activity-Based Phenomenological Classification System. *Frontiers in Psychology*, *12*. https://doi.org/10.3389/fpsyg.2021.795077

Sparby, T., & Sacchet, M. D. (2024). Toward a Unified Account of Advanced Concentrative Absorption Meditation: A Systematic Definition and Classification of Jhāna. *Mindfulness*. https://doi.org/10.1007/s12671-024-02367-w

Sperduti, M., Makowski, D., & Piolino, P. (2016). The protective role of long-term meditation on the decline of the executive component of attention in aging: A preliminary cross-sectional study. *Neuropsychology, Development, and Cognition. Section B, Aging, Neuropsychology and Cognition*, *23*(6), 691–702. https://doi.org/10.1080/13825585.2016.1159652

Spielberg, J., Engels, A. S., Banich, M., Sutton, B., Warren, S. L., Heller, W., Crocker, L. D., & Miller, G. A. (2012). A brain network instantiating approach and avoidance motivation. *Psychophysiology*, *49 9*, 1200–1214. https://doi.org/10.1111/j.1469-8986.2012.01443.x

Sprague, T. C., Itthipuripat, S., Vo, V. A., & Serences, J. T. (2018). Dissociable signatures of visual salience and behavioral relevance across attentional priority maps in human cortex. *Journal of Neurophysiology*, *119*(6), 2153–2165. https://doi.org/10.1152/jn.00059.2018

Sturm, W., & Willmes, K. (2001). On the functional neuroanatomy of intrinsic and phasic alertness. *NeuroImage*, *14*(1 Pt 2), S76-84. https://doi.org/10.1006/nimg.2001.0839

Sumantry, D., & Stewart, K. E. (2021). Meditation, Mindfulness, and Attention: A Meta-analysis. *Mindfulness*, *12*(6), 1332–1349. https://doi.org/10.1007/s12671-021-01593-w

Taatgen, N. A., Juvina, I., Schipper, M., Borst, J. P., & Martens, S. (2009). Too much control can hurt: A threaded cognition model of the attentional blink. *Cognitive Psychology*, *59*(1), 1–29. https://doi.org/10.1016/j.cogpsych.2008.12.002

Tal, H., Wright, M., Prest, S., Sandved-Smith, L., & Sacchet, M. (2025). *Active Inference, Computational Phenomenology, and Advanced Meditation: Toward the Formalization of the Experience of Meditation*. OSF. https://doi.org/10.31234/osf.io/pm5y2_v2

Tang, Y.-Y., Hölzel, B. K., & Posner, M. I. (2015). The neuroscience of mindfulness meditation. *Nature Reviews Neuroscience*, *16*(4), Article 4. https://doi.org/10.1038/nrn3916

Tang, Y.-Y., Ma, Y., Wang, J., Fan, Y., Feng, S., Lu, Q., Yu, Q., Sui, D., Rothbart, M. K., Fan, M., & Posner, M. I. (2007). Short-term meditation training improves attention and self-regulation.

Proceedings of the National Academy of Sciences, *104*(43), 17152–17156. https://doi.org/10.1073/pnas.0707678104

Tiwari, M. (1988). Samatha Meditation in Theravada Buddhism: (According to the Pali texts). *Buddhist Studies Review*, *5*(1), 21–37. https://doi.org/10.1558/bsrv.v5i1.15948

Treves, I. N., Kucyi, A., Park, M., Kral, T. R. A., Goldberg, S. B., Davidson, R. J., Rosenkranz, M., Whitfield-Gabrieli, S., & Gabrieli, J. D. E. (2025). Connectome-Based Predictive Modeling of Trait Mindfulness. *Human Brain Mapping*, *46*(1), e70123. https://doi.org/10.1002/hbm.70123

Treves, I. N., Pichappan, K., Hammoud, J., Bauer, C. C. C., Ehmann, S., Sacchet, M. D., & Gabrieli, J. D. E. (2024). The Mindful Brain: A Systematic Review of the Neural Correlates of Trait Mindfulness. *Journal of Cognitive Neuroscience*, 1–38. https://doi.org/10.1162/jocn_a_02230

Tsai, M.-H., & Chou, W.-L. (2016). Attentional orienting and executive control are affected by different types of meditation practice. *Consciousness and Cognition*, *46*, 110–126. https://doi.org/10.1016/j.concog.2016.09.020

Tsai, N., Treves, I. N., Bauer, C. C. C., Scherer, E., Caballero, C., West, M. R., & Gabrieli, J. D. E. (2024). Dispositional mindfulness: Dissociable affective and cognitive processes. *Psychonomic Bulletin & Review*, *31*(4), 1798–1808. https://doi.org/10.3758/s13423-024-02462-y

Vago, D. R., Farb, N., & Spreng, R. N. (2022). Clarifying Internally-Directed Cognition: A Commentary on the Attention to Thoughts Model. *Psychological Inquiry*, *33*(4), 261–272. https://doi.org/10.1080/1047840X.2022.2141005

Vago, D. R., Gupta, R. S., & Lazar, S. W. (2019). Measuring cognitive outcomes in mindfulness-based intervention research: A reflection on confounding factors and methodological limitations. *Current Opinion in Psychology*, *28*, 143–150. https://doi.org/10.1016/j.copsyc.2018.12.015

Vago, D. R., & Silbersweig, D. A. (2012). Self-awareness, self-regulation, and self-transcendence (S-ART): A framework for understanding the neurobiological mechanisms of mindfulness. *Frontiers in Human Neuroscience*, *6*, 296. https://doi.org/10.3389/fnhum.2012.00296

Vago, D. R., & Zeidan, F. (2016). The brain on silent: Mind wandering, mindful awareness, and states of mental tranquility. *Annals of the New York Academy of Sciences*, *1373*(1), 96–113. https://doi.org/10.1111/nyas.13171

Valentine, E. R., & Sweet, P. L. G. (1999). Meditation and attention: A comparison of the effects of concentrative and mindfulness meditation on sustained attention. *Mental Health, Religion & Culture*, *2*(1), 59–70. https://doi.org/10.1080/13674679908406332

Van Calster, L., D'Argembeau, A., & Majerus, S. (2018). Measuring individual differences in internal versus external attention: The attentional style questionnaire. *Personality and Individual Differences*, *128*, 25–32. https://doi.org/10.1016/j.paid.2018.02.014

Van Dam, N. T., van Vugt, M. K., Vago, D. R., Schmalzl, L., Saron, C. D., Olendzki, A., Meissner, T., Lazar, S. W., Kerr, C. E., Gorchov, J., Fox, K. C. R., Field, B. A., Britton, W. B., Brefczynski-Lewis, J. A., & Meyer, D. E. (2018). Mind the Hype: A Critical Evaluation and Prescriptive Agenda for Research on Mindfulness and Meditation. *Perspectives on Psychological Science*, *13*(1), 36–61. https://doi.org/10.1177/1745691617709589

van den Hurk, P. A. M., Giommi, F., Gielen, S. C., Speckens, A. E. M., & Barendregt, H. P. (2010). Greater efficiency in attentional processing related to mindfulness meditation. *Quarterly Journal of Experimental Psychology*, *63*(6), 1168–1180. https://doi.org/10.1080/17470210903249365

Van der Werf, Y. D., Witter, M. P., & Groenewegen, H. J. (2002). The intralaminar and midline nuclei of the thalamus. Anatomical and functional evidence for participation in processes of arousal and awareness. *Brain Research Reviews*, *39*(2), 107–140. https://doi.org/10.1016/S0165-0173(02)00181-9

van Leeuwen, S., Singer, W., & Melloni, L. (2012). Meditation Increases the Depth of Information Processing and Improves the Allocation of Attention in Space. *Frontiers in Human Neuroscience*, *6*, 133. https://doi.org/10.3389/fnhum.2012.00133

van Vugt, M. K., & Slagter, H. A. (2014). Control over experience? Magnitude of the attentional blink depends on meditative state. *Consciousness and Cognition*, *23*, 32–39. https://doi.org/10.1016/j.concog.2013.11.001

Ventura, B., Çatal, Y., Wolman, A., Buccellato, A., Cooper, A. C., & Northoff, G. (2024). Intrinsic neural timescales exhibit different lengths in distinct meditation techniques. *NeuroImage*, *297*, 120745. https://doi.org/10.1016/j.neuroimage.2024.120745

Vertes, R. P., Linley, S. B., & Rojas, A. K. P. (2022). Structural and functional organization of the midline and intralaminar nuclei of the thalamus. *Frontiers in Behavioral Neuroscience*, *16*. https://doi.org/10.3389/fnbeh.2022.964644

Vincent, J. L., Kahn, I., Snyder, A. Z., Raichle, M. E., & Buckner, R. L. (2008). Evidence for a Frontoparietal Control System Revealed by Intrinsic Functional Connectivity. *Journal of Neurophysiology*, *100*(6), 3328–3342. https://doi.org/10.1152/jn.90355.2008

Vinchurkar, S. A., Singh, D., & Visweswaraiah, N. K. (2014). Self-reported measures of mindfulness in meditators and non-meditators: A cross-sectional study. *International Journal of Yoga*, *7*(2), 142. https://doi.org/10.4103/0973-6131.133898

Vossel, S., Geng, J. J., & Fink, G. R. (2014). Dorsal and ventral attention systems: Distinct neural circuits but collaborative roles. *The Neuroscientist: A Review Journal Bringing Neurobiology, Neurology and Psychiatry*, *20*(2), 150–159. https://doi.org/10.1177/1073858413494269

Walach, H., Buchheld, N., Buttenmüller, V., Kleinknecht, N., & Schmidt, S. (2006). Measuring mindfulness—The Freiburg Mindfulness Inventory (FMI). *Personality and Individual Differences*, *40*(8), 1543–1555. https://doi.org/10.1016/j.paid.2005.11.025

Wang, H., & Fan, J. (2007). Human attentional networks: A connectionist model. *Journal of Cognitive Neuroscience*, *19*(10), 1678–1689. https://doi.org/10.1162/jocn.2007.19.10.1678

Ward, R., Duncan, J., & Shapiro, K. (1996). The Slow Time-Course of Visual Attention. *Cognitive Psychology*, *30*(1), 79–109. https://doi.org/10.1006/cogp.1996.0003

Wipplinger, F., Holthof, N., Andereggen, L., Urman, R. D., Luedi, M. M., & Bello, C. (2023). Meditation as an Adjunct to the Management of Acute Pain. *Current Pain and Headache Reports*, *27*(8), 209–216. https://doi.org/10.1007/s11916-023-01119-0

Woldorff, M. G., Hazlett, C. J., Fichtenholtz, H. M., Weissman, D. H., Dale, A. M., & Song, A. W. (2004). Functional Parcellation of Attentional Control Regions of the Brain. *Journal of Cognitive Neuroscience*, *16*(1), 149–165. https://doi.org/10.1162/089892904322755638

Wright, M. J., Sanguinetti, J. L., Young, S., & Sacchet, M. D. (2023). Uniting Contemplative Theory and Scientific Investigation: Toward a Comprehensive Model of the Mind. *Mindfulness*. https://doi.org/10.1007/s12671-023-02101-y

Wyble, B., Bowman, H., & Nieuwenstein, M. (2009). The attentional blink provides episodic distinctiveness. *Journal of Experimental Psychology. Human Perception and Performance*, *35*(3), 787–807. https://doi.org/10.1037/a0013902

Xuan, B., Mackie, M.-A., Spagna, A., Wu, T., Tian, Y., Hof, P. R., & Fan, J. (2016). The activation of interactive attentional networks. *NeuroImage*, *129*, 308–319. https://doi.org/10.1016/j.neuroimage.2016.01.017

Yang, W. F. Z., Sparby, T., Wright, M., Kim, E., & Sacchet, M. D. (2024). Volitional mental absorption in meditation: Toward a scientific understanding of advanced concentrative absorption meditation and the case of jhana. *Heliyon*, *10*(10). https://doi.org/10.1016/j.heliyon.2024.e31223

Yoo, K., Rosenberg, M., Hsu, W., Zhang, S., Li, C., Scheinost, D., Constable, T., & Chun, M. (2018). Connectome-based predictive modeling of attention: Comparing different functional connectivity features and prediction methods across datasets. *NeuroImage*, *167*, 11–22. https://doi.org/10.1016/j.neuroimage.2017.11.010

Young, S. (2016a). *What is Mindfulness?* https://doi.org/10.1002/9781118938003.ch3

Young, S. (2016b). What Is Mindfulness? A Contemplative Perspective. In K. A. Schonert-Reichl & R. W. Roeser (Eds.), *Handbook of Mindfulness in Education* (pp. 29–45). Springer New York. https://doi.org/10.1007/978-1-4939-3506-2_3

Zanesco, A. P., King, B. G., MacLean, K. A., Jacobs, T. L., Aichele, S. R., Wallace, B. A., Smallwood, J., Schooler, J. W., & Saron, C. D. (2016). Meditation training influences mind wandering and mindless reading. *Psychology of Consciousness: Theory, Research, and Practice*, *3*(1), 12–33. https://doi.org/10.1037/cns0000082

Zanesco, A. P., King, B., MacLean, K., & Saron, C. D. (2013). Executive control and felt concentrative engagement following intensive meditation training. *Frontiers in Human Neuroscience*, *7*. https://doi.org/10.3389/fnhum.2013.00566

Zhuang, K., Bi, M., Li, Y., Xia, Y., Guo, X., Chen, Q., Du, X., Wang, K., Wei, D., Yin, H., & Qiu, J. (2017). A distinction between two instruments measuring dispositional mindfulness and the correlations between those measurements and the neuroanatomical structure. *Scientific Reports*, *7*(1), 6252. https://doi.org/10.1038/s41598-017-06599-w

Table 1

Behavioral attentional studies of long-term mindfulness meditators. Study design, assessment type, practice experience, meditation type, and summary of major findings of each article. N = number of participants.

Article	Study design	Assessment	Participants	Meditation experience	Meditation type	Findings
2.1. Executive Attention, 2.2. and 2.2.1. Conventional and Hierarchical Attentional Orienting, and 2.3. Alertness						
Van den Hurk et al., 2010	Comparative, cross-sectional (naïve vs. experienced)	Attentional Network Task	Meditation-naïve (*n* = 20, F = 11), Experts (*n* = 20, F = 11)	14.5 years, *SD* = 11.1, .25–35 years, 60–420 min weekly	Mindfulness meditation	**Experts:** Mean RT difference: ↘ orienting network: $p < .05$ ↗ total: $p = .059$ Mean error score: ↘ executive network: $p = .07$; for incongruent flankers $p < .05$ ↘ total: $p = .084$ Speed-accuracy distribution (processing efficiency): ↗ 60,40,20ms: $p = < .05$; $< .05$; $< .01$ RT predicting accuracy: $\beta RT = -.009$, $p < .001$, exp(B) = 0.991
Tsai & Chou, 2016	Comparative, cross-sectional (naïve vs. experienced)	Attentional Network Task	Controls (*n* = 30, F = 10), Experts (*n* = 30, F = 15)	9.8 years, *SD* = 8.5, 3–30 years	Dandao meditation	**Experts:** Mean RT difference: ↘ orienting network: $p = .08$, $p = .03$ favoring *observe-and-focus* ↘ executive network: $p < .01$ Mean error score: ↘ alerting network: $p = .07$
Sperduti et al., 2015	Comparative, cross-sectional (naïve older adults vs. naïve younger adults vs. experienced older adults)	Attentional Network Task	Meditation-naïve older (*n* = 16, F = 10), Meditation-naïve younger (*n* = 19, F = 9), Experts older (*n* = 16, F = 8)	22.5 years, *SD* = 9.9, 11–44 years	Zen and Tibetan Buddhism (mostly *observe-and-release*)	**Meditation-naïve older:** Mean RT difference: ↗ executive network: $p = .055$ Corrected ratio score for age: ↗ executive network: $p = .08$
Braboszcz et al., 2013	Quasi-experimental, longitudinal (3-month retreat; experienced)	Stroop task, Attentional Blink Task (ABT), Global Local Task (GLT)	Practitioners (*n* = 82)	Shoonya: 4 years, *SD* = 2.8, 6.5 days weekly, *SD* = 0.5; Samyama: 3 years, *SD* = 2, 3.2 days weekly, *SD* = 2.1	Shoonya and Samyama	**Pre retreat:** Mean correct responses, Stroop: ↗ incongruent stimuli correlating with meditation experience: $r = .16$, $p < .005$ ↗ neutral stimuli correlating with meditation experience: $r = .05$, $p < .05$ Mean reaction time, GLT: ↘ local task, incongruent: $p = .04$

Article	Study design	Assessment	Participants	Meditation experience	Meditation type	Findings
						Post retreat: Mean correct responses, Stroop: ↗ incongruent stimuli: $p < .05$ ↘ incongruent stimuli correlating with meditation experience: $r = -.07$, $p < .01$ Target accuracy improvement, ABT: ↗ stimulus 2 (T2), short: p < .0001 ↗ T2 short vs. T1: $p < .0002$ ↗ T2 short vs. T2 long: $p < .001$ ↗ T2 short vs. T2 absent: $p < .005$ **General** Mean reaction time, GLT: ↘ congruent vs. incongruent: $p < .005$ Congruency effects, local: $p = .057$
Chan & Woollacott, 2007	Comparative, cross-sectional (naïve vs. experienced)	Stroop task, Global Local Task (GLT)	Meditation-naïve (n = 10, F = 5), Practitioners (n = 50, F = 28)	82–19,200 hours, 6–150 min daily	Diverse	**Practitioners:** Stroop scores: ↗ congruent stimuli: $p < .001$ ↗ incongruent stimuli: $p < .002$ ↘ interference: $p = .03$ ↘ interference correlation with daily meditation amount: $r = -0.31$, $p < .005$ Mean reaction time, GLT: ↘ all conditions, global: $p = .04–.08$ ↘ neutral, local: $p < .05$ ↘ correlations with daily meditation experience, global: $r = –.22$ to $–.31$ ↗ correlations with daily meditation amount, local: $r = .27$ **General** Mean reaction time, GLT: ↘ congruent vs. incongruent: $p < .0001$ ↘ neutral vs. incongruent: $p < .0001$ Congruency effects, local: $p = .04$
Jha et al., 2007	Quasi-experimental, longitudinal (1 month-retreat; practitioners) vs. 8-week MBSR vs. meditation naïve	Attentional Network Task	Meditation-naïve (n = 17), Practitioners (n = 17), MBSR (n = 17)	5 years, .33–30 years	Mindfulness meditation, emphasis on *observe-and-focus* activities	**Pre MBSR and retreat:** Mean RT difference: ↘ executive network, practitioners: $p < .03$ Mean error score: ↘ executive network, practitioners: $p < .001$ **Post MBSR and retreat:** Mean RT difference: ↘ orienting network, MBSR: $p < .046$

Article	Study design	Assessment	Participants	Meditation experience	Meditation type	Findings
						↘ alerting network, retreat: p < .001 ↗ alerting correlating with meditation experience: r = – .52, p < .03
Van Leeuwen et al., 2012	Quasi experimental cross-sectional, longitudinal comparison (experienced vs. meditation naïve)	Global Local Task (GLT)	Cross-sectional: Meditation naïve (*n* = 8, F = 3) Experts (*n* = 8, F = 3) Longitudinal: Meditation naïve (*n* = 8, F = 3), Experts (*n* = 6, F = 4)	Cross-sectional: 5 years, *SD* = 2; Longitudinal: 3 years, *SD* = 1 year	Cross-sectional: Zen: *Observe-and-focus* and *observe-and-release* Longitudinal: habitually: *observe-and-focus;* retreat: *observe-and-release*	**Cross-sectional:** Mean reaction time, GLT: ↘ overall RT (meditators 122 ms faster than controls): *p* = .057 ↘ global precedence effect (meditators: 21.5 ms; controls: 56.4 ms): *p* < .05 **Longitudinal:** Mean reaction time, GLT: ↗ Local precedence pre-retreat, meditators (38.5 ms difference). ↘ Local precedence post-retreat, meditators: Local vs. global RT difference reduced (11 ms). ↗ Global precedence, controls.
Kruis et al., 2016	Quasi-experimental, cross-sectional longitudinal, comparison (experienced vs. mediation naïve vs. MBSR vs. active control)	Spontenious Eyeblink Rate (sEBR), Intereyeblink Intervals (IEBR)	Mediation naïve ($n = 118$, $n_{MBSR} = 36$, $n_{control} = 29$, $n_{active} = 36$), Experts (*n* = 27)	9,154 hours, 1,439–29,046 hours	Theravāda or Tibetan Buddhism	**Experts** Mean sEBR scores: ↘ baseline: *p* < .01 Mean IEBR scores: ↗ baseline: *p* < .001 IEBR max scores: ↗ baseline: *p* < .001 IEBR SD scores: ↗ baseline: *p* < .001
2.1.1. Response Inhibition						
Sahdra et al., 2011	Quasi-experimental, longitudinal (3-month retreat; experienced)	Response Inhibition Task (RIT), Various Self-Report Measures	Waitlist control (*n* = 30), Retreat group (*n* = 30)	13 years, minimum 3 5–10-day retreats	Heterogenous	**Retreat group** RIT threshold: ↘ mid retreat: *p* = .04 RIT accuracy: ↗ training related increases over time: *p* = .02 Adaptive functioning: ↗ post retreat: M = .526 ↗ five-month follow up: M = .419 ↗ changes associated with previous RIT scores
Zanesco et al., 2013	Quasi-experimental, longitudinal (1-month retreat; controls vs. experienced)	Response Inhibition Task (RIT)	Control (*n* = 24, F = 19), Practitioners (*n* = 24, F = 18)	Controls: 1,767 hours, 76–9,265 hours. Practitioners: 3,311 hours, 165–15,000 hours.	Vipassanā, Loving-kindness meditation	**Retreat group** RIT accuracy: ↗ training related increases over time: *p* = .029 RT variability: ↘ training related increases over time: *p* < .001 Concentration: ↗ post retreat: p = .011 Concentration predicting RIT and RT variability: ↗ post retreat, RIT: R^2 = .368, *p* < .001

Article	Study design	Assessment	Participants	Meditation experience	Meditation type	Findings
						↗ post retreat, RT: R^2 = .403, p < .001 Training changes in concentration predicting RIT and RT: ↗ post retreat, RT: R^2 = .079, p = .037
Andreu et al., 2019	Comparative, cross-sectional (athletes vs. experienced)	Emotional Go/No-go Task	Athletes (n = 31), Meditators (n = 31)	Athletes: 7.1 years, *SD* = 5.62; 2,460 hours, *SD* = 2,492, 133–11,520 hours. Meditators: 5.1 years, *SD* = 3.73; 2,500 hours, *SD* = 2,658, 375–12550 hours.	Vipassanā	**Meditators** Error rates: ↘ independent of valence and trial type: p = .093
Korponay et al., 2019	Comparative, cross-sectional (naïve vs. experienced)	Go/No-go Task, Barratt Impulsiveness Scale (BIS-11), Spontaneous Eyeblink Rate,	Meditation-naïve (n = 105, F = 65), Experts (n = 28, F = 15)	9,154 hours, SD = 1,439–29,046 hours	Heterogenous: Theravāda or Tibetan Buddhism	**Meditation-naïve** Go-Nogo task accuracy: ↗ go-trial: p = .039 **Experts** BIS-11: ↘ attentional impulsivity: p = .027 ↗ motor impulsivity: p = .049 ↗ non-planning impulsivity: p = .049 Mean sEBR scores: ↘ experts: p = .015
2.3.1. Sustained Attention						
Valentine & Sweet, 1999	Quasi-experimental (naïve vs. experienced)	Wilkins' Counting Task	Meditation-naïve (n = 24, F = 14), Practitioners (n = 19, F = 11)	Two groups with less or more than 24 months of experience	Two groups: *observe-and-focus* or *observe-and-release*	Mean counting task scores: ↗ experts vs controls: p < .001 ↗ long-term vs short-term meditators: p < .01 ↗ *observe-and-release*, unexpected stimulus: p < .001
Lutz et al., 2009	Quasi-experimental longitudinal (3-month retreat; naïve vs. experienced)	Attentional Blink Task, Dichotic Listening Task, EEG	Meditation-naïve (n = 23, F = 14), Practitioners (n = 17, F = 10)	2,967 hours, *SD* = 3,162	Vipassanā	**Experts post retreat:** Phase-locking factor to deviant tones: ↗ theta-band (4–8 Hz), 300–500 ms: p < .005 ↗ broadband (attended and unattended): p < .05 RT-variability: ↘ target tones: p < .005 RT-variability correlating with PLF: ↘ r = –0.40, p < .05 RT-variability correlating with PLF: ↘ r = –0.40, p < .05 Stimulus locking: Delta-band (1–4 Hz): p < .05
Lee et al., 2012	Quasi-experimental 2x2 factorial design (naïve vs.	Continuous Performance Test (CPT),	Meditation naïve (n = 22, n_{FAM} = 11,	FAM: 5,248 hours, *SD* = 5,248, 810 –	Theravāda Buddhism:	**Experts** CPT, baseline:

Article	Study design	Assessment	Participants	Meditation experience	Meditation type	Findings
	experienced, focused attention vs. loving-kindness)	Emotional Processing Task, fMRI	n_{metta} = 11), Experts (n = 22, n_{FAM} = 11, n_{metta} = 11)	17,850 hours; Metta: 7,491 hours, *SD* = 6,681, 588–17,850 hours	*observe-and-focus* or *metta*	↘ omission errors: $p < .032$ CPT, meditation state: ↘ omission errors: $p < .010$ ↘ comission errors: $p < .062$
2.3.1.1. Mind-Wandering						
Brandmeyer & Delrome, 2018	Quasi-experimental repeated-measures design (beginner vs. experienced)	Experience-sampling probes, EEG	Meditation beginner (n = 11, F = 10), Experts (n = 11, F = 3)	Experts: minimum 2 hours per day in the last year, mean = 14.8 hours weekly, *SD* = 1.6. Beginners: mean = 3.2, *SD* = 3.1.	Himalayan Yoga: *observe-and-focus* and *observe-and-release*	**Experts** Mind-wandering depth: ↘ compared to beginners: $p = .03$ ↗ correlating with drowsiness: $r = .66$, $p = .0013$ Meditation trials vs. mind-wandering trials: ↗ compared to beginners: $p = .00014$ Meditation depth: ↗ $p = .06$ Meditative state vs mind-wandering state, EEG: ↗ fronto-cortical theta (4–7 Hz) modulation: $p < .02$ ↗ somatosensory alpha (9–11 Hz) modulation: $p < .02$ ↗ correlation between theta and alpha differences: $r = .42$, $p = .02$
Vugt & Slagter, 2014	Experimental design, counterbalanced (experienced)	Attentional Blink Task	Experts (n = 30, F = 20)	6,041 hours, 786–31,937 hours	Zen, Tibetan, and Vipassanā: *Observe-and-focus* and *observe-and-release*	**Experts** Main effect of lag: ↘ *observe-and-release*, experienced: $p < .05$, $d = .61$

Note. ABT = Attentional Blink Task; ANT = Attentional Network Task; BIS = Barratt Impulsiveness Scale–11(BIS–11); CPT = Continuous Performance Task; DST = Digit Span Task; *d* = Cohen's (effect size); F = Number of female participants; GLT = Global–Local Task; IEBR = Inter-Eyeblink Interval; M = Mean; MBSR = Mindfulness-Based Stress Reduction; *n* = Number of participants; *p* = *p*-value; *r* = Pearson correlation coefficient; R^2 = Coefficient of determination; RIT = Response Inhibition Task; RT = Reaction Time; sEBR = Spontaneous Eyeblink Rate; ToH = Tower of Hanoi Task; WCST-CV4 = Wisconsin Card Sorting Test; β = Standardized regression coefficient; exp(B) = Exponentiated coefficient from logistic regression.