Mindfulness
https://doi.org/10.1007/s12671-026-02802-0

RESEARCH

Differential Effects of Meditation States on Neural Pain Processing in Novice and Long-Term Meditators

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Received: 17 May 2025 / Accepted: 22 February 2026

Abstract

Objectives The main objective of the present study was to explore the effects of different types of meditation on the neurophysiologic mechanisms of pain processing.

Method EEG responses to electric median nerve stimulation were recorded in short-term and long-term meditators (STM, LTM) during rest and three forms of meditation engaging attentional and affective regulation in different ways: focused attention meditation (FAM), open monitoring meditation (OMM), and loving-kindness meditation (LKM). EEG responses were analysed in the time- and time-frequency domains to compute local components, and temporal and spatial synchronizations of multi-spectral pain-related oscillations (PROs) in order to characterize bottom-up processes, proactive modulation of cortical excitability, cognitive/affective appraisal, and the connectivity of performance monitoring (fronto-medial) and attentional (fronto-parietal) networks during pain processing.

Results STM manifested a significant decrease in the connectedness of the fronto-medial theta-alpha network and a significant reduction of the P3b during LKM. In contrast, changes in LTM were observed during FAM and OMM. They were characterized by pre-stimulus alpha increase at somatosensory areas, and modulations of fronto-medial and fronto-parietal theta-alpha synchronizations.

Conclusions Different meditation states do not influence bottom-up sensory pain processing. However, they significantly alter cognitive/affective pain mechanisms in state- and trait-dependent ways. In novice meditators, a positive emotional disposition during meditation can suppress the distribution and cognitive/affective appraisal of nociceptive signals. In expert meditators, the effects of meditation states on pain processing are critically guided by advanced control of internal attention leading to fine-tuned involvement and functional segregation of cognitive control and attention networks.

Preregistration This study is not preregistered.

Keywords Pain · Meditation · EEG · Pain-related oscillations · Pain-related potentials · FAM · OMM · LKM · Synchronization · Bottom-up/top-down

Meditation states and traits have been consistently associated with a decrease in perceived subjective pain. These positive effects are suggested to result mainly from altered processing of emotional and evaluative components of pain (Bakhshani et al., 2016; Brefczynski-Lewis et al., 2007; Grant & Rainville, 2009; Grossman et al., 2007; Kasai et al.,

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2017; Morone et al., 2008; Nicolardi et al., 2022; Nielsen & Kaszniak, 2006; Schmidt et al., 2011; Su et al., 2016), though the precise neural mechanisms remain debatable. One neurophysiological model posits that major effects of meditation on pain rely on *reactive cognitive control*, whereby noxious stimuli are sensed as really painful but the unpleasantness/affect (i.e. the emotional/cognitive appraisal) is reduced or does not occur (Gard et al., 2012; Grant et al., 2011; Jinich-Diamant et al., 2020; Perlman et al., 2010; Zeidan & Vago, 2016). Thus, the sensory experience of pain is separated from the subsequent negative evaluation (Zorn et al., 2020, 2021). An alternative model posits that *proactive cognitive mechanisms* are crucial for pain processing in meditation (Zeidan et al., 2011a, 2011b, 2015). According to this model, effortful cognitive processes mediated by executive attention downregulate pain signals in the thalamus and transform ascending nociceptive information from painful to innocuous (sensory), thus avoiding the need for further extensive cognitive/affective reappraisal (Jinich-Diamant et al., 2020; Zeidan et al., 2011a, 2011b).

These two models of pain processing in meditation may not be mutually exclusive. It has been demonstrated that in standard conditions, proactive and reactive modes of information processing may manifest a dynamic interaction, with dominance of either mode depending on neurocognitive capacity, cognitive style, context, task demands and current brain state (Mäki-Marttunen et al., 2019). As detailed below, various meditation types exist engaging attention, emotion and awareness in specific ways (Chiesa & Malinowski, 2011; Davidson & Dahl, 2017; Lutz et al., 2015). Moreover, meditation practice is a dynamic process entailing a transition from effortful to effortless maintenance of brain states (Fell et al., 2010; Lutz et al., 2008) accompanied by neuroplastic changes in attentional, cognitive control and pain networks (Fox et al., 2014; Guidotti et al., 2023; Lu et al., 2023a, 2023b; Tang et al., 2015; Yordanova et al., 2020a, 2020b, 2021). Hence, the proactive and reactive modes of pain processing in meditation may be sequential, competing, or complementary. Accordingly, the two suggested models may operate in specific and interactive ways according to meditation expertise in a *trait-like* manner (guided by enduring, cross-situational, and relatively stable characteristics achieved as a result of meditation practice) and meditation type in a *state-like* manner (guided by transient, context, time-, task-, or mood-dependent fluctuations) (Hur et al., 2015; Zilcha-Mano et al., 2022).

A neurocognitive classification of meditation practices from different traditions has identified three major meditation types with specific neurocognitive characteristics (Cahn & Polich, 2006; Dahl et al., 2015; Lutz et al., 2008; Raffone et al., 2014, 2019; Vago & Silbersweig, 2012). As representing specific contexts and brain states, meditation types have been suggested to exert differential effects on pain perception and neural processing (Wiech, 2016).

Focused attention meditation (FAM) entails voluntary focusing attention on a chosen object in a sustained fashion. The attentional focus in FAM can be on physical objects in the external world, bodily sensations, such as the breath, but also on mental objects, including thoughts, emotions, or imagined visual forms. Focusing and sustaining attention on a single object requires maintaining object representation, controlling the focus of attention, detecting distraction, disengaging attention from the source of distraction, and (re)directing and engaging attention to the intended object (Lutz et al., 2008, 2015; Malinowski, 2013). Hence, specific neural systems associated with selective attention, sustained attention, and conflict monitoring are involved in inducing and maintaining the state of FAM (Hasenkamp et al., 2012; Lutz et al., 2008; Yordanova et al., 2021). Upon pain stimulation in FAM, focusing attention on a single object different from pain is expected to reallocate attention away from pain stimuli. In line with this notion, even after short-term training in novices, attention meditation can reduce both pain intensity and unpleasantness by increased activation of cognitive control regions such as the orbitofrontal cortex, anterior cingulate cortex (ACC), and dorsolateral prefrontal cortex, suggesting top-down modulation of nociception (Fox et al., 2016; Nakata, 2014a, 2014b; Perlman et al., 2010; Zeidan, 2012, 2016; Zeidan et al., 2011a, 2011b). In contrast, long-term practitioners often display reduced affective appraisal with even enhanced sensory responses in insula and thalamus, consistent with preserved painful sensations and reduced reactive appraisal (Brown & Jones, 2010; Grant & Rainville, 2009, 2011).

Open monitoring meditation (OMM) entails moment-to-moment monitoring of the contents of experience, mental processes, or any object appearing in the present moment in a non-reactive way, by avoiding explicit attentional selection or focus on any specific object (Lutz et al., 2008). OMM requires awareness and meta-awareness of momentary sensations, thoughts and feelings, an ability closely linked to mindfulness (Isbel & Summers, 2017; Malinowski, 2013; Raffone et al., 2019). In contrast to FAM requiring the narrowest attention focus, OMM regulates attention with the widest possible aperture (Dahl et al., 2015; Lutz et al., 2015). Hence, the induction and maintenance of OMM rely on brain systems associated mainly with divided attention, monitoring, awareness, and attention/mind wandering regulation (Isbel & Summers, 2017; Malinowski, 2013; Raffone & Srinivasan, 2009). Upon pain stimulation in OMM, the imposed enhanced monitoring and awareness of all external and internal events would include pain events, but limited emotional reactivity and cognitive evaluation of pain sensation are expected from the equanimity stance. Indeed, previous research has demonstrated that OMM appears to more selectively reduce pain unpleasantness rather than raw intensity, likely by reactive decoupling sensory input from evaluative appraisal (Lu et al., 2023a, 2023b; Nakata, 2014a, 2014b; Zorn et al., 2020). Neuroimaging studies report increased recruitment of the insula and ACC, and modulation of fronto-parietal salience and control networks, consistent with heightened interoceptive awareness combined, however, with reduced emotional reactivity (Fox et al., 2016; Lutz et al., 2013; Zeidan, 2019).

Loving-kindness meditation/compassion meditation (LKM) is another major meditation style, which refers to the cultivation and maintenance of positive affective mental states associated with caring feelings, attitudes and intentions, acceptance, and motivation towards wellbeing of self and others, with equanimity (Dahl et al., 2015; Lutz et al., 2008). In contrast to FAM and OMM, LKM does not emphasize attention and meta-cognitive awareness although it also requires a certain degree of top-down regulation of mind wandering, attentional control and monitoring of meditation-relevant representations (Dahl et al., 2015; Raffone et al., 2014, 2019). Upon pain stimulation, LKM may primarily affect the cognitive/affective appraisal of pain stimuli. In support of the reactive mode of affect evaluation, imaging studies show recruitment of medial orbitofrontal, medial prefrontal, and reward-related regions (Mascaro et al., 2015; Weng et al., 2013) and pilot clinical studies indicate reductions in pain severity, anger, and improved acceptance in chronic pain patients in compassion meditation (Chapin et al., 2014).

Taken together, the neurocognitive considerations imply that FAM, OMM, and LKM modulate pain processing by engaging attention and emotion systems in distinct ways (e.g.Lutz et al., 2008; Yordanova et al., 2021). Existing pain research further suggests that meditation styles exert partly distinct but overlapping mechanisms of proactive and reactive modes: FAM via both proactive downregulation and reactive attentional/cognitive control, OMM via reactive decoupling of sensation from affective elaboration, and LKM via reactive enhancement of positive affect. Because findings remain inconsistent and do not provide a coherent picture of whether and how different meditation types affect the sensory and cognitive components of pain in specific ways, one aim of the present study was to further characterize the neurophysiologic pain mechanisms during FAM, OMM, and LKM. However, the level of meditation experience appears as a crucial moderator of nociception (Ehmann et al., 2025; Fox et al., 2014, 2016; Zeidan, 2012, 2016; Zeidan et al., 2011a, 2011b). Our previous study (Yordanova et al., 2025) has revealed that in the non-meditative resting state, experienced meditators exhibit a trait-like, proactive, top-down inhibition of somatosensory areas and suppression of afferent sensory processing at early stages of pain input. Also, expert meditators reduce but preserve the emotional/cognitive appraisal of pain manifesting a capacity to dissociate proactive and reactive top-down pain control. These trait-like observations imply that experienced meditators may employ distinctive nociception mechanisms during different meditation styles. Therefore, another aim was to assess if pain processes in different meditation styles differ between practitioners with short or long practice.

For these aims, in the present study, electroencephalographic (EEG) responses to pain were recorded during rest and three meditation conditions, FAM, OMM, and LKM, in two groups of meditators—novice meditators with little meditation experience, here termed short-term meditators (STM) and highly experienced meditation experts, here termed long-term meditators (LTM). A set of neuroelectric parameters was selected to reflect bottom-up and top-down proactive and reactive pain processes during maintenance of different meditation types.

EEG pain research has demonstrated that evoked pain-related potentials (PRPs) and phase-locked oscillatory alpha-to-gamma responses to noxious stimuli at primary somatosensory (S1) and secondary somatosensory/insular (S2-IC) regions are predominantly associated with bottom-up processes (Babiloni et al., 2002; Hauck et al., 2015; Nickel et al., 2022; Strube et al., 2021; Tiemann et al., 2015). In the present study, local time-domain PRP components and the temporal phase synchronization of multi-spectral pain-related oscillations (PROs) were analysed to reflect the effects of specific meditation states on bottom-up pain processes.

In contrast to bottom-up processes, top-down influences on pain processing have been mainly associated with spatial synchronization of alpha and gamma oscillatory networks after painful stimulation (Bott et al., 2023). Further, it has been shown that the spatial synchronization of S1 and S2-IC regions following a pain stimulus is sensitive to meditation expertise (Yordanova et al., 2025). To study if specific meditation states are associated with distinct communication patterns across key regions of pain processing (Peyron et al., 2000), the spatial synchronization of theta-to-gamma oscillatory networks between S1, S2-IC, and fronto-medial (FM)/ACC regions was analysed.

Proactive top-down influences on somatosensory processing have been correlated with ongoing oscillatory activity from alpha and beta frequency ranges preceding event delivery (Babiloni et al., 2006; Pfurtscheller & Lopes da Silva, 1999; van Ede et al., 2010, 2011). Specifically, attention orientation to upcoming painful stimuli has been consistently verified by a pronounced alpha desynchronization at the contra-lateral S1 and S2 (Babiloni et al., 2003, 2004, 2006; Peng et al., 2015; Ploner et al., 2006a, 2006b, 2017). In the present study, to explore proactive preparatory attention to pain stimulus in different meditation states, alpha and beta activities preceding pain stimulus delivery were analysed.

Extensive research has provided consistent evidence for the association between the late parietal P3b component of event-related potentials and the amount of attention allocated to cognitive stimulus evaluation (Polich, 2007). P3b has been identified as a reliable index of involuntary attentional shifts and emotional processing of nociceptive events (Legrain et al., 2002, 2009, 2012). In the present study, the P3b component of time-domain PRPs was analysed to explore whether meditation might influence the reactive top-down processes of cognitive and emotional appraisal of pain information, and if such effects differ between FAM, OMM, and LKM in short- and long-term meditators.

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Previously, significantly enhanced theta (4–8 Hz) oscillations have been observed at medial-frontal electrodes (centred on FCz) in different sensorimotor conditions in relation to a variety of executive and cognitive control functions—conflict processing, detection of errors, inhibition, performance monitoring, amount of cognitive control, and behavioural re-adjustment (Cavanagh & Frank, 2014; Cavanagh et al., 2009; Cohen, 2011, 2014; Cohen & Donner, 2013; Cohen & van Gaal, 2013; Fusco et al., 2018, 2022; Kolev et al., 2009, 2024; Nigbur et al., 2012; Yordanova et al., 2004, 2020a, 2020b, 2024). Given the role of a fronto-medial theta "hub" in mediating these control functions and coordinating behaviour according to contexts (Cohen, 2011, 2014; Duprez et al., 2020), specific meditation types imposing particular demands on attentional focus, inhibition and monitoring would rely on the specialized activation of the medial theta networks during pain processing. Previous studies in no-pain resting states have revealed a substantial reorganization of the fronto-medial theta "hub" in experienced meditators as compared to novices (Jo et al., 2017; Yordanova et al., 2021). Thus, the connectedness of the fronto-medial area was studied here to explore if the differential contexts and requirements for cognitive monitoring during specific meditation types affect pain processing in STM and LTM.

Fronto-parietal (FP) networks have been recognized as the neural substrate of focused attention and attention re-allocation (Corbetta & Shulman, 2011; Vossel et al., 2014). Specifically, the dorsal FP networks are involved in the control of spatial and feature-based attention and in stimulus-response mapping, while the right-lateralized ventral FP network is linked to re-orienting of attention to unexpected but behaviourally relevant events (Chica et al., 2013; Corbetta & Shulman, 2002; Vossel et al., 2014). FP networks also sub-serve attention-based conscious perception (Chica et al., 2013; Dehaene & Changeux, 2011; Dehaene et al., 1998; Rees, 2013), cognitive control and working memory (Bressler & Menon, 2010; Egner et al., 2008; Menon, 2013; Rottschy et al., 2012, 2013). Major operating frequencies of FP networks have been established mainly for slow-frequency (theta) EEG ranges (Daitch et al., 2013; Sadaghiani & Kleinschmidt, 2016; Yordanova et al., 2017). Importantly, relevant activations of frontal and parietal regions have been observed during pain sensation (Peyron et al., 2000). However, the question of how FP networks contribute to pain processing during different meditation states has not been addressed systematically. The FP synchronization of theta oscillations was computed here to capture expected differences in the involvement of attentional networks during pain processing as a function of the specific meditation form.

A first hypothesis of the present study was that the neural mechanisms of pain processing would differ between FAM, OMM, and LKM due to the specific contextual influences and cognitive demands of these meditation styles (Apkarian et al., 2005; Atlas, 2023; Kucyi & Davis, 2015; Peerdeman et al., 2016; Wiech, 2016). A second hypothesis was that the effects of different meditation states on neural pain mechanisms would be specific for STM and LTM groups. The two groups are expected to manifest dissimilar neural reactions to pain in each meditation type due to (a) dissimilar abilities in achieving and sustaining meditation, (b) a considerable difference in the amount of invested cognitive effort to control the meditation style (Fell et al., 2010; Lutz et al., 2008), (c) the profound neuroplastic modification of cognitive and pain-related networks (Fox et al., 2014; Guidotti et al., 2023; Lu et al., 2023a, 2023b; Tang et al., 2015; Yordanova et al., 2020a, 2020b, 2021), and (d) the trait-like alterations of neural mechanisms of pain processing (e.g. Yordanova et al., 2025).

Method

Participants

The present study is based on a substantial data set used in previous reports (Nicolardi et al., 2022; Yordanova et al., 2025), but the results are new and have not been reported elsewhere. The previously collected data from a total of 34 subjects were used, subdivided into a group of 19 long-term meditators

(LTM; 3 females, mean age = 44.6 ± 10.9, mean number of years in monastery = 18 ± 12.7; mean lifetime duration of meditation practice 19,358 h, $SE = 3164$, range 900–50,600 h) and a group of 15 short-term meditators (STM; 6 females, mean age = 44.8 ± 8.2, with less than 250 h of meditation experience, range 60–250 h). Gender distribution did not differ significantly between groups ($\chi^2 = 1.448$, $df = 1$, $p = 0.23$). Although the sample sizes are relatively small, given the rarity and heterogeneity of highly experienced practitioners, such sample sizes are common in the literature and the number of our LTM subjects is consistent with prior studies of experienced meditators (≈10–40; typically < 20; rev. Lomas et al., 2015—Table 1). To address the issue, we include effect sizes in the statistical reports. Also, our group definitions (STM and LTM) are consistent with ranges reported in previous studies of LTM. Currently, there is wide variability in the criteria used to define

Table 1 Summary of analysed neurophysiological processes, parameters, and effects

Process	Measures	Analysed parameters	Effects in STM	Effects in LTM
(A) Bottom-up somatosensory processes	Time-domain PRP and temporal synchronization (PLF) of multispectral PROs at S1 and S2-IC	1. N1 and P2 amplitude at S1 and S2-IC	NS	NS
		2. N1 and P2 latency at S1 and S2-IC	NS	NS
		3. Theta-alpha PLF at S1 and S2-IC	NS	NS
		4. Beta PLF at S1 and S2-IC	NS	NS
		5. Gamma-1 PLF at S1 and S2-IC	NS	NS
		6. Gamma-2 PLF at S1 and S2-IC	NS	NS
(B) Communication of pain information across relevant cortical regions	Spatial synchronization (PLV) of frequency-specific networks between S1-S2-IC, S1-FM, and S2-IC-FM	1. PLV between S1 and S2-IC		
		- Theta-alpha	NS	NS
		- Beta	NS	NS
		- Gamma-1	NS	NS
		- Gamma-2	NS	NS
		2. PLV between S1 and FM		
		- Theta-alpha	**↑FAM,OMM**	NS
		- Beta	NS	NS
		- Gamma-1	NS	NS
		- Gamma-2	NS	NS
		3. PLV between S2-IC and FM		
		- Theta-alpha	NS	NS
		- Beta	NS	NS
		- Gamma-1	NS	NS
		- Gamma-2	NS	NS
(C) Proactive processes of attention allocation	Total power (TOTP) of alpha and beta activity before pain stimulus	1. Pre-stimulus alpha TOTP at S1, S2-IC, and FM	NS	↑**FAM**, OMM, **LKM** S1/S2-IC
		2. Pre-stimulus beta TOTP at S1, S2-IC, and FM	NS	NS
(D) Reactive top-down processes of cognitive and emotional appraisal of pain information	Amplitude and latency of the centro-parietal P3b component of time-domain PRPs	1. P3b amplitude at CP3, CPz, CP4	**↓LKM**	NS
		2. P3b latency at CP3, CPz, CP4	NS	NS
(E) Activation of fronto-medial cognitive network	Connectedness (R-PLV) of fronto-medial region	1. Theta-alpha R-PLV at FM	**↓LKM**	**↓ FAM, OMM**
		2. Beta R-PLV at FM	NS	**↑ FAM, OMM**
		3. Gamma-1 R-PLV at FM	NS	NS
		4. Gamma-2 R-PLV at FM	NS	NS
(F) Activation of attentional networks during pain processing	Synchronization (PLV) of fronto-parietal pairs	1. Theta-alpha PLV of F5-P5, F3-P3, F4-P4, F6-P6	NS	**FAM, OMM**

STM, short-term meditators; *LTM*, long-term meditators; *PRP*, pain-related potential; *PLF*, phase-locking factor; *PLV*, phase-locking value; *R-PLV*, regional phase-locking value; *S1*, primary somatosensory cortex; *S2-IC*, secondary somatosensory/insular cortex; *FM*, fronto-medial cortex; *NS*, non-significant; ↑, increase; ↓, decrease; *FAM*, focused attention meditation; *OMM*, open-minded meditation; *LKM*, loving-kindness meditation; meditation states with significant changes are presented in bold short-term and long-term meditators based on lifetime practice hours (Ehmann et al., 2025). For example, Panitz et al. (2025) reported LTM experience ranging from ~936 to ~29,293 h, while Kral et al. (2022) described LTMs with ~780 up to ~19,656 h of practice, and Lutz et al. (2018) defined advanced experts as having more than 10,000 h of practice.

The LTM group comprised monks and nuns residing at Amaravati Buddhist Monastery, in Southern England, and at Santacittarama Monastery, in Central Italy. Despite the different geographic locations, practices at both monasteries are aligned with the Thai Forest Theravada Buddhist tradition, which is now widely acknowledged in the West. In this tradition, the participants from the LTM group practiced FAM, OMM, and LKM forms in a balanced way, often in integrated sessions, typically 2 h per day with the monastery community, with a regular intensification of practice during retreats (with several silent meditation sittings during the 3 months winter retreat). As suggested by the abbots of the monasteries, monastics were included who had an average of 100 h of practice per month during monastic life, with a balance of meditation facets. In the present study, meditation expertise was measured in hours, taking into account both practice in the monastic tradition and practice before monastic life. Irrespective of previous short-term meditative training, the STM participants practiced the FAM, OMM, and LKM for 10 days before the study, 20 min per day for each form of meditation. All participants were right-handed healthy volunteers, without a history of neurologic, psychiatric, chronic somatic, or other problems.

Procedure

Neural responses to pain were elicited by applying painful electrical stimuli. The electrical stimuli were pulses generated by a monophasic constant current stimulator (STIM140, H.T.L. srl, Amaro, UD, Italy). Stimuli were delivered through two surface electrodes (diameter 6 mm, Ag/AgCl, Electro-Cap International, Inc. Eaton, Ohio) placed 5 mm from each other. The stimulation site was on the dorsal digital branch of the radial nerve, on the medial surface of the back of the left hand. The intensity range allowed by the instrument was between 2 and 50 mA.

Before experimental stimulation blocks, (1) the absolute pain threshold was determined, and (2) stimulus intensity calibration was performed. Using the ascending and descending method of limits (Säterö et al., 2000; Valentini et al., 2017), the absolute pain threshold of each participant was identified as the minimum intensity of a stimulus that was perceived as painful. During calibration, suprathreshold electric stimuli were delivered with a staircase procedure until the participant associated the same stimulus intensity with a moderate pain sensation in 50 ± 10% of probes. Hence, individually adjusted stimuli with moderate intensity for each participant were used.

During the experimental phase painful stimuli delivered as single events during conditions which the participants had to maintain in succession: a non-meditative resting state (REST), and meditation conditions (FAM, OMM, and LKM). The instructions for the four conditions, which were written together with the abbot of Amaravati Monastery, were as follows (Nicolardi et al., 2022): Rest—“Rest in a non-meditative relaxed state, without falling in sleep, while allowing any spontaneous thoughts and feelings to arise and unfold in the field of experience”; FAM—“Sustain the focus of attention on breath sensations, such as at the nostrils, noticing readily and with acceptance any arising distraction, such as on thoughts or stimuli, and in case of detected distraction, return readily and gently to focus attention on the breath sensations”; OMM—“With an open receptive awareness, observe the contents of experience as they arise, change and fade from moment to moment, without restrictions or judgments—such contents including breath and body sensations, sensations arising from contact with external stimuli, feelings and thoughts”; LKM—“Generate and sustain metta, acceptance and friendliness towards yourself and the experience in the present moment, as well as towards any being, in any state or condition”. The switch to each condition was signalled by means of an audio instruction. This sequence of meditative conditions (REST, FAM, OMM, LKM) was repeated three times, leading to a total of 12 blocks, with each block including 10 trials (a total of 30 trials for each condition). For analysis, trials from each block/per condition were used thus capturing brain states at distributed time-points. Although the conditions were not fully randomized, the repetitive presentation of different meditative states across blocks during the entire session was designed to minimize order effects linked to fatigue and habituation. In the present experimental design, the duration of each trial was approximately 10 s (9 to 13 s). The painful stimulus (electrical stimulus with 50 ms duration) was delivered randomly 4.5 to 8.5 s after beginning of the trial. One and a half seconds after stimulus delivery, participants were asked to rate (scale 1–100) three dimensions of subjective experience related to the nociceptive stimulation: pain, aversion, and identification (Nicolardi et al., 2022).

According to the experimental procedure, meditation states were induced in brief cued blocks (approx. 2 min each) following established experimental protocols for transient (short-lived) state manipulation (Lutz et al., 2004; Perlman et al., 2010). To quantify state fidelity, we collected subjective self-reports after the session and also computed intermittent attentional probes during blocks using frontal and parieto-occipital theta-alpha activity (Online Resource 1, Supplementary Information 1). The frontal theta-alpha modulation was used as a marker of internal attention control, while the parieto-occipital theta-alpha modulation was used to index relaxation (Aftanas & Golocheikine, 2001; Cahn & Polich, 2006; Lomas et al., 2015). Both STM and LTM groups manifested power increase at anterior and posterior regions during meditative states suggesting an activation of meditation-induced processes. Although in STM, in contrast to LTM, the increase was not statistically reliable as expected, it is important to note that in each group, the patterns of power increase in meditative states relative to rest were similar in no-pain and pain conditions. This verification provides grounds to accept that the participants engaged in the instructed meditative states during pain conditions, despite task-related interference (pain stimulation, required subjective scoring of pain, and short duration of experimental blocks).

Measures

EEG recording and processing are presented in detail in Yordanova et al. (2025). Here, major analytic steps are summarized. EEG was recorded by a mobile wireless system (Cognionics; https://www.cognionics.net/mobile-128) using an electrode cap with 64 active Ag/AgCl electrodes located in accordance with the extended international 10/10 system and referenced to linked mastoids. Electrode impedances were kept below 10 kOhm and EEG signals were collected at a sampling rate of 500 Hz (resampled off-line to 250 Hz for data analysis).

EEG analysis was performed with Brain Vision Analyzer ver. 2.2.2 (Brain Products GmbH, Gilching, Germany). EEG was visually inspected for gross ocular and other artefacts at 64 channels. Contaminated trials were discarded along with EEG records exceeding ± 100 µV. Bad channels were interpolated using topographic interpolation (Perrin et al., 1989). Slight horizontal and vertical eye movements preserved in the accepted trials were corrected by means of independent component analysis (ICA, Makeig et al., 1997). After artefact rejection, the mean number of artefact-free trials used for analysis was 27 for each condition ($SD = 2.3$, range 24–29).

To achieve a reference-free evaluation and control for volume conduction current source density (CSD) transform of the signals was performed (see, e.g.Nunez et al., 1997; Perrin et al., 1989 for details). All EEG epochs were analysed after a CSD transform of the signals.

Data Analyses

Analysis of Pain-Related EEG Responses Pain EEG responses were analysed in the time- and time-frequency domains. Time-domain analysis was performed by averaging 1.5-s-long artefact-free pain-related EEG epochs, including 0.5 s before and 1 s after electric stimulus. Time-frequency (TF) analysis of pain-related potentials was performed by means of a continuous wavelet transform (CWT) with Morlet wavelets as basis functions (Mallat, 1999). Details of CWT and Morlet basis functions are presented in Yordanova et al. (2025).

Two types of epochs were analysed in the TF domain: (1) For slow-frequency PROs from delta, theta, and alpha frequency bands, EEG epochs were 1.5 s long, including 0.5 s before and 1 s after electric stimulus, in the frequency range 0.5–25 Hz with a central frequency at 0.6-Hz intervals; (2) for fast-frequency PROs from beta and gamma frequency bands, EEG epochs were 0.85 s long, with 0.25 s before and 0.6 s after stimulus, in the frequency range 15–50 Hz with a central frequency at 1.75-Hz intervals.

Analysis of Pain-Related Oscillations

Total power of PROs Single trials were first transformed to the TF domain and then averaged. For each trial, the time-varying power for each frequency scale (total power, TOTP) was calculated by squaring the absolute value of the convolution of the signal with the complex wavelet. In the present study, TOTP was used for analysis of alpha and beta pre-stimulus activity. For statistical evaluation, TOTP was *log10*-transformed.

Temporal Synchronization of PROs: Phase-Locking Factor The temporal phase synchronization across trials was analysed by means of the phase-locking factor (PLF, e.g.Lachaux et al., 1999; Tallon-Baudry et al., 1997; Yordanova et al., 2025). The values of PLF yield a number between 0 and 1 determining the degree of between-trial phase-locking, where 1 indicates perfect phase alignment across trials and values close to 0 reflect the highest phase variability. PLFs were computed for different TF scales at each time-point, each electrode, condition, and subject.

Spatial Synchronization of PROs: Phase-Locking Value The phase-locking value (PLV) is measured between electrode channels and reflects the extent to which oscillation phase angle differences between electrodes are consistent over trials at each time/frequency point. PLV varies between one (constant phase difference) and zero (random phase difference). After excluding the edge electrodes prone to signal distortion and reducing the number of electrodes to 35, PLV was computed for each pair of electrodes, resulting in a total of 630 pairs for each subject. PLVs were computed for different TF scales at each time-point, condition, and subject.

To identify regions with maximal connectivity during PRPs, the mean of all pairs connected with each single electrode was computed for each electrode. Following this procedure, a quantifier "regional PLV" (R-PLV) was established. For R-PLV computation, the selected 35 electrodes were used (F5, F3, Fz, F4, F6, FC5, FC3, FCz, FC4, FC6, C5, C3, Cz, C4, C6, CP5, CP3, CPz, CP4, CP6, P7, P5, P3, Pz, P4, P6, P8, PO7, PO3, POz, PO4, PO8, O1, Oz, and O2). R-PLV was computed for different TF scales at each time-point, electrode, condition, and subject.

Measurements and Parameters

Pain-Related Potentials N1 PRP component was identified as the maximal negative peak within 130–250 ms after stimulus onset. P2 PRP component was identified as the maximal positive peak within 180–300 ms after stimulus onset. P3b was identified as the maximal positive peak with centro-parietal/parietal distribution within 300–500 ms after stimulus (Polich, 2007). Peak amplitude and latency of PRP components were measured against a baseline of 300 ms before stimulus.

Pain-Related Oscillations As argued in Yordanova et al. (2025), PROs from 5 relevant frequency ranges were analysed: theta-alpha with $f_0 = 7.5$ Hz (4.7–10.7 Hz), beta with $f_0 = 18.14$ Hz (15.8–22.9 Hz), gamma-1 with $f_0 = 32.1$ Hz (30.8–35.9 Hz), and gamma-2 with $f_0 = 43.5$ Hz (38.8–42.9 Hz). PLF and R-PLV were measured as the maximal value within defined epochs after stimulus for each frequency band, subject, and electrode as follows: theta-alpha (within 20–250 ms), beta (within 10–150 ms), gamma-1 (within 10–150 ms), gamma-2 (10–100 ms). The measures were baseline corrected by subtracting the mean value of a baseline of −300/−50 ms for slow and −200/−50 ms for fast-frequency TF components.

Pre-stimulus Activity Pre-stimulus activity was measured by computing the mean value of TOTP for alpha ($f_0 = 7.5$ and 10.1 Hz) within −450/−50 ms and beta (−250/−50 ms) frequency bands. These were chosen for analysis of pre-stimulus activity as relevant for correlates of proactive attention modulation (Peng et al., 2015; van Ede et al., 2010).

Regions of Interest TF analyses were performed for sets of electrodes covering three regions of interest (ROIs): (1) contra-lateral primary somatosensory cortex (S1), (2) contra-lateral secondary somatosensory cortex including the insular cortex (S2-IC), and (3) frontal medial cortex including the ACC and supplementary motor areas (FM). As argued in Yordanova et al. (2025), these three ROIs were selected based on (1) theoretical accounts according to which S1, S2, IC, and ACC are the major regions with relevant cortical projections involved in pain processing (Chen, 2023; Peyron et al., 2000); (2) observations from current data on phase-locked pain-related activity (Online Resource 1, Supplementary Information 2); (3) previous detailed topographic analysis of phase-locked PROs evoked by similar nociceptive stimulation (Babiloni et al., 2002); and (4) previous approaches for analysis of synchronized pain-related oscillations and spatial connections (Bott et al., 2023; Nickel et al., 2022). Following the correspondence of electrode positions of the 10-10 system to these areas (Koessler et al., 2008; Scrivener & Reader, 2022), S1 included Cz, C4, CPz, and CP4; S2-IC included C6, CP6, and P6; and FM included Fz and FCz electrodes (Babiloni et al., 2002; Bott et al., 2023; Nickel et al., 2022). For analysis of time-domain PRPs, pain-related oscillations, and pre-stimulus activity at each ROI, single-electrode measures were used.

Figure 1 and Table 1 summarize the parameters analysed in the present study with respect to the objectives:

(A) To analyse bottom-up somatosensory processes: (1) time-domain PRP components N1 and P2 at S1 and S2-IC; (2) PLF of theta-alpha, beta, gamma-1, and gamma-2 PROs at S1, S2-IC, and FM—Fig. 1A.
(B) To analyse the communication of pain information across relevant cortical regions: PLV of theta-alpha, beta, gamma-1 and gamma-2 PROs of selected pairs of electrodes included in S1, S2-IC, and FM—Fig. 1B.
(C) To analyse proactive processes of attention direction to or away from pain stimulus: pre-stimulus alpha and beta TOTP at S1, S2-IC, and FM—Fig. 1C.
(D) To analyse reactive top-down processes of cognitive/emotional appraisal of pain information: time-domain P3b component at centro-parietal electrodes CP3, CPz, and CP4—Fig. 1D.
(E) To analyse the activation of the FM cognitive network: R-PLV of theta-alpha, beta, gamma-1, and gamma-2 oscillations at FM—Fig. 1E.
(F) To analyse the activation of attentional networks during pain processing: PLV of electrode pairs P5-F5, P3-F3, P4-F4, and P6-F6. These pairs were selected to capture fronto-parietal synchronization of dorsal and ventral FP networks in the left and right hemispheres (Yordanova et al., 2017, 2021)—Fig. 1F.

Statistical Analysis In Yordanova et al. (2025), we demonstrated that PRPs and PRO parameters analysed here differ between STM and LTM already during REST. Therefore, the effects of meditation states were tested in each group separately. For each parameter, a repeated measures ANOVA design was applied with a within-subjects variable Condition (REST vs. FAM vs. OMM vs. LKM). Post hoc contrasts were carried out to test significant Condition effects and compare REST with each meditation state. Analyses were performed for each ROI (including single electrodes relevant for S1, S2-IC, and FM as levels of another within-subjects variable electrode in ANOVAs) or for selected PLV pairs, and each frequency-specific PLF/PLV/R-PLV/TOTP measure. For factors with more than two levels, the Greenhouse–Geisser correction was

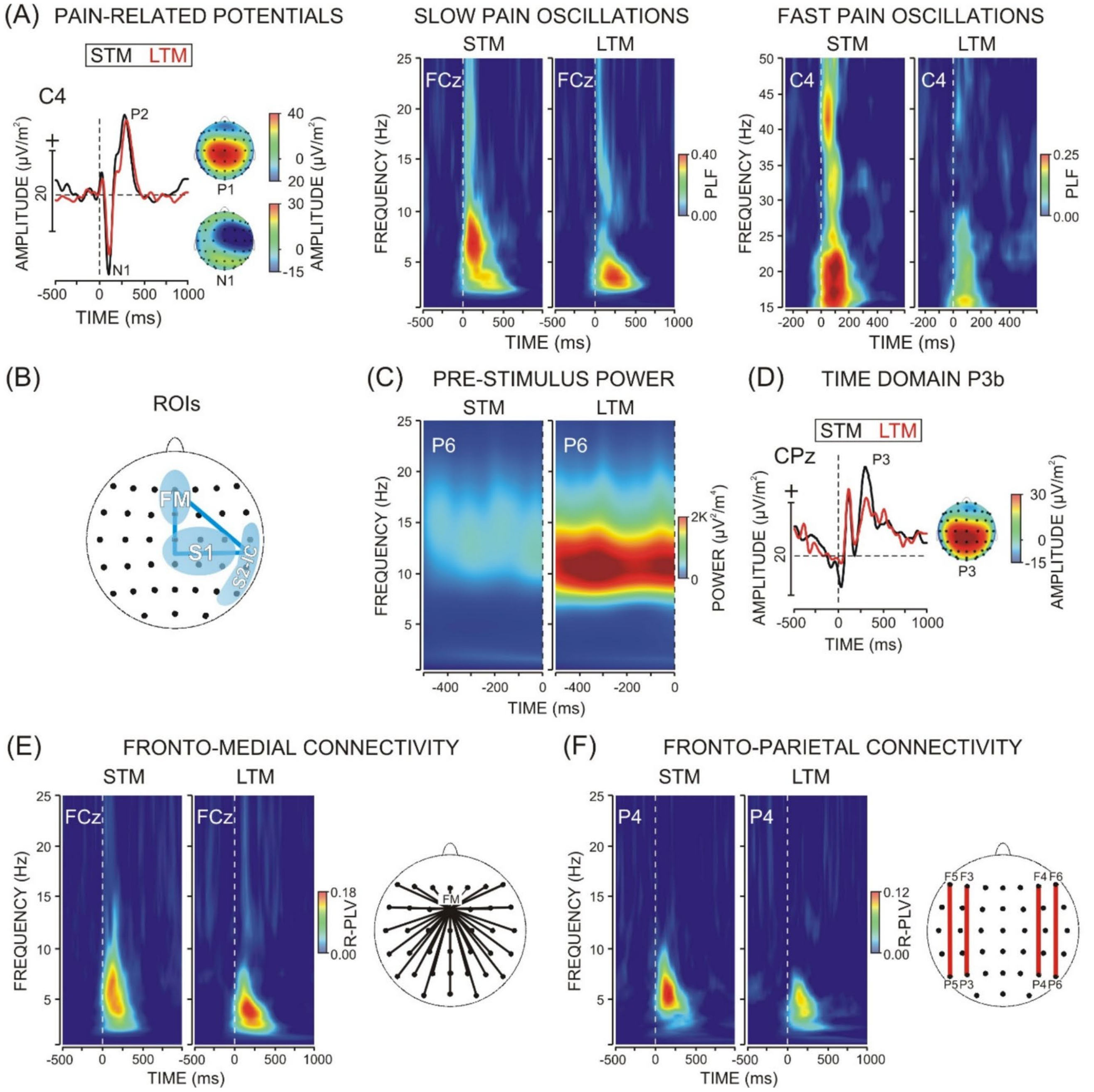


Fig. 1 Neuroelectric parameters of pain processing in the two experimental groups—short-term meditators (STM) and long-term meditators (LTM). **A** Pain-related potentials (PRP) at S1 (C4 electrode) and topography maps of N1 and P2 PRP components (left panel); time-frequency plots of PLF for slow- and fast-frequency oscillations at relevant electrodes (FCz and C4) (right panel) during REST. **B** Schematic presentation of the connections across S1, S2-IC, and FM regions analysed by means of inter-regional synchronization (PLV). **C** Pre-stimulus alpha activity (TOTP) during REST. **D** Waveform and topographic distribution of P3b PRP component during REST. **E** Time-frequency plots of R-PLV during REST and a schematic presentation of the connectedness (R-PLV) of the fronto-medial region. **F** Time-frequency plots of PLV of fronto-parietal pairs during REST and a schematic presentation of 4 FP used for analysis. Stimulus occurrence at 0 ms

applied to the degrees of freedom (*df*). Original *df*, corrected *p*-values, and partial eta squared (η^2) are reported, along with mean group values ± standard error (*SE*) whenever relevant. To control for multiple testing effects, FDR correction was applied (Benjamini & Hochberg, 1995). For conciseness, only statistical outcomes remaining statistically significant after corrections are presented in detail in the results.

Results

Subjective Pain Indices

Figure 2 demonstrates that each of the parameters of subjective pain reflection (subjective pain intensity, aversion, and identification) decreased in LKM relative to REST in STM. This was evidenced by the significant effects of Condition in ANOVA for subjective pain intensity ($F(3, 42) = 5.76$, $p = 0.01$, $\eta^2 = 0.31$), aversion ($F(3, 42) = 10.45$, $p < 0.001$, $\eta^2 = 0.45$), and identification ($F(3, 42) = 8.02$, $p = 0.002$, $\eta^2 = 0.382$), with $p < 0.05$ for the REST vs. LKM post hoc contrasts for each parameter. The effects of meditation states on subjective pain measures were not significant in LTM (Condition; $F(3, 54) = 1.38$, 3.07, $p = 0.26$, 0.08, $\eta^2 = 0.112$, 0.218)—Fig. 2.

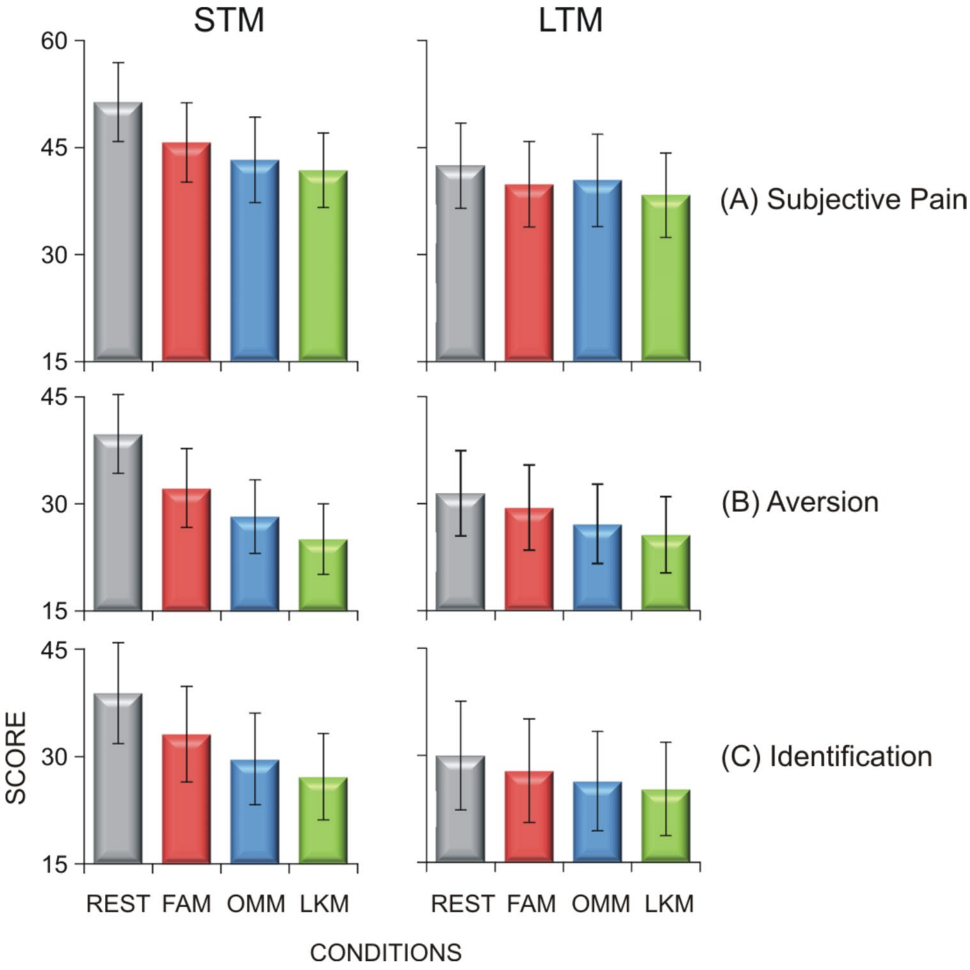
Neuroelectric Parameters

Bottom-Up Somatosensory Processes (Table 1, Fig. 3A) In none of the groups was there any effect of meditation states on the parameters of local time-domain PRPs and PROs as verified by non-significant Condition effects.

Communication of Pain Information Across Cortical Regions (Table 1, Fig. 3B) No effects of meditation states were yielded for the synchronization between S1 and S2-IC for any of the frequency-specific oscillations in either of the two groups (Condition, NS).

As demonstrated in Fig. 3B and *verified* by the Condition effect in ANOVA and post hoc contrasts, in the group of STM, the synchronization between S1 and FM regions supported by theta-alpha networks significantly increased in FAM and OMM relative to REST (Condition, $F(3, 42) = 5.92$, $p = 0.01$, $\eta^2 = 0.29$; REST vs. FAM, $F(1, 14) = 15.02$, $p = 0.002$, $\eta^2 = 0.58$; REST vs. OMM, $F(1, 14) = 8.53$, $p = 0.01$, $\eta^2 = 0.389$), whereas no difference in theta-alpha connections between S2-IC and FM was yielded. The synchronization between S1/S2-IC and FM supported by beta and gamma networks was not affected by meditation states in STM.

Fig. 2 Subjective pain parameters: **A** subjective pain intensity, **B** aversion, and **C** identification in groups of short-term meditators (STM) and long-term meditators (LTM) in four conditions: REST, FAM, OMM, and LKM



In the group of LTM, theta-alpha S1/S2-IC-FM connections were not modulated by meditation states (Fig. 3B), nor were there any reliable changes in the synchronization with FM of beta and gamma networks as a function of meditation states.

Proactive Processes of Attention Direction (Table 1, Fig. 3C) In the group of STM, pre-stimulus alpha activity did not vary with meditation states at any ROI: (Condition, $F(3, 54) < 0.68$, $p > 0.6$, $\eta^2 < 0.04$).

In LTM, pre-stimulus alpha was significantly affected by meditation states at S1 (Condition, $F(3, 54) = 5.63$, $p = 0.006$, $\eta^2 = 0.24$) and S2-IC (Condition, $F(3, 54) = 4.59$, $p = 0.03$, $\eta^2 = 0.2$) by manifesting a significant increase in FAM vs. REST (S1: $F(1, 18) = 6.34$, $p = 0.02$, $\eta^2 = 0.26$; S2-IC: $F(1, 18) = 5.74$, $p = 0.03$. $\eta^2 = 0.24$) and LKM vs. REST (S1: $F(1, 18) = 15.46$, $p = 0.001$, $\eta^2 = 0.46$; S2-IC: $F(1, 18) = 7.11$, $p = 0.01$, $\eta^2 = 0.28$). Meditation states in LTM were not associated with modulation of pre-stimulus alpha at the FM region. No effects of meditation states were detected for pre-stimulus beta activity at any ROI in any of the two groups (Condition, $p > 0.3$).

Cognitive/Emotional Appraisal of Pain Information (Table 1, Fig. 3D) Meditation states had an effect on P3b amplitude only in STM (Condition, $F(3/42) = 5.53$, $p = 0.007$, $\eta^2 = 0.28$) resulting from a significant P3b decrease in LKM as compared to all other states ($F(1/14) = 4.83$–10.86, $p = 0.05$–0.005, $\eta^2 = 0.24$–0.46). Interestingly, the maintenance of different meditation states in the group of LTM did not affect P3b amplitude (Condition, $F(3/52) = 1.23$, $p = 0.3$, $\eta^2 = 0.06$). No effects on P3b latency were observed.

Fronto-medial Networks (Table 1, Fig. 3E) ANOVA results and post hoc contrasts showed that in *STM*, the FM theta-alpha synchronization was substantially reduced only during LKM as compared not only with REST but also with other meditation states, with no changes detected for FAM and OMM vs. REST (Condition, $F(3, 42) = 4.84$, $p = 0.009$, $\eta^2 = 0.25$; LKM vs. REST, FAM, OMM, $F(1, 14) = 5.44$–21.44, $p = 0.03$–0.001, $\eta^2 = 0.39$–0.6).

In LTM, the effect of meditation states on FM theta-alpha synchronization also was significant (Condition, $F(3, 54) = 4.69$, $p = 0.01$, $\eta^2 = 0.21$), but this was due to a significant reduction in all meditation states relative to REST, mostly expressed during OMM (REST vs. FAM, OMM, LKM, $F(1, 18) = 4.22, 22.56, 5.50$, $p = 0.05, 0.001, 0.03$, $\eta^2 = 0.15, 0.59, 0.23$). Notably, opposite to theta-alpha, the FM beta synchronization was significantly enhanced during FAM and OMM in LTM (Condition, $F(3, 54) = 5.69$, $p = 0.008$, $\eta^2 = 0.31$; REST vs. FAM, OMM, $F(1, 18) = 19.14, 20.05$, $p < 0.001$, $\eta^2 = 0.49, 0.5$).

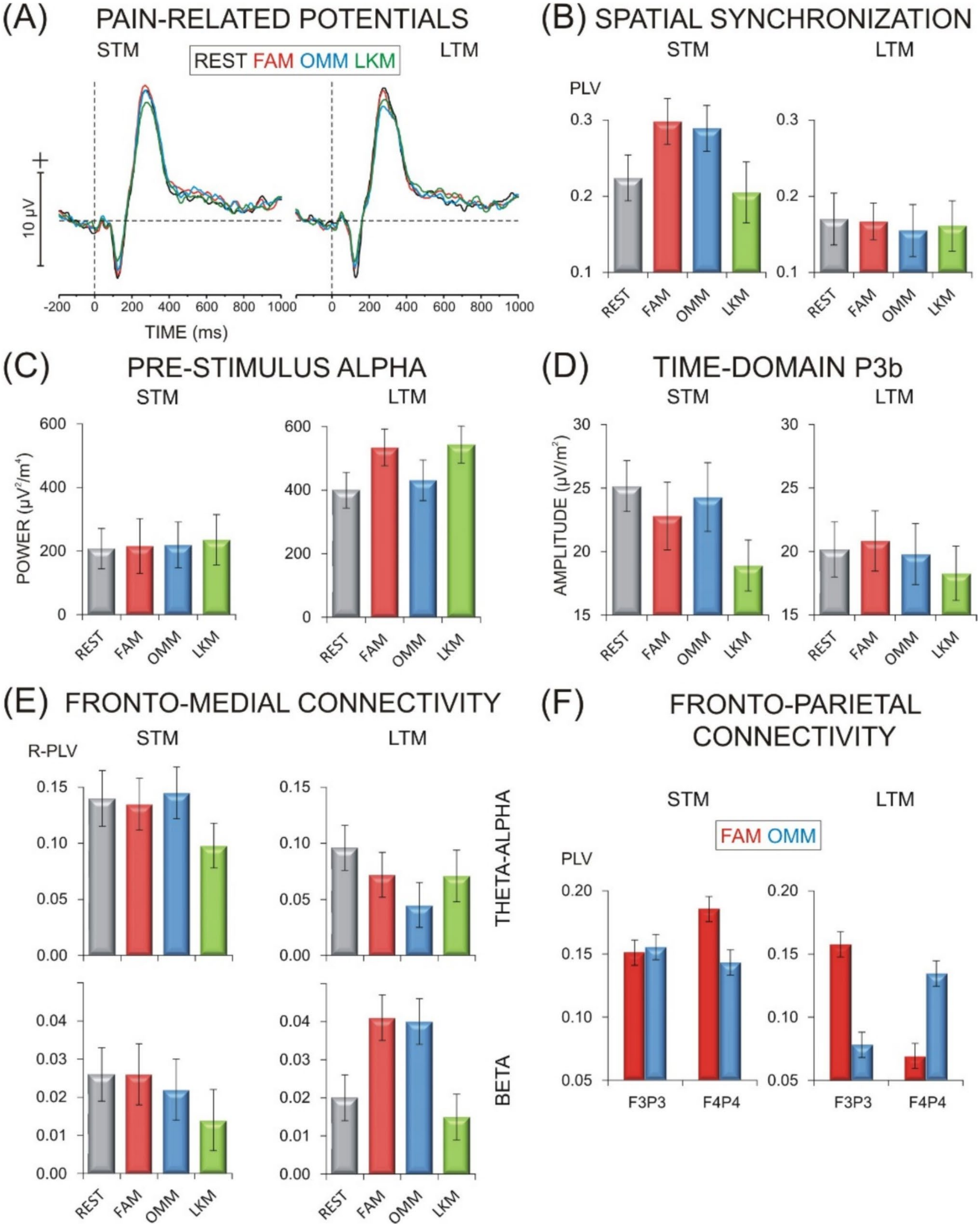
Fronto-parietal Networks (Table 1, Fig. 3F) Four pairs of FP electrodes were chosen to represent the dorsal and ventral attentional networks in the left and right hemispheres (F5-P5, F3-P3, F4-P4, and F6-P6). The FP synchronization was analysed in a Condition (4 levels) × Pairs (4 levels) repeated measures ANOVA design in each of the two groups.

In STM, meditation states were not associated with different synchronization of FP pairs (Condition, $F(3, 42) = 0.49$, $p = 0.7$, $\eta^2 = 0.04$; Condition × Pair, $F(9, 126) = 1.33$, $p = 0.3$, $\eta^2 = 0.09$). However, in LTM, the synchronization of particular FP pairs was sensitive to specific meditation states (Condition × Pair, $F(9, 162) = 3.2$, $p = 0.05$, $\eta^2 = 0.18$). Specifically, FAM and OMM produced lateralized modulations of theta-alpha FP synchronization. During FAM, an enhancement of F3-P3 synchronization was accompanied by a prominent decrease of F4-P4 synchronization ($F(1, 18) = 10.8$, $p = 0.004$, $\eta^2 = 0.37$). Exactly the opposite modulations of F3-P3 and F4-P4 were observed during OMM, characterized by enhanced synchronization on the right and reduced synchronization on the left ($F(1, 18) = 5.54$, $p = 0.03$, $\eta^2 = 0.24$). Of note, although non-significant, the opposite relations for the involvement of the right FP pair F4-P4 in FAM and OMM were observed in STM.

Discussion

The present study aimed to characterize the effects of different meditation states on neurophysiologic mechanisms of pain processing. For that aim, three forms of meditation (FAM, OMM, and LKM) were explored, in which attentional and affective regulation were engaged in specific ways. Because extensive meditation practice cultivates advanced modes of awareness and attention/emotion regulation, two groups of meditation practitioners were studied, novices and experts. Several neurophysiologic indices of pain processes were analysed to characterize bottom-up and top-down mechanisms. It was expected that the states of meditation would affect neural mechanisms of pain processing in specific ways depending on (a) the type of meditation and (b) meditation expertise.

Bottom-Up and Top-Down Mechanisms One major result of the study is that the bottom-up mechanisms of pain processing did not differ significantly between meditation types. We conclude this because the neural signatures that are sensitive to bottom-up processes (Bingel et al., 2004; Hauck et al., 2015; Nickel et al., 2022; Strube et al., 2021; Tiemann et al.,


(A) PAIN-RELATED POTENTIALS
STM
LTM
REST FAM OMM LKM
10 µV
+
-200 0 200 400 600 800 1000
0 200 400 600 800 1000
TIME (ms)
(B) SPATIAL SYNCHRONIZATION
STM
LTM
PLV
0.3
0.2
0.1
REST FAM OMM LKM
(C) PRE-STIMULUS ALPHA
STM
LTM
POWER ($\mu V^2/m^4$)
600
400
200
0
REST FAM OMM LKM
(D) TIME-DOMAIN P3b
STM
LTM
AMPLITUDE ($\mu V/m^2$)
30
25
20
15
REST FAM OMM LKM
(E) FRONTO-MEDIAL CONNECTIVITY
STM
LTM
R-PLV
0.15
0.10
0.05
0.00
THETA-ALPHA
0.04
0.03
0.02
0.01
0.00
BETA
REST FAM OMM LKM
(F) FRONTO-PARIETAL CONNECTIVITY
STM
LTM
FAM OMM
PLV
0.20
0.15
0.10
0.05
F3P3
F4P4

◂**Fig. 3** Group means ± *SE* of neuroelectric parameters of pain processing in four conditions (REST, FAM, OMM, and LKM) in two groups—short-term meditators (STM) and long-term meditators (LTM). A Grand average pain-related potentials (PRP) at S1 (C4 electrode). B Spatial synchronization (PLV) of theta-alpha networks between S1 and FM. C Pre-stimulus alpha activity (TOTP) at S1. D Amplitude of centro-parietal P3b component of PRPs. E Connectedness (R-PLV) of fronto-medial region supported by theta-alpha and beta oscillatory networks. F Synchronization (PLV) of fronto-parietal pairs F3-P3 and F4-P4 during FAM and OMM

2015), namely the PRP components at contra-lateral S1 and S2-IC and the local temporal synchronization of multi-spectral pain-related oscillations, did not depend on meditation type in any of the groups.

However, it is important to note that our previous analyses during REST yielded differences between LTM and STM for the same parameters (Yordanova et al., 2025). These analyses revealed significantly lower phase-locked multi-spectral PROs at contra-lateral S1 and S2-IC regions in LTM than in STM, suggesting a profound trait-like modulation of the somatosensory component of pain responses. This modulation possibly arises from long-term neuroplastic changes, potentially involving a suppression of bottom-up pain mechanisms associated with meditation expertise increase. In this regard, if meditation is associated with a downregulation of ascending nociceptive signals in somatosensory areas (Brown & Jones, 2010; Jinich-Diamant et al., 2020; Zeidan & Vago, 2016; Zeidan et al., 2011a, 2011b), such sensory filtering may result primarily from neuroplastic network reorganization rather than from phasic brain states associated with specific meditation states.

In contrast to bottom-up processes, the correlates of top-down mechanisms of pain were affected by different meditation states. Importantly, these differences also depended on meditation expertise, indicated by the differential effects of meditation states in novices and experts.

STM-Specific Effects Specifically, STM manifested (1) enhanced theta-alpha synchronization of the S1-FM connections during FAM and OMM (Fig. 3B), (2) a significant decrease in the regional synchronization of the theta-alpha network centred at frontal midline regions during LKM (Fig. 3D), and (3) a significant reduction of P3b PRP component also during LKM (Fig. 3E; also see Table 1 for summaries). These results show that during meditation in STM, the most distinguished changes in pain processing are associated with LKM, i.e. the state expected to induce a shift towards positive emotional attitude, tone and reflection. Moreover, these mechanisms involved in STM during LKM appear to be specific as they were not sensitive to other meditation types nor were they involved during LKM in experts. Likewise, the theta-alpha S1-FM connection that was only sensitive to attention-related meditation states (FAM and OMM) in STM, was not affected by any meditation type in experts.

LTM-Specific Effects In contrast, in LTM, the most conspicuous meditation state-related changes in top-down pain mechanisms emerged during FAM and OMM, i.e. meditation states that entail sustained attention regulation, in terms of a narrowed attentional focus for FAM and a maximally expanded attentional focus for OMM. Specifically, (1) pre-stimulus alpha increased at S1 and S2-IC, mostly in FAM (Fig. 3C), (2) the connectedness of the fronto-medial region supported by theta-alpha networks was suppressed in all meditation states, mostly in OMM (Fig. 3E top panels), (3) this suppressed theta-alpha fronto-medial synchronization was paralleled by increased beta synchronization of the fronto-medial region in FAM and OMM (Fig. 3E bottom panels), (4) there was a lateralized asymmetric synchronization of the fronto-parietal connections during FAM and OMM (Fig. 3F; also see Table 1 for a summary). These results reveal distinctive patterns in experienced meditators during FAM and OMM that did not occur in novices, implying that the advanced attention/awareness control plausibly mobilized in experienced practitioners during FAM and OMM has highly specific effects on neural pain processing.

We can now ask the question how these differential effects contribute to deepening our understanding of meditation state-related pain processing in the brain:

Communication Across Regions of Primary and Higher-Level Pain Processing The synchronization between S1 and S2-IC can reflect a sequential (hierarchical) transmission of sensory pain information from S1 to S2-IC (Della Penna et al., 2004; Dockstader et al., 2010; Hagiwara et al., 2010) or a simultaneous co-activation of the two cortical regions (Garcia-Larrea et al., 2003). Although this communication may depend on focused attention (Dockstader et al., 2010; Hauck et al., 2007), no effects of meditation states were yielded here for any of the frequency-specific oscillations in either STM or LTM.

Only the synchronization between S1 and FM areas in the theta-alpha band in novices was altered during FAM and OMM. When interpreting this result we need to consider the fact that neural responses from the FM region capture activations of the ACC, a key structure for integrative pain processing (rev. Peyron et al., 2000) that is involved in the affective and attentional components of pain sensation (Garcia-Larrea & Peyron, 2013; Garcia-Larrea et al., 2003; Peyron et al., 1999, 2000). A recent study in rats demonstrated that the sensory pain information encoded in the primary somatosensory cortex S1 is projected to a subset of neurons in the ACC, with increased ACC responses to noxious stimuli upon activation of the S1 axon terminals (Singh et al., 2020). In light of these findings, our results from STM suggest that the increased attention control (as in FAM and OMM) facilitates the transfer of noxious information from S1 to ACC. This increase, however, was not accompanied by higher subjective ratings of pain intensity or aversion (Fig. 2). Moreover, the projections from S1 to other pain regions (S2/insular) appear to be supported primarily by high-frequency (gamma) oscillations (e.g. Hagiwara et al., 2010), which were not selectively influenced by meditation states. Hence, we conclude that the enhanced theta-alpha S1-FM synchronization in STM may not merely index the transmission of specific noxious information from S1 to ACC. Instead, it may be a reflection of the involvement of ACC in domain-general integrative control systems operating in the theta frequency range (Cohen, 2011; Duprez et al., 2020). From this perspective, the results from STM imply that imposing a high load on attentional regulation in novices engages fronto-medial (ACC) control mechanisms whereby the communication with primary sensory regions is specifically emphasized. No such mechanisms were evident in LTM, suggesting that expert meditators do not strengthen connections between sensory and cognitive control regions upon intense attention regulation.

Proactive Processes of Attention Direction Pre-stimulus alpha during meditation was only increased in LTM (Fig. 3C). This result extends our previous results from the same data set, which showed that by modulating ongoing alpha activity, expert meditators are able to proactively decrease the excitability of primary and secondary somatosensory cortices already during REST (Yordanova et al., 2025).

Although enhanced pre-stimulus alpha emerged in all meditation states, it was most pronounced in FAM and least pronounced in OMM. FAM involves a stable attentional focus on the relatively subtle sensation of breathing, which is likely to direct the attentional focus away from pain. Hence, we suggest that the additional amplification of pre-stimulus alpha at S1 and S2-IC during FAM corresponds to the re-direction of attention away from pain (Babiloni et al., 2006; Klimesch et al., 2007; Peng et al., 2015; Pfurtscheller & Lopes Silva, 1999) that is central to FAM. In contrast, the wide attention aperture during OMM entails the detection and awareness of pain stimuli as inevitable ingredients of the entire information stream, which may have prevented further alpha amplification. These observations in LTM offer additional evidence regarding the ability of expert meditators to precisely tune the excitability of sensory regions in a proactive manner through functionally distinctive influences from attentional systems on alpha oscillations (Hauck et al., 2007; Peng et al., 2015; Ploner et al., 2006a, 2006b). This may be critically associated with their capacity to sustain a stable and distinctive focus of internal attention (Lutz et al., 2008, 2015; Malinowski, 2013). Such a proactive mechanism was not evident in novice meditators, potentially because they have not yet developed the same level of skill in sustaining specific modes of internal attention (Fell et al., 2010; Lutz et al., 2008). These results do not rule out that less experienced meditators are able to sustain an attentional focus that is directed away from pain when attention is attracted to imperative or salient goals (Atlas, 2023; Legrain et al., 2005, 2011, 2013; Peerdeman et al., 2016). The important implication of the current results from FAM in experienced meditation practitioners is that their possibly advanced control of internal attention away from pain input provides additional support to their ability to volitionally modulate the excitability of relevant sensory cortical regions through alpha oscillations.

Cognitive/Emotional Appraisal of Pain Information The current result that P3b was reduced only in STM during LKM suggests a crucial role of affective states in novice meditators to restrain pain appraisal (Legrain et al., 2002, 2012). Hence, positive emotion states appear to diminish the cognitive/affective/motivational value of a pain stimulus leading to less re-allocated attention and less update in working memory of pain information (Polich, 2007). In support, this P3b decrease corresponded to lower subjective intensity, aversion, and identification scores yielded only in novices during LKM (Fig. 2). In contrast, meditation types did not influence substantially P3b in experienced meditators. This observation can be explained with generally reduced emotional involvement in LTM due to adopted equanimity attitude following long-term meditation training (Raffone & Srinivasan, 2009). Also, the present experimental design required subjective ratings after each pain stimulus, which might have preserved the cognitive evaluative component in LTM on the background of overall limited emotional processing.

Cognitive Fronto-medial Networks The fronto-medial connectedness was analysed here to capture the activity of a critical cognitive hub including the ACC, which supports a variety of executive functions and integrates various information inputs to coordinate and synchronize behaviour (Cohen, 2011, 2014; Duprez et al., 2020). Although some sub-sections of the ACC are specifically responsible for integrating responses to pain (Wager et al., 2016), the central role of the ACC in affective and attentional pain processing (Garcia-Larrea et al., 2003) is certainly related to its multi-facet cognitive functionality and participation in domain-general control (Atlas, 2023; Wager et al., 2016).

The observation that the connectivity of the FM theta-alpha network was overall decreased in LTM during all meditative states may reflect a suppression of pain communication across cortical regions minimizing the influence of pain information on the complex coordination of behaviour (Duprez et al., 2020). Notably, STM manifested a suppression of theta-alpha FM synchronization only during LKM suggesting (1) pronounced influence of positive emotional shifts and (2) the presence of strong interactions between emotional and fronto-medial cognitive control networks in novice meditators. It will be interesting to explore whether this effect is specific to pain processing or also applies to other, non-nociceptive stimuli. Given the similar effects on P3b only during LKM in STM, generalized effects of emotional activation on different cognitive systems can be suggested for novices. In contrast, in LTM, theta-alpha FM synchronization was reduced during FAM and OMM. Hence, the enhanced attention regulation imposed by these meditation types appeared efficient to block the distribution and integration of nociceptive signals suggesting the presence of dominant interactions between attentional and medio-frontal integrative cognitive systems in LTM.

At the same time, the synchronization of FM beta networks was enhanced during FAM and OMM in LTM, indicating that fast-frequency networks are specifically entrained during enhanced attention regulation in experienced meditators. Previously, beta synchronization has been associated with a top-down amplification of attended information (Buschman & Miller, 2007), or with mediating the link between top-down attentional selection and awareness (Driver & Mattingley, 1998; Fries, 2015; Gaillard et al., 2009; Gross et al., 2004; Yordanova et al., 2017). Also, medial-frontal beta activity has been associated with monitoring of conflicts and subsequent behavioural adjustments and adaptation (Zavala et al., 2018). Thus, although the suppressed connectedness of the theta-alpha FM hub reveals a restricted integration of nociceptive signals during meditation in LTM, the co-existing increase of MF beta connectivity in FAM and OMM implies a simultaneous intensification of pain event monitoring possibly related to raised awareness. This observation is of special interest as it points to a capacity of expert meditators to employ attention mechanisms in order to segregate precisely information processing streams: While they may minimize the integration of negative pain representations as suggested by suppressed FM theta-alpha synchronization, the simultaneous recruitment of high-frequency networks may reflect a concurrent enhancement of awareness of sensory pain signals.

Attentional Fronto-parietal Networks Analyses of FP PLV during pain processing in different meditation states revealed that the effects of meditation types on theta-alpha FP synchronization were only present in experienced meditators. Specifically, a lateralized asymmetric pattern appeared for dorsal attention networks, as reflected by state-specific modulations of P3-F3 and P4-F4 electrode pairs (Fig. 3F). They were characterized by a left-hemisphere increase/right-hemisphere decrease during FAM, and an opposite right-hemisphere increase/left-hemisphere decrease during OMM. This hemispheric asymmetry may result from the different roles that the right and left hemispheres play for the association between executive attention and awareness (Posner & Rothbart, 1998). Specifically, it has been suggested that attention networks in the right hemisphere are engaged in top-down controlled sensory awareness, while attention networks in the left hemisphere are responsible for voluntary motor control (Rounis et al., 2007; Rushworth et al., 1997, 2001, 2003). This account is consistent with the key processes required by OMM including open monitoring and enhanced awareness of ongoing events (Malinowski, 2013), which might have evoked a greater activation of right-hemisphere attentional networks. An additional explanation for the FP hemispheric asymmetry observed here may be linked to a right-lateralized superimposed influence from the ventral attention network controlling attention re-orienting to distracting, novel or salient events (Chica et al., 2011, 2013; Corbetta & Shulman, 2002; Vossel et al., 2014). It can be suggested that in OMM, in contrast to FAM, the need to monitor consciously all external and internal events by avoiding at the same time any distraction to a specific signal produced a greater activation of the right-hemisphere ventral network. In contrast, since the ventral network has been found to be suppressed during guided focused attention to restrict distraction and protect goal-driven targets (Shulman et al., 2003, 2007; Todd et al., 2005), which was the intended state in FAM, a strong suppression in the right hemisphere may be responsible for the left-hemisphere dominance during FAM. It is to be emphasized that meditation states did not produce significant changes in the synchronization of FP networks in novice meditators suggesting that these networks had a limited role for distinctive pain processing during meditation in this group.

Limitations and Future Directions

The present study has several limitations. According to the experimental design, sequential meditation states had to be entered and sustained for approximately 2 min. Whereas expert meditators often show near-instantaneous transition into the target state (OMM or LKM) during short blocks, suggesting automatic access (Lutz et al., 2004; Kerr et al., 2013), the brief sessions may have prevented a successful transition or state achievement in short-term meditators. Yet, post-session verbal reports indicated, at the level of subjective experience, that meditative states were effectively maintained. Control analyses of theta-alpha power performed to verify meditative state fidelity further suggest that participants from each group engaged in the instructed meditation process. Also, it cannot be fully excluded that the requirement to give subjective ratings of pain stimuli (intensity, aversion, identification) on each trial might have interfered with the adopted non-evaluative attitude during meditative states, especially during OMM. Finally, the conclusions from statistical analyses should be considered with caution since both positive and negative outcomes may have been affected by low sensitivity or statistical power stemming from large individual variance and limited sample size.

Analysis of neural pain responses during meditation in novice and experienced practitioners demonstrated that the maintenance of specific meditation states does not alter the sensory processing of pain, possibly not affecting bottom-up mechanisms. However, it does alter in state-dependent ways the cognitive/evaluative component of pain processing associated with top-down mechanisms. These state-dependent changes are also trait-related as they differ according to meditation expertise.

In novice meditators, only the compassion meditation (LKM) characterized by intentional shifts towards positive emotional reflection appeared effective in modulating the sensation and top-down mechanisms of pain processing. This result suggests that the meditation-induced positive emotional state may reduce the subjective experience of pain (intensity, unpleasantness, and self-identification) by attenuating the communication and limiting affective-cognitive appraisal of nociceptive signals. Notably, the two meditation types that primarily emphasize sustained attentional focus did not significantly alter pain processing in novices.

In contrast, in experienced meditators, the maintenance of meditative states appears to modulate top-down processing of pain primarily through the regulation of internal attentional focus as imposed during FAM and OMM practices. Neural correlates during attention-control meditative states imply (a) a proactive reduction in the excitability of somatosensory regions, (b) a distinct reactivity within the fronto-medial cognitive control network that may be tentatively associated with a suppressed communication of nociceptive signals and a concurrent enhancement of awareness, and (c) a lateralized functional activation of attentional networks probably reflecting the specialized control of different attentional modes. Although these neural modulations are not consistently associated with changes in subjective pain ratings, they suggest fine-grained tuning and functional differentiation within cognitive control and attention networks during meditation states in LTM. Such neurofunctional patterns in long-term meditators probably stem from neuroplastic reorganization of large-scale cognitive and pain-processing systems resulting from extensive meditative training, not present in less experienced practitioners.

The present results may have specific therapeutic value as they point to the role contemplative states inducing positive emotions and attitudes may play: Generating positive emotional states may be a useful approach for subjective pain relief in the general population. Only experienced meditators can additionally alter specific pain processes during meditation by engaging advanced and highly segregated functionality of cognitive control and attention networks. Thus, long-term attention training using specific meditation practices may provide a relevant additional approach in practical pain management in the long run or in chronic pain conditions.

The combined consideration of meditation state and trait-like effects may have relevant implications for existing models of pain processes in meditation. In light of our previous results that high meditation expertise essentially alters the neural correlates of sensory processing and early-stage communication of pain information (Yordanova et al., 2025), it may be speculated that the model according to which meditation is associated with lower signalling in somatosensory areas and diminished processing of the sensory pain component due to a downregulation of ascending nociceptive signals (Jinich-Diamant et al., 2020; Zeidan & Vago, 2016; Zeidan et al., 2011a, 2011b) may refer primarily to long-term trait-like effects of meditation. In view of the current results, the model proposing that meditation alters pain sensation by separating the sensory experience of pain from the corresponding evaluation of unpleasantness/affect (Gard et al., 2012; Grant et al., 2011; Perlman et al., 2010; Zeidan & Vago, 2016; Zorn et al., 2020, 2021), may be suggested to apply mostly to phasic changes of brain states associated with different meditation forms.

Supplementary information The online version contains supplementary material available at https://doi.org/10.1007/s12671-026-02802-0.

Acknowledgements We would like to express our gratitude and appreciation to the monks, nuns, and novices of Amaravati and Santacittarama Buddhist Monasteries for their outstanding dedication and participation in our study.

Author Contribution Vasil Kolev: investigation, methodology, data analysis, writing – original draft, project administration, resources. Peter Malinowski: investigation, writing – review and editing. Antonino Raffone: conceptualization, investigation, supervision, writing – review and editing, project administration, resources. Valentina Nicolardi: investigation, writing – review and editing. Luca Simione: investigation, writing – review and editing. Salvatore M. Aglioti: conceptualization, writing – review and editing. Juliana Yordanova: conceptualization, methodology, investigation, writing – original draft, data curation, statistical analysis.

Funding Open access funding provided by Università degli Studi di Roma La Sapienza within the CRUI-CARE Agreement. This work has been supported by a grant from BIAL Foundation (Portugal) for the project "Advancements on the aware mind-brain: New insights about the neural correlates of meditation states and traits", and by the National Research Fund by the Ministry of Education and Science, Sofia, Bulgaria (Project KP-06-N33/11/2019).

Data Availability The datasets used and analysed during the current study are available from the corresponding author on reasonable request.

Declarations

Ethics Information The study had prior approval by the dedicated Research Ethics Committee at Sapienza University of Rome, Italy.

Informed Consent All participants gave informed consent before participation, and the study was in accordance with the Declaration of Helsinki.

Conflict of interest The authors declare no competing interests.

Use of Artificial Intelligence Artificial intelligence was not used in the writing of this manuscript.

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