UNIVERSITY OF PAVIA – IUSS SCHOOL FOR ADVANCED STUDIES PAVIA

Department of Brain and Behavioral Sciences (DBBS)

MSc in Psychology, Neuroscience and Human Sciences

Effects of Long-Term Zen Meditation Practice on Inhibitory Control in the Presence of Emotional Stimuli: An EEG Study

Supervisors:

Prof. Giulia Mattavelli

Co-supervisor:

Anna De Chino

Thesis written by

Magdalena Iwan (549666)

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Abstract

Over the past decade, a trend for exploring psychological and physiological mechanisms underlying meditation grew exponentially within the scientific community. Meditation has been associated with various potential benefits, including improving the immune system, promoting healthy ageing and positively affecting mental health. Moreover, contemplative practices have been found to have an effect on practitioners' cognitive abilities. The present study aimed to investigate the effects of long-term Zen meditation on attentional and inhibitory processes by combining behavioural, electrophysiological (EEG) and physiological (HRV) measures in experienced meditators and novices during an emotional Go/No-Go paradigm. The study population consisted of sixty-five participants, including thirty-two experienced meditators and thirty-three non-meditators. Behavioural findings suggest that emotional stimuli had a different effect on meditators and non-meditators inhibitory processes, as Zen practitioners showed a tendency towards more stable task performance across conditions compared to novices. Emotional stimuli were associated with modulation of neuronal activity reflected in N2- and P3-like ERP components, regardless of meditation experience. Overall, the findings suggest that, in the presence of emotional information Zen meditation may contribute to more stable behavioural performance. Nevertheless, emotional stimuli seem to have a robust effect on behavioural and neurophysiological indices of inhibitory processes in both meditators and non-meditators.

Keywords: Zen meditation; inhibitory control; Go/No-Go task; electroencephalography; event-related potentials

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1. Introduction

1.1 Understanding Meditation

Defining meditation in a “clear and comprehensive” way can be challenging due to the broad range of meditation techniques and the various classification systems, including classical, contemporary and holistic approaches (Sparby & Sacchet, 2022). After thoroughly analysing different practices, Sparby and Sacchet (2022) proposed definition was: “meditation is at least one of several intentional awareness activities such as observe, focus, release, produce, imagine, and move, underpinned and unified by the activity of awareness of awareness, performed in a formal or informal setting” (p. 14). A unified definition of meditation is important for scientific reasons; nevertheless, understanding the similarities and differences among various approaches may contribute to a more comprehensive perspective on contemplative practices. While training awareness and voluntary control is the common ground of various practices, they differ in the object of awareness (e.g., breath or emotions), attentional strategies and intermediate aims (Walsh, 1983). The heightened awareness state enables individuals to recognize their bodily reactions to thoughts, facilitating change, forgiveness and letting go of maladaptive thinking patterns, while developing more nourishing ones (Valluri et al., 2024). Jon Kabat-Zinn, the founder of the world-renowned Mindfulness-Based Stress Reduction (MBSR) program, emphasizes that “the real meditation practice, involves letting life itself become coextensive with your meditation practice and recognizing that everything that unfolds within it, the wanted and the unwanted and the unnoticed, is the real curriculum” and above all each practitioner should develop a more personal approach, that feels both “intuitive and trustworthy” (Kabat-Zinn, 2021, p. 785). Given the diversity of meditation practices, it is essential to distinguish some of the main techniques, as they may bring both overlapping and distinct effects (Sparby & Sacchet, 2022).

1.1.2 Two Main Pathways of Meditation

Standard meditation practices can be classified into two more generalised categories: focused attention (FA) and open monitoring (OM), which differ in the object of focus, as well as the regulation of attention. It is important to recognize that in scientific research these classifications are used to detect the specific cognitive mechanisms and to generate neuro-functional predictions (Lutz et al., 2008; Roy & Subramanya, 2025). Furthermore, both styles can be found in numerous meditation techniques, including Zen, one of the most traditional contemplative practices rooted in Buddhism (Chiesa, 2009; Lutz et al., 2008).

1.1.2.1 Focused Attention. Focused attention (FA) is characterized by deliberately engaging one's attention on a specific object, typically practitioners own interoceptive signals or an external stimulus in a continuous manner, while detaching from possible internal (e.g., mind-wandering) and external distraction (e.g., visual or auditory stimulus) (Ganesan et al., 2022; Manna et al., 2010). According to Lutz et al. (2008), with continued practice, FA may facilitate developing three crucial attentional regulatory skills such as:

- The ability to be attentive to potential distractions without compromising the intended focus.
- Being able to detach yourself from distracting stimuli, without further engagement.
- Redirecting one's attention to the object of focus.

As further mentioned, over time, the skills become "progressively effortless". Neuroimaging findings show that FA practice decreases amygdala activity and increases prefrontal integration of the amygdala, indicating its effectiveness in emotional regulation (Doll et al., 2016). Furthermore, FA research showed greater activation of regions related to high-level cognition and response inhibition, such as the left superior frontal gyrus, left middle frontal gyrus and inferior frontal gyrus (Brefczynski-Lewis et al., 2007), as well as the right dorsolateral prefrontal cortex, which in context of meditation is thought to be associated with repeatedly redirecting or maintaining attention to target of focus (Lippelt et al., 2014). Additionally, it was demonstrated that FA may reduce perceived stress (Roy & Subramanya, 2025).

1.1.2.2 Open Monitoring. Long-term meditation practices typically begin with FA, then transition to open monitoring (OM), either within a single session of practice or over the course of several sessions (Lodha & Gupta, 2022). In contrast to FA, OM does not rely on any specific stimulus. Instead, meditators direct their attention toward awareness itself and any ongoing experiences as they naturally arise, while abstaining from judgment and preserving the monitoring state (Lippelt et al., 2014). OM entails maintaining a receptive awareness of all stimuli as they arise from moment-to-moment, likely leading to "greater distress tolerance, non-reactivity habituation to difficult cognitive and emotional events and experiences" (Brown et al., 2022). According to the study performed by Colzato et. al. (2012), the difference in both approaches can be seen in convergent ("the process of generating one possible solution to a particular problem") and divergent thinking ("a style of thinking that allows many new ideas of being generated"), with OM enhancing divergent thinking while FA being associated with slight improvement of convergent thinking. Neuroimaging studies further confirm the differences in brain activity regarding the two meditation approaches. As compared with FA, OM practice showed lateral prefrontal activation in both hemispheres, additionally the activity patterns in monks practicing OM mirrored their ordinary brain resting state, in contrast to FA meditation which was associated with notably different neural activity in both states (Manna et. al., 2010). Therefore, recognizing the distinctions between the two approaches, appears to be crucial not only in everyday practice, but also when conducting scientific research.

1.1.3 Foundations of Zen Meditation

Zen meditation (Zazen) is one of the practices that integrates elements from both open monitoring and focused attention (Travis & Shear, 2010). Originated in India and first introduced to China in the sixth century by Bodhidharma, who is thought to be the first patriarch of Zen Buddhism. The practice later spread to Korea from the seventh to ninth centuries, thereafter to Japan in the twelfth century. More recently, Zen became a worldwide phenomenon, as it was transmitted to the West (Masuda & O'Donohue, 2017). Zazen falls within a category, which might be commonly known as mindfulness-based approaches (Chiesa & Malinowski, 2011). Although the consensus on the mindfulness definition has not yet been reached, Jon Kabat-Zinn (2015), a pioneer in the area of mindfulness-based interventions defines it as follows:

> Mindfulness can be thought of as moment-to-moment, non-judgmental awareness, cultivated by paying attention in a specific way, that is, in the present moment, and as non-reactively, as non-judgmentally, and as openheartedly as possible. When it is cultivated intentionally, it is sometimes referred to as *deliberate mindfulness*. When it spontaneously arises, as it tends to do more and more the more it is cultivated intentionally, it is sometimes referred to as effortless mindfulness (p. 1481).

Furthermore, he refers to the words of Nyanaponika Thera, a Buddhist scholar and a monk, who described mindfulness as “the heart of Buddhist meditation”. This understanding of mindfulness broadly reflects the principles of Zen practice.

To fully understand the concept of Zen it is crucial to examine the specific methods and aims underlying the practice. Zen meditation is often referred to as Zazen (“sitting meditation”), where people usually sit in a lotus position while focusing their attention (Masuda & O'Donohue, 2017; Strick et al., 2012). Following the *Fukanzazengi* (Universally Recommended Instructions for Zazen), by Zen master Dogen (1200-1253), meditation practice begins with the awareness of one's body, especially its posture and placement in the environment. He details the specific posture that is supposed to ensure balance, alignment and steadiness. To illustrate, practitioners seated on a cushion in a lotus posture should place their right hand on their left foot and the left hand on the right palm, maintaining an upright body position, while aligning the ears with the shoulder and the nose with the navel. After correctly adjusting the posture, one should focus on their breathing, slowly and gently through their nose, while keeping their eyes open. Once the correct posture is adopted, meditators are encouraged to "think of not-thinking", a concept that represents a core principle of Zazen. Furthermore, in Dogen's teachings, Zazen itself is a form of enlightenment ("dropping away of body and mind"), an embodiment of awakened awareness (Eubanks, 2016; Waddell & Abe, 1973). Meditators should disregard both external and internal stimuli, while attention can be directed towards one's breath. The quality of concentration and the nature of conscious awareness changes through the stages of practice (Odajnyk, 1998).

Alongside the conceptual literature on the topic of Zen, empirical research has been investigating its psychological and neurobiological effects. Since the 1960s the scientific research has gradually expanded, showing the growing academic interest in various contemplative practices, including Zen meditation. A study examining the rate of age-related decline of cerebral grey matter, showed that Zen meditators demonstrated a reduced grey matter decline compared to non-practicing control subjects, particularly in the left putamen, a structure related to attentional processing. These findings suggest potential neuroprotective effects associated with the long-term practice (Pagnoni & Cekic, 2007). Furthermore, Zen meditators show increased cortical thickness in the dorsal anterior cingulate cortex, bilateral secondary somatosensory cortex and pain related brain regions, including the anterior cingulate cortex, anterior insula, and parahippocampal gyrus. This was associated with lower pain sensitivity compared with matched control participants. Additionally, longer Zen meditation practice and hours of practice predicted greater bilateral cortical thickness in primary somatosensory cortex important for body representation (Grant et al., 2010). Fayed et al. (2013) using Proton Magnetic Resonance Spectroscopy and Diffusion Tensor Imaging investigated alterations of metabolites in long-term Zen meditators. The results showed that meditation was associated with higher Inositol (reported to have antidepressant properties) in the posterior cingulate gyrus and decreased glutamate (primary excitatory neurotransmitter), N-acetyl-aspartate (NAA, involved in the synthesis of neurotransmitters) and N-acetyl-aspartate/Creatine (NAA/Cr), in the left thalamus. Additionally, the apparent diffusion coefficient was negatively correlated with years of practice in parietal white matter, indicating greater white matter integrity in long-term meditators. These findings suggest that meditation can influence not only neuronal activity, but also cerebral metabolism and axonal changes.

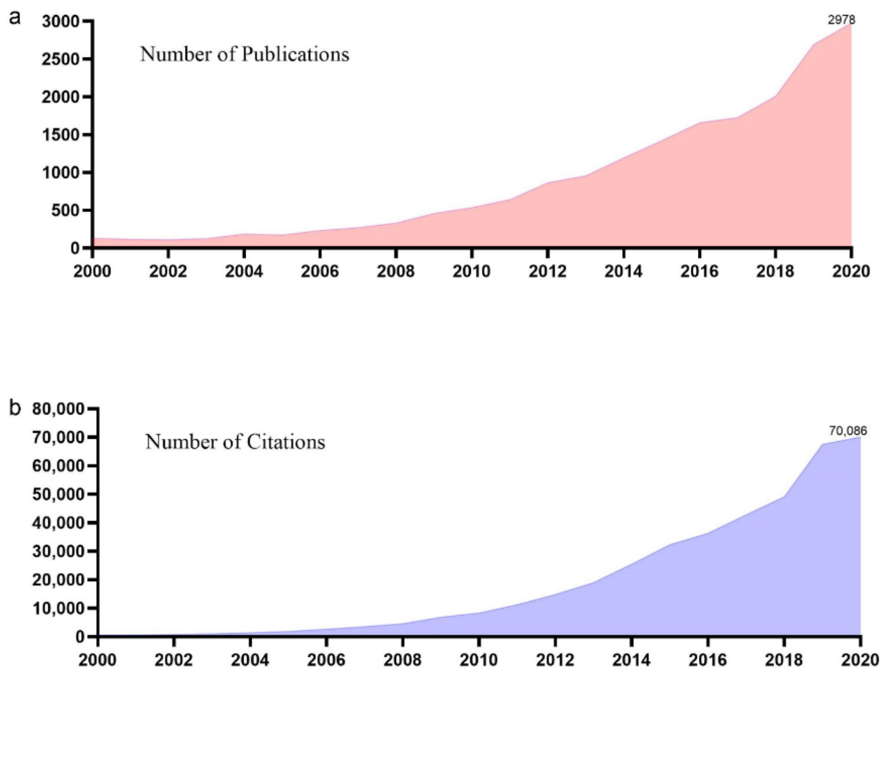
Nonetheless, to obtain a more comprehensive understanding of the impact of Zen meditation, it is necessary to consider not only long-term, but also short-term meditation practice. Research showed that short-term meditation practice (three hours per week for three months) selectively improves executive functioning, including planning efficiency, cognitive interference and attentional control (Linares et al., 2021). However, as previously mentioned, the duration of practice appears to show significant differences at the neurological level. Baron Short et al. (2010) compared activation of brain regions related to attentional control, including the dorsal lateral prefrontal cortex (DLPFC) and the anterior cingulate cortex (ACC) in long-term meditators (>10 years) and short-term practitioners (<10 years). Both DLPFC and ACC showed different activation patterns over time between the two groups. Short-term meditators showed decreased DLPFC and increased ACC activity over the course of practice, which may reflect the difficulties with maintaining attention and increased error monitoring. In contrast, expert Zen meditators showed increased DLPFC and decreased ACC activity over time, which may have correlated with greater sustained attention.

1.1.4 Mindfulness in Scientific Research

Wang et al. (2021) conducted biometric analysis of research publications regarding meditation, particularly mindfulness from 1900 to 2021. They provided a detailed overview of the progression of mindfulness literature, analysing 19,752 publications, including their distribution, collaborations among authors, institutions and co-citations. According to the authors, the first meditation article was published in 1963, over a half century ago. After that, the number of published research gradually increased each decade, from the 1960s to the 1990s, rising from 5 to 625 by 2000. From that time onwards, that number grew annually, with several years showing an increase of over 30% by 2020 (see Figure 1).

Figure 1

Mindfulness Research Publications (a) and Citations (b) Between 2000 and 2020



Note. From "A Bibliometric and Visualization Analysis of Mindfulness and Meditation Research from 1900 to 2021," by Y. Wang, L. Liao, X. Lin et al., 2021, *International Journal of Environmental Research and Public Health, 18*(24), 13150 (https://doi.org/10.3390/ijerph182413150).

Considering the ongoing growth of the scientific research regarding the contemplative practices, it is necessary to mention issues the researchers may encounter. One of the major challenges is the definition of meditation. As mentioned previously, there is no consensus reached upon a single unified definition of meditation, often treating different practices as equal. This may result in inaccurate comparisons of findings, as well as difficulties for replication studies (Awasthi, 2013). Additionally, according to Walsh and Shapiro (2006), studies face several methodological and conceptual limitations related to the assessment, participants and study design. Common problems include small sample sizes, selection bias, a limited number of randomized control trials and reliance on self-report measurements. The authors argue that there is also a misunderstanding between the Western psychology and meditative disciplines, with each field being dismissive about the other. They suggest that mutual integration of both psychology and meditation fields is crucial to achieve greater systematic and holistic conceptual framework. Both “etic” (outsider) and “emic” (insider) perspectives should be considered ensuring a comprehensive understanding and greater interdisciplinary communication.

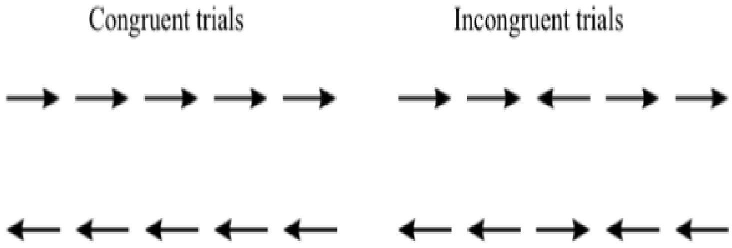
1.2 Behavioural Paradigms for Cognitive Control

1.2.1 Executive Control and Selective Attention: The Flanker Effect

Eriksen and Eriksen (1974), proposed a “non-search task” in which participants were asked to respond only to a target stimulus that was always shown in the same location (0.5 degrees above the fixation point) and to ignore any other stimuli that might appear coincidentally with the target. Importantly, the target was surrounded by noise stimuli (flankers) on each side, whereas in the two control conditions the target stimuli was always displayed alone. A key feature of the task were the noise conditions, which varied in how the flankers related to the target and its associated response (see Figure 2).

Figure 2

Example of Congruent and Incongruent Trials in Arrow Flanker Task



Note. Own illustration based on *Ridderinkhof et al. (2020)*

Additionally, the authors introduced a second manipulation, involving three different spacings angles between the letters in the display (0.06 deg., 0,5 deg., 1 deg. of visual angle), to test whether the increased spatial separation would facilitate spatial discrimination and improve reaction time (RT). The authors further hypothesized that faster RTs would be obtained by blocked trials, that the incongruent noise would show the longest RTs, that congruent noise would show minimal interference effect, and that RT time should improve as the spacing between the stimuli increases. Most of the hypotheses were confirmed; however, several important findings should be noted. A significant interaction was observed between the noise conditions and spacing, with all conditions showing decreased RTs as the separation between the stimuli increased, reflecting that great interference occurred when the stimuli were at the closest spacing. The results also showed a significant difference, of around 30 milliseconds between mixed and blocked trials, with faster RTs in blocked trials. As predicted, longest RTs were observed in the opposite-response noise condition, which also produced the highest number of errors, particularly at close spacing. In comparison, the fastest RTs were obtained when flankers were identical to the target condition. Notably, dissimilar noise showed longer RTs than similar noise, while similar noise slightly enhanced the performance. Overall, the data demonstrated that the flanker stimuli slowed RT regarding the identification of the target. The authors concluded that the interference effect of noise letters may be results of "response competition", but also that some of the noise stimuli are processed simultaneously with the target enough to activate competing responses. This reflects a limit of visual attentional capacity. Furthermore, they proposed a limited-energy parallel processing model, which suggests that limited processing resources are distributed across multiple stimuli, resulting in decreased speed processing of a single stimulus, which could potentially explain the noise effect. Regarding the source of the spacing effect, Eriksen and Eriksen (1974) mainly assumed ease of location discrimination. Additionally, inhibitory processes must occur during response selection, to suppress responses until the correct selection has been made. Over time, the task has been adapted using different visual stimuli, with arrows becoming one of the most influential, due to their automatic representation of the spatial direction (Ridderinkhof et al., 2020). Taking everything stated above into account, the flanker task is a measure of inhibitory control, selective attention, executive control, conflict resolution and speed-accuracy trade off (Kałamała et al., 2018; Lee & Pitt, 2024; Van der Lubbe et al., 2025; Żurawska vel Grajewska et al., 2011). Individual task analyses in a meta-analysis of neuroimaging studies showed that flanker task showed activation clusters in the right dorsolateral prefrontal cortex and right insula (Nee et al., 2007).

As previously discussed, mindfulness is closely associated with attention and executive control. When reviewing scientific articles, one can encounter various experiments that use different attentional tasks, such as flanker tasks to assess the effects of meditation practice on cognitive control. More recent empirical evidence demonstrated that, when completing the flanker task, meditators showed enhanced monitoring performance, including its components such as error detection and monitoring of ongoing processes compared with non-meditators (Andreu et al., 2017). Higher mindfulness traits were associated with decreased congruency interference and faster reaction times, indicating enhanced executive control (Lin et al., 2018).

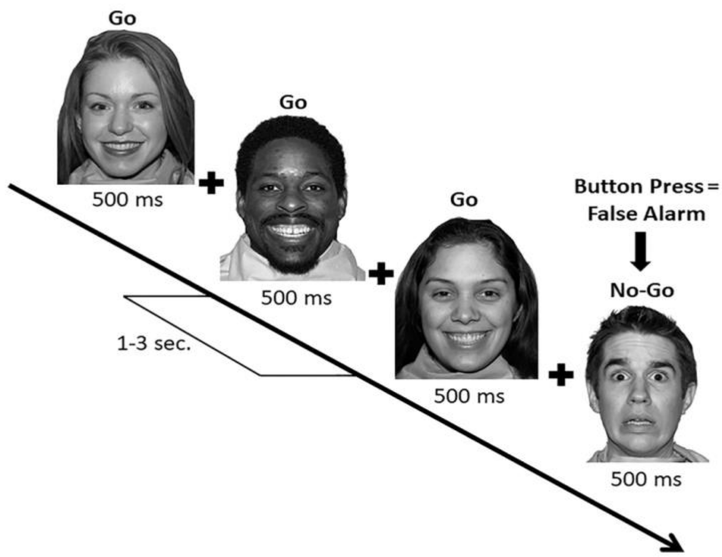
Furthermore, regular meditation practice appears to have neuroprotective effects, reducing cognitive decline associated with healthy aging (Hu et al., 2011). Additionally, research has shown that mindful awareness practices improved sustained attention, commission errors and detectability in patients with attention deficit hyperactivity disorder (ADHD) (Bueno et al., 2015). Norris et al. (2018) suggested that even a brief 10-minute meditation practice may improve attention among novices. A meta-analysis of 86 studies, including 5,027 participants, demonstrated that although mindfulness practice can improve speed, greater results are observed in accuracy. The most reliable effects were found in sustained attention and inhibitory control, rather than in updating and shifting. Moreover, engaging in more mindfulness sessions showed greater effects on attentional performance compared to the duration of individual sessions (Verhaeghen, 2021).

1.2.2 Impulse Control and Response Inhibition: The Go/No-Go Task

A Go/No-Go discrimination task requires participants to respond to a stimulus by making one of two choices while withholding their response to an alternative option (Gomez et al., 2007). It assesses subjects' ability to withhold a response, also known as response inhibition, which is a main component of executive control (Wright et al., 2014). Since the task relies on repetitive motor responses to a visual stimulus, it also assesses motor impulsivity, which is thought to be easier to test compared to cognitive inhibition, as it involves more constrained set of behaviours (Barakat et al., 2025; Littman & Takács, 2017). One version of the task involves the use of emotional stimuli to assess not only behavioural inhibition but also emotional modulation and processing (see Figure 3). To illustrate the task, participants view pictures showing two contrasting facial expressions (e.g., happy vs. sad) and are instructed to respond as quickly as possible by pressing a mouse button to a target stimulus ("go" cues) while withholding their responses to nontarget stimuli ("no-go" cues) (Schulz et al., 2007). A study examining effects on mindfulness training (MT) on behavioural responses in an emotional go/no-go task showed that MT impacts emotional recognition, leading to greater improvement in discrimination across happy, neutral, or fearful facial expressions. Moreover, MT improved both the speed and accuracy of the behavioural performance (Quaglia et al., 2019). Similar results were observed when comparing meditators to a control group. Meditators showed significantly lower total error rate on both go and no-go trials and reported lower valence and arousal ratings of emotional pictures, reflecting enhanced response inhibition and emotional reactivity (Andreu et al., 2019). In general, meditation is thought to enhance attentional capacity (Sumantry & Stewart, 2021).

Figure 3

Example of Emotional Go/No-Go Task



Note. Happy facial expressions serve as Go-targets, whereas fearful facial expressions serve as No-Go targets. From "Brief mindfulness training enhances cognitive control in socioemotional contexts: Behavioral and neural evidence," by Quaglia et al., 2019, PLOS ONE, 14(7), e0219862.

1.3 Neurophysiological Measurements of Meditation

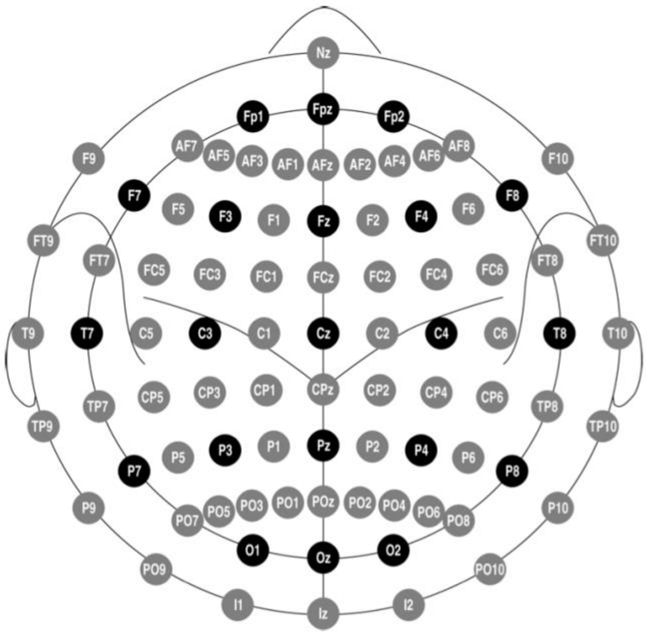
1.3.1 Electroencephalography (EEG)

Electroencephalography (EEG) is a non-invasive imaging technique that enables measurement of the brain's electrical activity, particularly the sum of the current flow of postsynaptic activity of the pyramidal neurons in the cerebral cortex (Teplan, 2002). It provides high temporal precision and direct recording of large-scale neural activity. Electrical activity is assessed by using electrodes placed on one's scalp according to the 10-20 standard system for EEG placement, creating a topographical map and facilitating spatial-component based or separation-based analysis (Cohen, 2017). The International Federation of Clinical Neurophysiology adopted the 10-20 placement, referring to the distance between the electrodes and the specific landmarks on the skull, set either at 10% or 20%. The system ensures coverage of all major brain areas for the efficacy of the EEG recordings, including frontal, parietal, temporal and occipital brain areas. Electrodes are identified by letters referring to a brain area (F, P, T, O, C) and numbers which indicate the left or right side of the brain (see Figure 4) (Arjoonsingh et al., 2024; Soufineyestani et al., 2020). Regardless of the analysis method used for EEG recording, it is crucial to acknowledge its topographic characteristics, as the signal varies depending on the scalp location it was recorded from (Lopes da Silva, 2010). EEG signals are associated with different frequency ranges measured in Hertz (Hz) ranging from 0 Hz to over 100 Hz. The analysis of the EEG activity related to different frequency bands, helps to understand functional and behavioural characteristics of human brain activity, as well as identify its normal and abnormal rhythms (Kumar & Bhuvaneswari, 2012).

EEG is employed in both research and clinical settings. It can be used as a diagnostic tool, detecting and assessing cognitive decline in neurodegenerative disorders, as Alzheimer's disease (Meghdadi et al., 2021) and Parkinson's disease (Anjum et al., 2024), as well as neurological disorders such as narcolepsy (Liu et al., 2008). In scientific research EEG is widely used in various areas such as cognitive neuroscience, neuromarketing (Yadava et al., 2017) or developmental neuroscience (Buzzell et al., 2023).

Figure 4

EEG Electrodes Position in the 10-20 Standard Placement



Note. From "The five percent electrode system for high-resolution EEG and ERP measurements," by R. Oostenveld and P. Praamstra, 2001, Clinical Neurophysiology, 112, p.715. Copyright 2001 by Elsevier.

1.3.2 Characteristics of Oscillatory and Event-Related Signals

At a physiological level, neuronal oscillations play a crucial role in synchronizing and coordinating activity within and across neuronal networks, enabling efficient communication between different brain regions (Buzsáki, 2006). EEG waveforms can be distinguished according to their frequency, wave shape and spatial distribution across the scalp. Five main frequency bands are identified based on signal frequency, each of which is associated with specific mental states of the brain. It should be noted that the frequency boundaries of EEG oscillations may slightly vary across the studies, as different authors report small variations in the Hz ranges assigned to individual oscillatory bands (Herrmann et al., 2016; Kumar & Bhuvaneswari, 2012).

Delta waves

Delta waves are characterized with the highest amplitude and the slowest EEG oscillations, from 0.1 Hz to 4 Hz. They are primely observed during the deep stages of sleep. In addition, event-related delta activity has been strongly associated with detecting a target (go-stimuli) among distractions (no-go stimuli). The required attentional engagement and evaluative processing typically reveal the P300 component of the event-related potentials (Herrmann et al., 2016; Kumar & Bhuvaneswari, 2012).

Theta waves

Theta waves are commonly linked to memory-related processes and subconscious activity, including meditation states. They are linked to neurotransmitters, such as serotonin and acetylcholine, which contribute to relaxation and memory. Theta activity can be also recorded during functional inhibition underlying executive functions. This oscillatory activity occurs within a frequency range of 4 Hz to 8 Hz (Herrmann et al., 2016; Kumar & Bhuvaneswari, 2012).

Alpha waves

Alpha waves typically occur during relaxed wakefulness, particularly when a person is awake, resting with their eyes closed. These oscillations are known to be modulated during sensory stimulation, with activity most prominent over the visual cortical areas, and are related to attentional and memory processes. Alpha activity ranges between 8Hz and 13 Hz (Herrmann et al., 2016; Kumar & Bhuvaneswari, 2012).

Beta waves

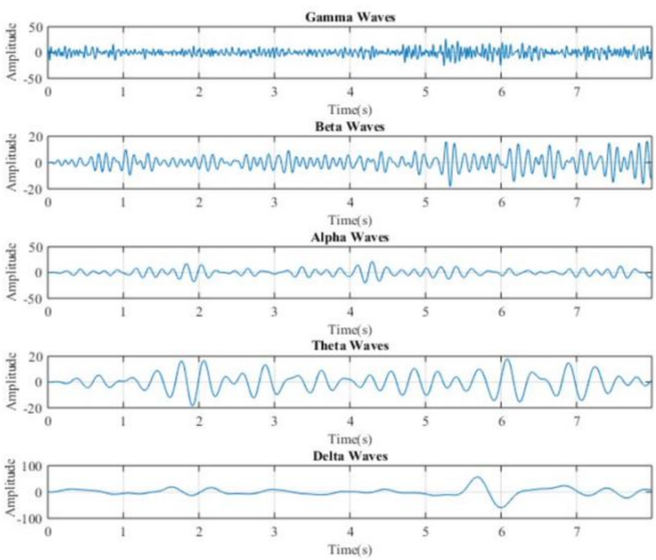
Beta waves are associated with a conscious state, including motor behaviour and mental processes, such as active thinking, decision making and verbal communication. Changes in beta oscillations have also been observed during a sensorimotor interaction involved in cognitive tasks. The frequency ranges between 13 Hz to 30 Hz (Herrmann et al., 2016; Kumar & Bhuvaneswari, 2012).

Gamma waves

Gamma waves are related to higher order cognitive processes such as perception, conscious awareness and attentive processing of information. These oscillations are frequently linked to states of alertness and integration of sensory inputs. The gamma frequency typically occurs between 30 Hz and 100 Hz (Herrmann et al., 2016; Kumar & Bhuvaneswari, 2012). Figure 5 presents normal patterns of brainwaves in a graph form.

Figure 5

Patterns of Normal EEG Frequency Bands



Note. From "Real Time EEG-Based Automatic Brainwave Regulation by Music," by A. Hossan and A. M. Mahmud Chowdhury (2017), conference paper. Copyright by the authors.

Another crucial component of EEG is event-related potentials (ERPs), which are small voltages that are time-synchronized with a motor, cognitive or sensory stimuli that enable to investigate psychophysiological processes underlying mental processes (Sur & Sinha, 2009). Based on their temporal and spatio-temporal features, various ERPs components can be classified, such as the P300 (P3) and N200 (N2) components (Blankertz et al., 2011). The P3 component is typically observed when an individual is actively engaged in a task requiring the detection of target stimuli (e.g., oddball paradigm or the go/no-go task), representing response-related evaluative processing and attention allocation. The term P300 reflects the peak latency at approximately 300 ms, which occurs when a subject makes a sensory discrimination (Huster et al., 2013; Picton, 1992). The N200 component is elicited between 180 ms and 325 ms following the presentation of a specific visual or auditory stimulus. It is associated with premotor responses, conscious stimulus processing and response inhibition. Both ERP components are thought to represent selective attention and cognitive processes underlying perception (Patel & Azzam, 2005).

ERPs are widely used to investigate cognitive processes of healthy individuals including attention and its subsystems such as working memory, perception and memory. Moreover, they are valuable tools for studying psychological disorders (Luck et al., 2000). Changes in ERPs can be observed in neurotic disorders, such as generalized anxiety disorder or dissociative disorder, as well as in psychiatric disorders including schizophrenia and alcohol dependence syndrome (Sur & Sinha, 2009).

1.3.3 Neuronal Oscillations Underlying Meditation

Investigating various meditation techniques involves several challenges, particularly in establishing a fully objective measure for assessing the efficacy and quality of the practice. Several methodological limitations may arise, including uncertainty regarding whether participants were actively meditating, inconsistent outcome measures, and inadequate control groups. Hence, the development of reliable and objective scientific measures for contemplative practices is crucial to strengthen the scientific foundation underlying the field. It is believed that EEG could be a suitable tool, as its signals are sensitive to meditation-related changes, particularly in EEG voltage and frequency bands activity (Ahani et al., 2014). The measurement of brain responses to a meditation practice relies on the assumption that different states of consciousness are linked to distinct neurophysiological changes, with the term "state" refering to short-term changes that can occur during meditation practice including altered state of consciousness (Cahn & Polich, 2006). Therefore, it is crucial to distinguish between state and trait aspects of awareness. Meditation states are reported to bring one peacefulness and a sense of calm, feeling of perceptual clarity, slowing of internal dialogue and awareness merging with the object of attention. In contrast, the term traits refer to longer-lasting changes that persist even when a person is not actively engaged in the practice. These changes may include greater sensory awareness, with enhanced sense of comfort. This distinction may be a crucial methodological approach in scientific research, as it can reduce effects related to self-selection bias, which is a common problem in meditation studies (Cahn & Polich, 2006).

Cahn and Polich (2006) conducting a comprehensive review of numerous studies investigating neurophysiological effects of different meditation techniques have shown that alpha power typically increases during meditation. Compared to non-meditating control subjects, the effect is typically stronger at rest in meditators, indicating both trait and state-related effects. Furthermore, increased theta band power has also been reported during meditation practice. The authors proposed that this increase might represent a specific state-related effect of meditation, reflecting greater internal attention and cognitive control. Additionally, theta enhancement can be observed in more experienced meditators, suggesting that longer meditation experience may influence the strength of neuronal oscillations. In conclusion, the reviewed studies have shown consistent results regarding increase of alpha and theta band power, as well as overall frequency slowing. Another crucial reported characteristic observed during meditation was increased EEG coherence, reflecting cross-correlation between EEG power within a frequency band among different cortical areas. Increased alpha and theta band coherence has been observed for state-related meditation effects both within and between hemispheres. Similar trait-related effects have also been observed in long-term meditators during rest and cognitive tasks. However, as the authors emphasize, it is important to acknowledge the limitations across studies, such as lack of standardized phenomenological description and insufficient topographic information (Cahn & Polich, 2006). Furthermore, several studies have shown that high-frequency brain activity, particularly within the gamma frequency band, tends to increase in experienced meditators during meditation, as well as prior to the onset of the meditation practice compared to control subjects. These findings suggest that greater competence in meditation practice may lead to long-term baseline changes in neuronal oscillatory patterns (Axmacher, Fell & Haupt, 2010). Overall, synchronized gamma activity is believed to have a crucial role in neuronal plasticity and may reflect the processes of cortical restructuring and learning (Fell et al., 2010).

1.3.3.1 Neuronal Oscillations Changes During Zen Meditation Practice. Kurek et al. (2025), compared bioelectric brain activity in Vietnamese monks experienced in Zen meditation with novice controls in an ecologically monastic setting. Between-group comparisons showed increased alpha and theta bands in frontal brain regions in the monk group, suggesting a deeper relaxation state, reduced arousal and greater vigilance. Throughout the short practice session (4 minutes) beta power activity remained unchanged; however, it increased during the end of long-meditation session (1.5-hour) in meditators. Moreover, meditators’ brain activity was exceptionally similar in a meditative state and neutral state (mind-wandering), with no significant difference between short and long-meditation sessions.

This may be explained by the ability of meditators to enter the meditation state even during rest. Another study, comparing Zazen with a no-task resting state, showed a right-hemispheric increase in alpha frequency in brain areas related to continuous proprioception, executive control and emotional processing. Moreover, decreased beta power in the bilateral posterior regions was observed during Zen practice, reflecting reduced visual imagination and more effortless awareness (Faber et al., 2015). Furthermore, Yu et. al., (2011), demonstrated that increased alpha band power and decrease theta band activity in the prefrontal cortex of Zen meditators were correlated with increase in blood serotonin levels (5-HT), which the authors speculated to be the cause of the EEG signal changes throughout the practice. Based on the studies mentioned, findings related to Zen meditation appear relatively consistent regarding increased changes in alpha oscillations. However, the inconclusive findings regarding theta and beta power bands may be influenced by the frequency of meditation practice and level of experience (Pasquini et al., 2015).

1.3.4 Electrocardiography (ECG) and Autonomic Regulation in Meditators

Electrocardiography (ECG) records the electrical activity of the heart generated by transmembrane ion currents that create a cardiac electrical field. It is widely used in clinical settings to detect any existing pathophysiological patterns and abnormalities that may indicate the presence of a disease (Mirvis & Goldberger, 2001). A crucial component observed in EEG recordings is heart rate variability (HRV), defined as the variation in time intervals between consecutive heartbeats. It is commonly used to investigate the function of the sympathetic and parasympathetic branches of the autonomic nervous system, as well as overall cardiac health. HRV is considered to reflect the heart's ability to adapt to changing circumstances through rapid detection of any response to unexpected external and internal stimuli (Acharya et al., 2006). In essence, HRV reflects the heart-brain interconnection, known as the intrinsic cardiac nervous system. Assessing HRV enables the evaluation of how various internal and external factors, such as lifestyle choices, thoughts, or feelings influence the nervous system. Low-frequency HRV (0.04-0.15 Hz) signifies activity of the sympathetic nervous system, which is activated by fight or flight conditions and may indicate possible pathological conditions. Conversely, high-frequency HRV (0.15-0.4 Hz) mainly reflects parasympathetic division activity and is associated with "higher cardiac fitness" (Tiwari et al., 2021).

Findings regarding the significant effect size of meditation training on increased HRV, vagal tone and improved autonomic regulation remain inconclusive and show several limitations, such as variations in practice duration and level of expertise (Chang et al., 2020; Tisdell et al., 2024; Tung & Hsieh, 2019). Nevertheless, including the HRV component in scientific research may be a valuable approach in meditation studies, as various contemplative practices may have a different breathing approach influencing autonomic nervous system functioning (Tung & Hsieh, 2019).

1.4 Objectives

The objectives of the present study were to investigate whether meditation practice can modulate inhibitory and attentional processes using different cognitive tasks and to examine the differences in cognitive performance between experienced meditators and non-meditators. During execution of the cognitive tasks, EEG recordings were used to assess possible neuronal activity changes associated with meditation experience. Furthermore, the study examined whether the behavioural stability observed in meditators can be related to stronger brain-heart synchronization. Taken all together, these measures aimed to assess whether long-term experience in meditation is associated with differences in cognitive, neuronal and cardiac functioning.

1.5 Rationale

Meditation practice is taught to affect various cognitive processes, particularly its ability to enhance attentional abilities (Chiesa et al., 2011). Moreover, meditation practice is associated with changes in both neuronal and cardiac activity (Duda et al., 2024; Steinhubl et al., 2015). The display of simultaneous measures of neuronal, cardiac and cognitive processes after meditation practice contributes towards a better understanding of the heart-brain interaction. Moreover, by comparing experienced meditators and non-meditators, the effects of long-term Zen meditation practice can be examined, therefore improving our knowledge of contemplative practices and contributing to the growing body of scientific literature.

2. The Study

2.1 Study Aims and Hypotheses

The aim of this study was to investigate the neurophysiological and behavioural correlates associated with Zen meditation, specifically, inhibitory control, as well as the attentional abilities in experienced meditators and novices. In addition, the focus of this study was to explore brain and cardiac activity during meditation practice and cognitive testing in both groups, contributing to a better understanding of the heart-brain interplay.

The hypothesis of the present study is a modulation of EEG components P300 and N200 associated with inhibitory control and attentional processing, assessed with Go/No-Go and Flanker tasks. Experienced meditators are expected to show more efficient neuronal processing, reflecting enhanced inhibitory control and attentional processes, with higher accuracy and less interference effects in both cognitive tasks.

Finally, meditators are expected to exhibit higher heart rate variability (HRV) compared to novices, which may reflect enhanced autonomic regulation associated with long-term meditation practice. The study has been approved by the Ethics Committee of the University of Pavia.

2.2 Materials and Methods

2.2.1 Participants

Sixty-five Italian adults participated in the study, however prior to the final analysis two outliers were excluded from the study. The sample consisted of 31 experienced meditators and 32 non-meditators (41M/ 22F), with mean age 52,1 (*SD* = 11,49) and mean of 16,8 years of education (*SD* = 4,49). Experienced meditators were recruited from a Zen Buddhist Centre, "Il Cerchio" in Milan, Naples and Padua, Italy. Previous research comparing performance (number of errors) between meditators and novices in Go/No-Go task reported an effect size of f = .34 (Andreu et al., 2019). Based on this effect size, the required sample size for an ANOVA design examining the main effect of Group was determined using G*Power (http://www.gpower.hhu.de/): f = .34, α = .05, power = .80. The estimated sample size was 54 participants, with an observed power of 0.80. To account for any potential dropouts, a total of 65 participants were recruited. This sample was consistent with previous EEG studies examining meditation (Andreu et al., 2019). All participants signed written data privacy management and consent forms before starting the experimental procedures.

2.2.2 Exclusion and Inclusion Criteria

Inclusion criteria included participants aged 18 and 75 years and signed informed consent. Experienced meditators were required to be engaged in regular meditation practice over the past year, whereas novices' participants could not have any prior experience in meditation practice. Exclusion criteria included the use of psychostimulants or psychotropic medications and diagnosed neurological or psychiatric disorders.

2.2.3 Self-Reported Questionaries

Prior to the experiment tasks participants completed the following self-reported questionaries:

The Difficulties in Emotion Regulation Scale (DERS; Gratz & Roemer, 2004; Victor & Klonsky, 2016)

The questionnaire was used to determine participants' emotional dysregulation. This scale consists of 18 items that make up six subsystems: Goals, Nonacceptance, Impulse, Clarity, Awareness and Strategy. Each statement was rated on a 5-point scale ranging from 1 (Almost Never) to 5 (Almost Always). Scores for each subsystem, as well as the global scores, were calculated by summing the relevant items.

Multidimensional Assessment of Interoceptive Awareness (MAIA; Mehling et al., 2012)

The MAIA questionnaire was used to assess aspects of interoceptive body awareness. The questionnaire involves 32 items grouped into eight-scale state-traits, each containing between 3 to 7 items: Noticing, Not-Distracting, Not-Worrying, Attention Regulation, Emotional Awareness, Self-Regulation, Body-listening and Trusting. Each item was rated on a scale from 0 (Never) to 5 (Always). The eight subscales reflect five broader dimensions: Awareness of Body Sensations, Emotional Reaction and Attentional Response to Sensations, Capacity to Regulate Attention, Awareness of Mind-Body Integration and Trusting Body Sensations.

Mindful Attention Awareness Scale (MAAS; Brown & Ryan, 2003)

Mindful Attention Awareness Scale is a 15-item scale that measures characteristics of mindfulness, particularly a receptive state of awareness in which attention is focused on experiences in the present moment. The statements are assessed using a 6-point Likert scale ranging from 1 (Almost Always) to 6 (Almost Never). A total score is calculated by the mean of the 15 items, with higher scores indicating greater awareness and acceptance of internal experiences, better emotional regulation and lower levels of anxiety and self-consciousness.

Five Facet Mindfulness Questionnaire (FFMQ; Baer et al., 2006)

This questionnaire is a tool to measure five facets associated with mindfulness: Observing, Describing, Acting with Awareness, Nonjudging of Inner Experience and Nonreactivity to Inner Experience. Each of the 39 items is rated on a scale from 1 ("never or very rarely true") to 5 ("very often or always true"). The average scores are calculated by dividing the total score in each category by the number of items within that category. The total score can be divided by 39 to obtain an average item score. Higher scores reflect greater mindfulness awareness, which is associated with better psychological adjustment, emotional regulation and flexible attention.

Penn State Worry Questionnaire (PSWQ; Meyer et al., 1990)

The main aim of this instrument is to assess the trait of worry with 16 items, rated on a scale from 1 ("not at all typical of me") to 5 ("very typical of me"). The total score is a sum of all the items rated that ranges from 16 to 80, with higher score indicating more severe worry problems.

Edinburgh Handedness Inventory (EHI; Oldfield, 1971)

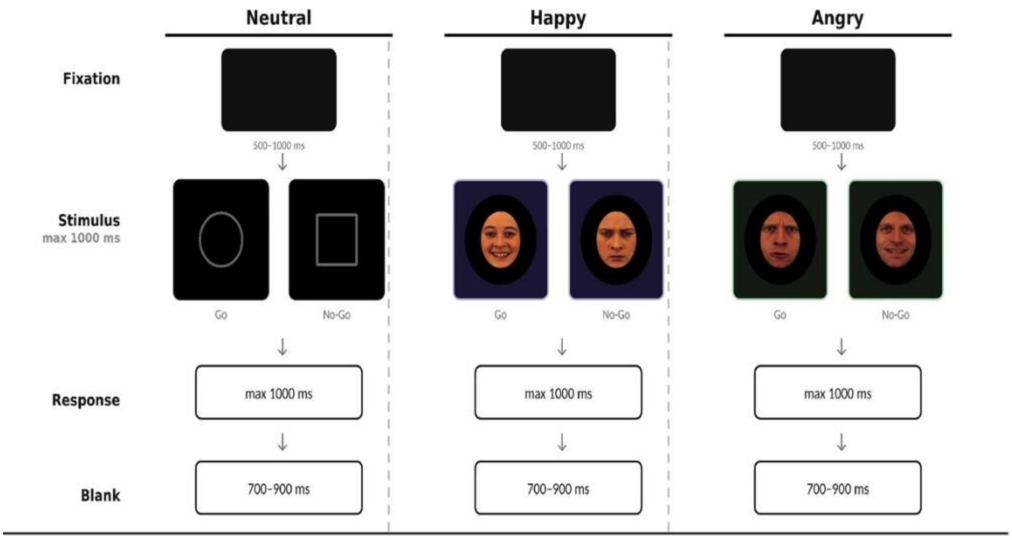
The 10-item Edinburgh Handedness Inventory was used to assess the handedness of the participants.

2.2.4 The Go/No-Go Task

The Go/No-Go task (GNG) was used to assess inhibitory control processes. Three versions of the task were administered, these included a Neutral condition (square-Go / circle–No-Go or circle-Go / square–No-Go), a Happy condition (happy-face Go / angry-face No-Go) and an Angry condition (angry-face Go / happy-face No-Go) (see Figure 6). The order of each task was randomized for each participant. Before proceeding with the experimental trials, participants were presented with written instructions on the computer screen, outlining the stimulus-response mapping for each block to ensure their understanding of the GNG paradigm. As a trial run participants completed 12 practice sessions designed to familiarize them with the task execution. All the three conditions followed the same procedure. Each trail began with a fixation cross in the center of a computer screen for a randomly varied interval between 500 and 1000 ms. The target stimulus (circle/square or happy/angry face image) was then presented centrally for up to 1000 ms, replacing the fixation cross. Following the participants' response, or at the timeout, a black screen appeared for a random amount of time between 700 and 900 ms. Participants were asked to press a designated keyboard key using the index finger of their right hand for the Go trials, while withholding a response for the No-Go trials. In order to establish a dominant button-press response, a total of 168 for condition trials were presented with a Go/No-Go ratio of 3:1. Participants were instructed to respond as quickly as possible, and no feedback regarding the performance was provided. Task performance was evaluated based on accuracy, consisting of the percentage of false alarms and misses (Go and No-Go errors), as well as response speed which was measured by the reaction times in false alarm and accurate Go trials responses.

Figure 6

Schematic Illustration for the Go/No-Go Task Conducted During the Experiment



Note. Go/No-Go ratio 3:1. Total of 168 trails. Pictures were taken from the KDEF database (Lundqvist et al., 1998).

2.2.5 Procedure

The experimental session took place at the Maugeri Scientific Clinical Institutes, Pavia, Italy. Prior to the start of the experiment, each participant received detailed information about the study characteristics, as well as its potential risks and benefits. After signing the consent form, participants were asked to read a prepared instruction manual containing information about the Go/No-Go and Flanker paradigms. The manual also explained what is required from participants during the EEG collection period. Afterwards, the ECG electrodes and EEG cap were mounted in a sound-attenuated and electrically shielded room. Both experimental tasks were preceded by a one session of a 25-minute guided meditation practice (see Image 1). The same meditation instructions were provided to both meditators and non-meditators. After the meditation session, all participants were asked to rate on a scale from one to ten the quality of their meditation experience and the degree they experienced mind-wandering while meditating. Following this, the participants completed the cognitive paradigms. EEG electrodes (64 channels) and ECG recordings were collected continuously throughout the experimental session. The study included one assessment session and no follow-ups. Data analysis was conducted after the last participant completed the study.

Image 1

Experienced Zen Meditator Following Zen Meditation Session

2.2.6 EEG Recordings

EEG was used to record cerebral electrical activity through a 64-electrode passive Ag/AgCl system arranged according to the international 10-20 system and mounted on an elastic cap. To ensure optimal signal quality, conductive electrolyte gel was applied to all of the electrodes and electrode-skin impedance was maintained below 10 kΩ throughout the montage period. EEG was recorded using a g.Hlamp amplifier (g.tec medical engineering GmbH) at a sampling rate of 1200 Hz.

2.2.7 Data Analysis

Behavioural data analysis was conducted using R software (Version 4.5.2; R Core Team, 2025). Dependent variables, including reaction times and accuracy, were analysed by comparing conditions and participant groups using parametric or non-parametric statistical models, depending on data distribution. Exploratory analyses were also performed to examine the potential influence of confounding variables. To account for these effects, linear mixed-effects regression models were applied, including group as a fixed effect and age, gender, and education as random effects, with task performance scores used as dependent variables. EEG analyses were conducted using MATLAB (Version R2026a; The Math Works, 2026) with the EEGLAB (Delorme & Makeig, 2004) and FieldTrip (Oostenveld et al., 2011) toolboxes. The signal was pre-processed, and event-related potentials (ERPs) were analysed within a time window of 0–800 ms following the stimulus presentation during the Go/No-Go paradigm.

3. Results

3.1 Self-Reported Questionnaires Results

The analyses for self-reported questionnaires were carried out using JASP (Version 0.19.3.0). Independent Sample t-tests were conducted, with significant results identified by $p < .05$. Cohen's d was measured to analyse the magnitude of differences between the two groups. The following interpretations were used to interpret the effect sizes: $d = 0.2$ suggests the effect size is small, $d = 0.5$ suggests the effect size is medium and $d = 0.8$ suggests large effect size (Cohen, 1988). All descriptive and inferential statistics are presented in table formats in Appendix A.

In the FFMQ, the overall score was higher in meditators (M = 146.5, SD = 19.1) than non-meditators (M = 134.5, SD = 18.3), $t(62) = 2.57$, $p = .012$, $d = 0.64$. Significant group differences were also observed in Observing, $t(62) = 3.15$, $p = .002$, $d = 0.79$, and Describing, $t(62) = 2.20$, $p = .031$, $d = 0.55$ subscales, with meditators scorning higher than novices. Analysis of MAIA scale revealed a significant group difference in the total scores $t(\text{df}) = 3.38$, $p = .001$, $d = 0.85$, with meditators scoring higher (M = 113.8, SD = 19.3) than non-meditators (M = 97.4, SD = 19.4). Furthermore, experts scored significantly higher in the dimensions of Attention Regulation, $t(61) = 2.81$, $p = .007$, $d = 0.71$, Self-Regulation, $t(61) = 4.63$, $p < .001$, $d = 1.17$ and Body-Listening $t(61) = 2.15$, $p = .036$, $d = 0.54$. Noticing, Not-Distracting, Not-Worrying, Emotional Awareness and Trusting facets showed no significant group difference (all p-values > .05).

MAAS total scores results showed no significant difference between experts (M = 4.6, SD = 1) and novices (M = 4.3, SD = 1), $t(62) = 1.47$, $p = .146$, $d = 0.37$. However, PSWQ results indicated a significant group difference, $t = -2.90$, $p = .005$, $d = -0.72$, with meditators reporting significantly lower worry tendencies (M = 42.5, SD = 9.03) compared to control group (M = 49.8, SD = 10.9).

Finally, the analysis of DERS questionnaire revealed no significant difference in total scores between meditators (M = 37.3, SD = 10) and novices (M = 37.6, SD = 11.6), $t(62) = -0.12$, $p = .909$, $d = -0.03$. Furthermore, no significant group differences were observed for the following: Goals, Nonacceptance, Impulse, Clarity and Strategies with all these subscales displaying $p > .05$. Nevertheless, meditators scored significantly lower ($M = 5$, $SD = 1.7$) on the Awareness domain than novices ($M = 1.7$, $SD = 2.6$), $t(56.57) = -2.27$, $p = .027$, $d = -0.5$.

3.2 Behavioural Results of the Go/No-Go Task

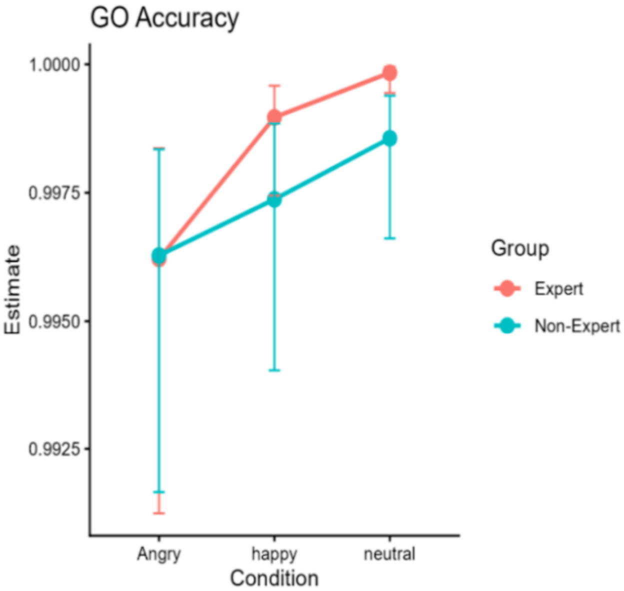
For the Go/ No-Go task, behavioural performance was analysed across five variables: Go accuracy, Go errors, No-Go accuracy, No-Go errors and reaction times (RTs). Behavioural performance was analysed using generalized linear mixed-effects models (GLMMs) for accuracy and error measures and linear mixed-effects models (LMMs) for reaction times. The fixed factors included Group (meditators and novices), Conditions (Angry, Happy and Neutral) and their interaction.

3.2.1 Accuracy Rates in the Go Trails

The results for the Go accuracy showed a significant main effect of Condition, $\chi^2(2) = 79.33$, $p < .001$, and a significant Condition by Group interaction, $\chi^2(2) = 23.83$, $p < .001$. Post-hoc comparisons showed that meditators achieved significantly higher GO accuracy than control group in the Neutral condition (OR = 8.73, $p = .004$). Both groups performed worse in the Angry and Happy conditions compared to the Neutral condition, as shown in Figure 7.

Figure 7

Go Accuracy Across Angry, Happy, Neutral Conditions in Expert and Non-Expert Groups

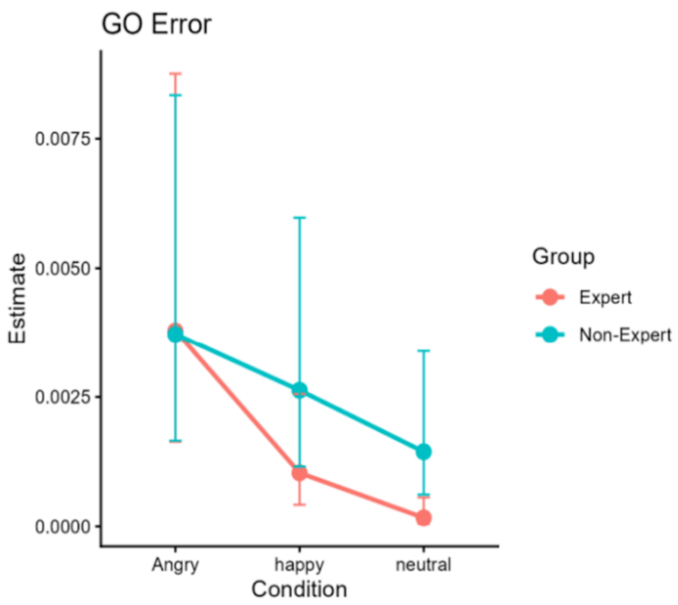


3.2.2 Error Rates in the Go Trials

A significant effect of the emotional stimulus, $\chi^2(2) = 79.33$, $p < .001$, with the highest error rates seen in Angry condition was observed, as well as a significant Condition by Group interaction, $\chi^2(2) = 23.83$, $p < .001$. As shown in Figure 8, meditators committed fewer Go errors than novices, specifically in the Happy and Neutral conditions. Go error rates varied less across the conditions in the control group.

Figure 8

Go Errors Across Angry, Happy, Neutral Conditions in Expert and Non-Expert Groups

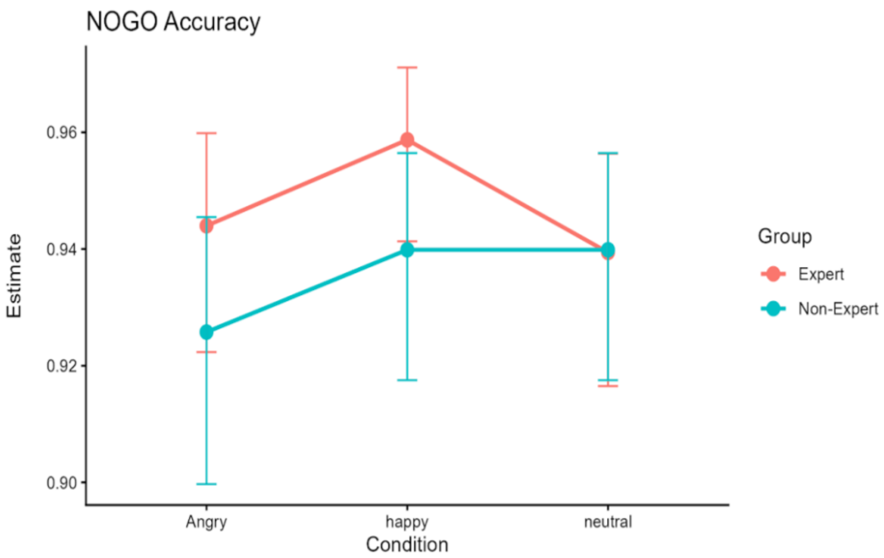


3.2.3 Accuracy Rates in the No-Go Trials

For the No-Go accuracy analysis, a significant main effect of Condition, $\chi^2(2) = 6.57$, $p = .038$ emarged. Within the expert group, post-hoc comparisons demonstrated greater accuracy in the Happy condition compared to the Neutral condition (OR = 1.50, $p = .040$). There were no significant effects of Group or Group by Condition interaction. As shown in Figure 9, No-Go accuracy varied slightly across the emotional conditions in both groups.

Figure 9

No-Go Accuracy Across Angry, Happy, Neutral Conditions in Expert and Non-Expert Groups

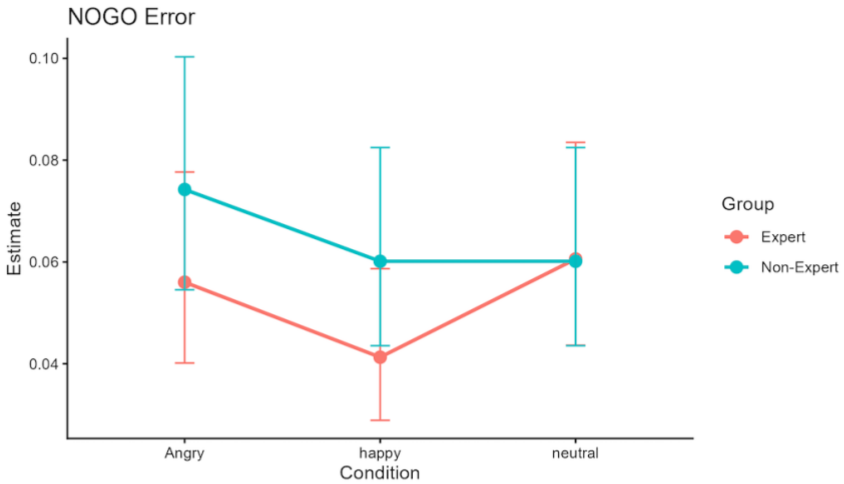


3.2.4 Error Rates in the No-Go Trials

The analysis of the No-Go error rates is consistent with the No-Go accuracy results. A significant main effect of Condition, $\chi^2(2) = 6.57$, $p = .038$, can be observed, however neither the main effect of Group nor the Group by Condition interaction reached statistical significance (see Figure 10).

Figure 10

No-Go Errors Across Angry, Happy, Neutral Conditions in Expert and Non-Expert Groups

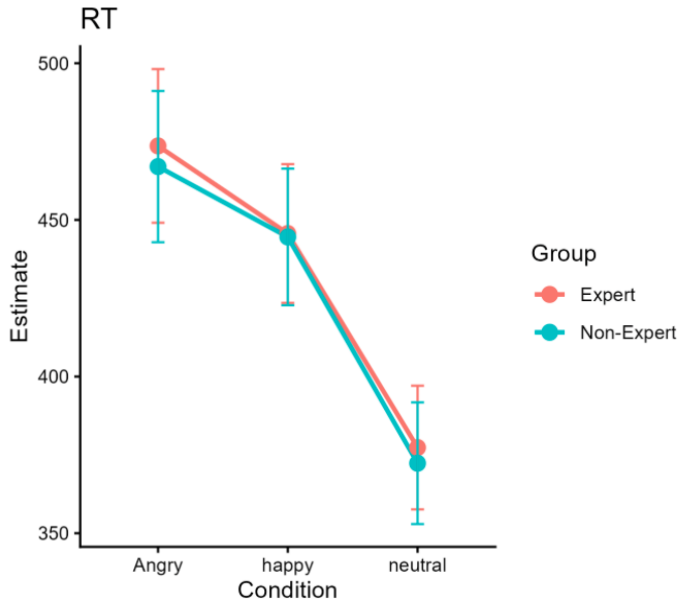


3.2.5 Reaction Times in the Go/No-Go Task

As shown in Figure 11, reaction times (RTs) varied across emotional conditions. Analysis of the RTs revealed a significant main effect of Condition, $\chi^2(2) = 208.07$, $p < .001$, indicating the influence of an emotional stimulus on the response speed. Both groups showed significantly slower responses in the emotional conditions compared to the neutral condition, with the slowest RTs seen in the Angry condition (all *p*-values < .01), followed by Happy and the fastest RTs observed in Neutral Condition. There was no significant speed difference between the two groups.

Figure 11

Mean Reaction Times During the Go/No-Go Task Across Conditions in Expert and Non-Expert Groups

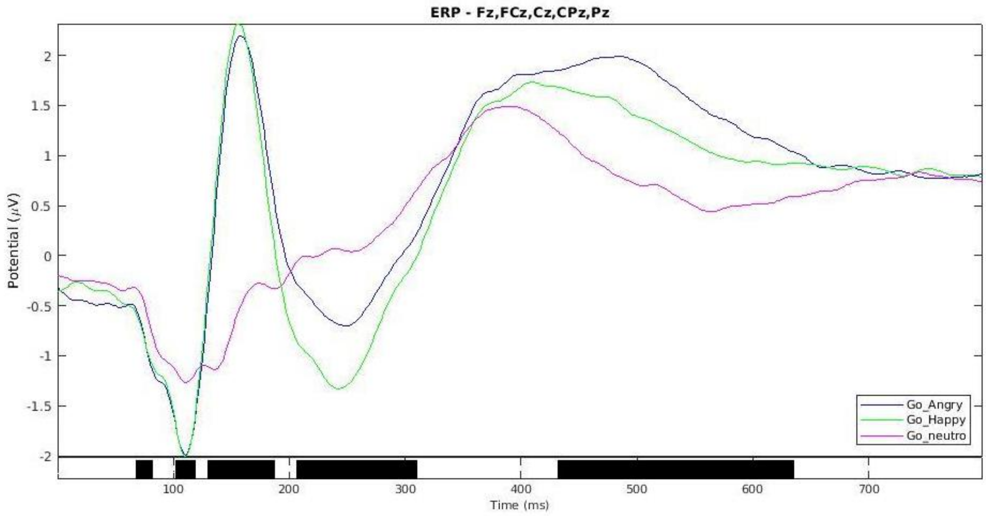


3.3 EEG Results for the Go and No-Go Trials

For the Go trials EEG analysis showed evident condition-related differences, specifically in the early and late post-stimulus time frame. Emotional trials showed a distinct early positive peak circa 150-170 ms, followed by a negative deflection occurring at 230-260 ms. Conversely, the Neutral stimuli decreased early positive response and diminished subsequent negativity, as seen in Figure 12. The most pronounced difference between the emotional and the neutral conditions can be seen between 120 and 280 ms. This may suggest that during the Go trails, angry and happy facial expressions can be associated with eliciting stronger early fronto-central activity. Specifically, the Happy condition elicited the greatest N2-like negativity, whereas the Angry condition showed a similar but less robust response trajectory.

Figure 12

Grand-average ERP Waveforms During the Go Trails Across the Angry, Happy and Neutral Conditions.

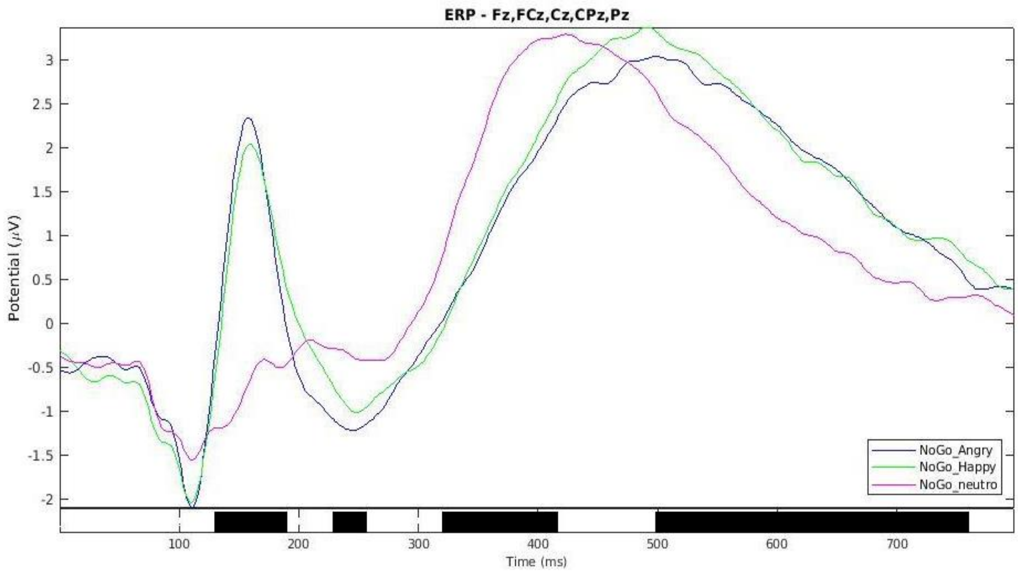


Note. The ERP signal was averaged across fronto-central and parietal midline Fz, FCz, Cz, CPz and Pz electrodes.

Similarly to the Go trials, the No-Go analysis of the ERP waveforms showed substantial differences across the conditions in the early and later post-stimulus time frames. Emotional conditions showed a clear positive peak at approximately 150-170 ms, which preceded negative deflection observed at 230-260 ms. During the same time window, weaker early positive response and decreased negative deflection for the neutral stimuli was observed. At approximately 350 and 650 ms time intervals a marked positive-going activity was observed, which is consistent with the P3-like component associated with inhibitory control in the No-Go trials. Neutral face expressions elicited an earlier and more prominent positivity peak, compared to emotional faces that showed a slower and later peak rise (see Figure 13). This ERP response suggests that emotional stimuli modified neuronal processes supporting inhibitory control. No significant differences were observed between the two groups, regarding neuronal changes during the experimental task.

Figure 13

Grand-average ERP Waveforms During the No-Go Trails Across the Angry, Happy and Neutral Conditions



Note. The ERP signal was averaged across fronto-central and parietal midline Fz, FCz, Cz, CPz and Pz electrodes.

4. Discussion

This study investigated the effects of Zen meditation on cognitive performance, as well as on neuronal activity changes in experienced meditators and novices during the emotional Go/No-Go paradigm. Throughout the whole experimental session, EEG and ECG recordings were applied.

4.1 Self-Reported Questionnaire Results Overview

Statistical analysis using Independent Sample t-tests was conducted to determine significant differences between meditators and non-meditators in meditation-related questionnaires. No significant difference was found between the groups in total MAAS score. While there were no significant differences in overall scores in DERS scale, the Awareness facet analysis demonstrated that non-meditators scored significantly higher compared to meditators, indicating lower self-reported emotional awareness. In contrast, in the FFMQ and MAIA scales significant difference in overall score was found between the groups, with meditators scoring higher than novices. Specifically, in the FFMQ scale, non-meditators scored considerably lower in the Observing subscale, which portrays paying attention to internal and external stimuli. Similar patterns of lower scores were observed in the Describing facet, related to expressing one's internal experiences and emotions through words. In the MAIA questionnaire assessing interoceptive abilities, meditators showed significantly higher scores than novices, specifically in Attention Regulation, Self-Regulation and Body-Listening components. The results of MAIA suggest that experienced meditators have greater abilities in maintaining their attention regarding body sensations, regulating distress by attending to their internal experiences and using their body signals as a source of insight. Lastly, non-meditators showed significantly greater worry tendencies as assessed by PSWQ scale. The results are consistent with previous studies, which suggest that meditation practice can be associated with more mindful attitude, greater interoceptive and attentional awareness, as well as emotional regulation (Ehmann et al., 2025; Fox et al., 2012; Lykins & Baer, 2009; Robins et al., 2012; Zhang et al., 2019). Furthermore, these findings indicate that the questionnaires used in the present study successfully detected group differences according to the original hypothesis.

4.2 Behavioural Results Overview

Accuracy, error rates and reaction times variables were analysed and compared between groups and the three conditions. Performance of both groups in the Go accuracy trials differed significantly between the conditions, as greater accuracy rates were observed in the Neutral condition compared to the emotional ones. These findings may be explained by the dual competition model which suggests that task irrelevant emotional information competes for limited processing resources involved in response inhibition and response execution, potentially leading to impaired behavioural performance (Pessoa, 2009). Furthermore, Post-hoc analysis showed that meditators outperformed novices, achieving significantly higher Go accuracy rates in the Neutral condition. Significant Group by Condition interaction can indicate that the emotional context influenced the performance differently across both groups, which may reflect that Zen meditation can modulate attentional performance in the presence of emotional distractions. Although studies specifically focusing on the effects of Zazen on affective stimuli are limited, this interpretation is supported by previous literature showing that mindfulness meditation may reduce emotional interference by more rapidly reorienting meditators' attention from emotionally salient stimuli (Ortner et al., 2007). In the No-Go accuracy trials a weaker pattern was observed, as there was no significant difference between the two groups. However, the accuracy varied across the conditions, with the highest accuracy in the Happy condition, compared to Neutral and Angry conditions. While meditators showed slightly better performance compared to novices across the three conditions, the main effect of Group was not significant. Taken together, the findings from the Go and No-Go accuracy trials suggest that emotional context affected task performance, overall reflecting a different effect of emotional stimuli on meditators and non-meditators in the Go trials.

The analysis of the omission rates in the Go trials showed a significant effect of the emotional stimuli on performance. In particular, the Angry condition exhibited the highest omission error rates, followed by Happy and Neutral conditions across both groups. Pandey and Gupta (2022) argued that the processing of angry facial expressions requires greater attentional resources than the processing of happy and neutral expressions, which may account for the present findings. Results also showed that experts committed fewer omission errors compared to novices in the Happy and Neutral conditions, further indicating different effects of emotional stimuli on meditators and non-meditators during the Go trials. The significant effect of Condition on No-Go commission errors suggests the emotional stimuli might have influenced inhibitory control, which aligns with Verbruggen and De Houwer (2007), who reported that emotional images can impair response inhibition by increasing stopping latencies. Contrary to the hypothesis, neither the main effect of Group nor Group by Condition interaction reached statistical significance in the No-Go error trials. Similarly, the reaction time (RT) analysis did not reveal any group differences in regard to response speed. However, a significant main effect of Condition was observed, as both experienced and non-experienced meditators showed slower RTs in the emotional conditions compared to the neutral condition. This may indicate that emotional stimuli could require greater cognitive processing demands in both meditators and non-meditators. Slower RTs observed in the emotional conditions are in line with previous research suggesting that the reaction time delay can be a consequence of emotional interference with the ongoing processing of relevant stimuli and response inhibition (Bailey, 2023; Verbruggen & De Houwer, 2007). Although no main effect of the Group was observed across the Go\No–Go task, the behavioural findings of the present study are in line with those reported by Andreu at al. (2019). In particular, both studies demonstrated emotional interference on response speed, while meditators committed less errors and showed higher accuracy rates in specific conditions compared to the control group.

4.3 EEG Results Overview

At a neurophysiological level, despite no significant effects of Group or effect of Group by Condition, a significant main effect of Condition was observed in the Go/No-Go paradigm. The analysis of the EEG waveforms signal revealed a modulation of ERP responses by the emotional conditions at the early and late post-stimulus time frame, suggesting that emotional stimuli influenced neuronal activity during the task execution. During the Go trails, N2 amplitudes were the largest for happy facial expression, followed by a smaller effect of angry expressions. Moreover, EEG waveforms suggested heightened fronto-central activity in response to emotional expression in the Go trials, which may reflect greater neuronal sensitivity to emotional rather than neutral stimuli. During the No-Go trials, happy and angry facial expressions were associated with slower rise and delayed peak of the P3-like amplitude. In contrast, neutral face expressions elicited earlier and more pronounced positive peaks. The findings suggest a presence of emotional interference on neuronal mechanisms underlying inhibitory processes. The absence of the main effect of Group may imply that effects of a long-term meditation might be subtle or may require more fine-grained analyses. These results align with Andreu et al. (2019) findings of a significant effect of emotional stimuli on N2 and P3 activity and that meditation-related neuronal differences may not consistently manifest through standard ERP amplitude measures, suggesting including more sensitive analyses approaches.

In summary, the hypothesis regarding enhanced behavioural performance by experienced Zen meditators than novice was partially met, as they demonstrated more stable behavioural performance and committed fewer omissions errors under emotional conditions. Observed modulation of P3-like and N2-like EEG components was specifically associated with emotional stimuli. Contrary to the initial hypothesis, expert meditators did not present an enhanced neuronal processing compared to novices.

4.4 Limitations and Future Research

The limitations of the present study should be acknowledged. Future research should consider recruiting larger and more age-homogeneous groups in order to reduce potential variabilities. Additionally, practicing meditation in a more natural setting rather than in a laboratory environment, could enhance meditation quality and ecological validity. Finally, it was difficult to ascertain whether the participants were actually engaged in the meditation practice, and the subjective ratings could be replaced by more thorough assessment. Future studies should also explore the effect of meditation practice in everyday life as the results may differ from the computerized tasks findings.

5. Conclusion

In conclusion, the present study suggests that long-term Zen meditation practice may be associated with a greater tendency towards behavioural stability regarding emotional interference. Although task performance of both groups was affected by emotional stimuli, experienced meditators showed more stable performance across the three conditions, whereas non-meditators appeared to be more influenced by emotional stimuli. Broadly speaking, these findings suggest that emotional interference may differently affect cognitive performance of meditators and non-meditators during response inhibition task. In contrast to the initial hypothesis, the EEG findings suggest that emotional facial expressions significantly influenced neuronal activity underlying response inhibition processes regardless of meditation expertise.

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Appendix A

Results of Self-Reported Questionnaires

Appendix A presents descriptive and inferential statistics for the self-reported questionnaires, including Five Facet Mindfulness Questionnaire (FFMQ), Multidimensional Assessment of Interoceptive Awareness (MAIA), Mindful Attention Awareness Scale (MAAS), Penn State Worry Questionnaire (PSWQ) and Difficulties in Emotion Regulation Scale (DERS).

Table A1

Questionnaire Results of Five Facet Mindfulness Questionnaire

FFMQ Scale	Meditators	Non-Meditators	*t* (62)	*p*	Cohen's *d*
	M (SD)	*M (SD)*			
Total Score	146.53 (19.12)	134.50 (18.27)	2.574	.012	0.64
Observing	31.16 (5.36)	27.19 (4.69)	3.154	.002	0.79
Describing	31.53 (5.38)	28.44 (5.84)	2.204	.031	0.55
Acting Awareness	28.56 (5.42)	28.69 (6.09)	−0.087	.931	-0.02
Non-Judging	31.22 (5.98)	30.00 (5.49)	0.849	.399	0.21
Non-Reactivity	23.06 (6.12)	20.88 (4.39)	0.644	.105	0.41

Note. M = Mean; *SD* = Standard Deviation

Table A2

Questionnaire Results of Multidimensional Assessment of Interoceptive Awareness

MAIA Scale	Meditators	Non-Meditators	*t* (*df*)	*p*	Cohen's *d*
	M (SD)	*M (SD)*			
Total Score	113.78 (19.30)	97.41 (19.42)	3.38 (62)	.001	0.85
Noticing	3.76 (0.80)	3.48 (1.00)	1.36 (62)	.230	0.30
Not-Distracting	2.55 (0.76)	2.27 (0.89)	1.36 (62)	.179	0.34
Not-Worrying	3.13 (1.06)	2.66 (1.07)	1.76 (62)	.084	0.44
Attention Regulation	3.67 (0.72)	3.07 (0.96)	2.81 (61)	.007	0.71
Emotional Awareness	3.96 (0.82)	3.53 (1.02)	1.90 (62)	.063	0.47
Self-Regulation	3.83 (0.73)	2.77 (1.06)	4.63 (61)	<.001	1.17
Body-Listening	3.26 (1.07)	2.68 (1.12)	2.15 (61)	.036	0.54
Trusting	3.71 (1.07)	3.65 (1.05)	0.236 (61)	.815	0.06

Note. M = Mean; *SD* = Standard Deviation

Table A3

Questionnaire Results of Mindful Attention Awareness Scale

MAAS Scale	Meditators	Non-Meditators	*t* (62)	*p*	*Cohen's d*
	M (SD)	*M (SD)*			
Total Score	4.59 (0.76)	4.32 (0.73)	1.47	.146	0.37

Note. M = mean; *SD* = Standard Deviation

Table A4

Questionnaire Scores of Penn State Worry Questionnaire

PSWQ Scale	*Meditators*	*Non-Meditators*	*t* (62)	*p*	*Cohen's d*
	M (SD)	*M (SD)*			
Total Score	42.53 (9.03)	49.78 (10.91)	-2.90	.005	-0.72

Note. M = mean; *SD* = standard deviation

Table A5

Questionnaire Scores of Difficulties in Emotion Regulation Scale

DERS Scale	Meditators	Non-Meditators	*t*	*p*	Cohen's *d*
	M (SD)	*M (SD)*			
Total Score	37.28 (10.05)	37.59 (11.61)	-0.12 (62)	.909	-0.03
Goals	6.56 (2.36)	6.16 (2.62)	0.65 (62)	.516	0.16
Nonacceptance	7.19 (2.07)	6.94 (2.51)	0.43 (62)	.666	0.11
Impulse	5.53 (2.36)	5.47 (1.85)	0.13 (62)	.899	0.03
Clarity	6.06 (2.00)	6.00 (2.51)	0.11 (62)	.913	0.03
Awareness	5.03 (1.69)	6.16 (2.62)	-2.27 (56.57)	.027	-0.57
Strategies	6.91 (2.09)	6.84 (2.90)	.010 (62)	.921	0.03

Note. M = mean; *SD* = standard deviation